Snow

Seminar Conducted by

WATER RESOURCES RESEARCH INSTITUTE

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Preface

The hydrology of snow and ice is an underdeveloped field of knowledge as compared to the hydrology of rainfall. To promote greater understanding of what is known about snow and ice hydrology and to identify areas of needed research, a series of weekly lectures was arranged during the Spring Quarter of 1969 on the Oregon State University campus.

Speakers were invited to address themselves to a wide range of subjects -- some of a general nature and others more technical. The mission was to appeal to an audience which included not only faculty members and students but also representatives of federal and state agencies, and the general public. We were fortunate in attracting to the lectern many outstanding men with years of experience in their professions. We trust the reader will find the following pages interesting as he reads about a subject which merits expanded consideration.

Emery N. Castle
Director

Corvallis, Oregon
July, 1969

The Institute

The Water Resources Research Institute was established at Oregon State University in 1960 by the State Board of Higher Education. It is designed to foster, encourage, and facilitate research and education related to all factors which affect the quantity and quality of water available for beneficial use. Membership includes personnel on campus who are engaged in water resources research and teaching, as well as those from other institutions of higher learning in the state who participate in the Institute's program.

Staff members provide both classroom and research instruction, and a graduate minor in water resources may be pursued by students majoring in one of numerous departments. At present, there are about 200 graduate students engaged in water-oriented programs in approximately 20 member departments.

Extensive facilities are available for both faculty and students. These include forested watershed lands and associated field equipment, soils laboratories, growth chambers, water and waste treatment plants, experimental waste treatment facilities, freshwater and marine science laboratories, experimental streams, a computing center, a hydraulics laboratory, a radiation center, and technical libraries.

Research assistantships and fellowships are available through many of the member departments. The Institute provides support for selected portions of the research and training program in water resources in Oregon. It works very closely with individuals and organizations off campus in helping to solve the state's water problems.

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Presented April 3, 1969 by WILLIAM P. ELLIOTT, Department of Oceanography, Oregon State University.

The Formation and Fall of Snow

If one tries to examine snowflakes captured outdoors in a snow storm one is usually disappointed to find they do not look like the lovely photographs seen in books. This is because very few snowflakes that reach the ground, particularly near sea-level, do look this way. Most of the photographs are made in the laboratory of laboratory-produced snow crystals and bear only a small resemblance to those nature delivers to our doorsteps. However, if one were to capture snow crystals in a cloud where they originally form, or observe them on mountain peaks near their source, the familiar symmetrical, usually hexagonal shapes, would be found. The explanation lies in the life history of the flake.

A single ice crystal is usually formed around a special small particle floating in the atmosphere. These particles are probably composed of certain clays which have been raised from the Earth's surface by the wind. There is also some thought that meteoric dust of extra-terrestrial origin may contribute some nuclei but this is not yet proven. In any event, if conditions are right, water vapor will freeze on these particles. When water freezes it does so usually in hexagonal crystals. The reasons for this shape are found in the crystal structure of water and the nature of the chemistry of the molecules.

Experiments have shown that the form of the crystal depends upon the temperature and the humidity of the air in which it forms. Some crystals look like the star patterns one frequently sees portrayed, others appear as hexagonal plates; still others as hexagonal columns or needles.

These crystals do not always form where the air temperature drops just below freezing, but usually do appear at much colder temperatures. Most of the particles need temperatures at least as low as -10°C before they will act as freezing nuclei and many need even colder temperatures. It is possible to find drops of unfrozen water floating in clouds at temperatures below -30°C in the absence of these nuclei.

WATER VAPOR ATTRACTED

Since the original snow crystal usually forms quite high up in the cloud it has a long distance to fall before reaching the ground. On its way to the ground it will pass through many layers with temperature and humidity distribution different from the one in which it formed. Thus it will have different patterns of growth as it falls through these layers and the snow flake which we finally see at the ground may be the result of all sorts of combinations of plates, branches, needles, etc. Furthermore, it may have bumped into other crystals with different past histories so it would be unusual if the flake arrived at the end of its journey with its original symmetry preserved.

Ice crystals have another important property; they attract water vapor much more easily than water droplets. If one should put an ice crystal into an atmosphere that has a lot of tiny water droplets in it one would see the ice crystal grow very rapidly and fall out while the original droplet would tend to evaporate. (Such an experiment can be done in the freezer).

This is of fundamental importance to the formation of precipitation, for it is one of the main mechanisms by which tiny cloud droplets form into a large rain drop. (It takes about a million cloud drops to form one raindrop.) It is on this basis, incidentally, that the ideas of artificial stimulation of rain by silver-iodide seeding are based. Silver iodide is a very efficient freezing nucleus and it appears to be active at warmer temperatures than normal freezing nuclei.

In our latitudes almost all rain starts as snow: snow becomes rain when it gets to temperatures above freezing. Thus it is more nearly correct to say that rain is melted snow rather than snow is frozen rain.[1]

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[1] For the sake of completeness it should be pointed out that rain can form in other ways besides this ice crystal process. The "bumping" together of droplets will also make enough big ones to fall but this process seems to be important in the initiation of rain only in regions nearer the Equator.

Besides sufficient water vapor and freezing nuclei the air must be cooled to allow the processes of condensation and freezing to take place. This is most readily accomplished by lifting the air to lower pressure where the expansion of the air permits it to cool. This lifting is usually brought about by one or more of three processes. Widespread lifting in storm systems (low-pressure areas where the air is brought into the system at low-levels and rises in the central part of the storm) is the most productive of precipitation. Also lifting of air masses blowing against mountain ranges can contribute to cooling and the combination of these effects in the Northwest brings about the high rainfall rates here.

Local hotspots can produce warm air "bubbles" which give rise to connective showers but, although the rain was originally snow, it is almost always too warm for the precipitation to be frozen when it reaches the ground. Thus it is only the first two mechanisms, lifting in storm systems and lifting by mountain barriers, that produce much snow on the ground.

WATER CONTENT OF SNOW

Before going on let us summarize the above. Snow forms when enough special nuclei are available at cold enough temperatures to produce ice crystals. These crystals grow at the expense of the surrounding droplets and eventually fall to the ground - still as snow if the air temperatures are about freezing. Large-scale storms encountering mountain ranges are the most efficient producers of snow (and indeed of all precipitation.)

Having followed the snow to the ground, we should now look at the geographical distribution of snowfall. From what has been said it is obvious that snow would be found where temperatures are cold, i.e. in high latitudes and on high mountains. While it occasionally snows on some of the high peaks in Hawaii and permanent snow cover can be found on some fo the mountains near the equator in South America and Africa, snow is largely a middle-latitude phenomenon. In the Arctic and the Antarctic less snow actually falls than in the subarctic but because of the extreme cold very little melts or evaporates.

Snowfall is commonly reported in inches of depth but this is less significant to the hydrologist than the water equivalent. One usually hears the rule-of-thumb that 10 inches of snow is equivalent to one inch of water but this is very rough indeed. It may take as much as fifteen inches or as little as 6 inches of snow to make an inch of water and extreme cases have been noted where 25 inches of snow were needed for an inch of water. Nevertheless, the following statistics will be given in inches of snow depth unless otherwise noted.

The snowiest regions of the United States are the Cascade-Sierra Ranges, the Rocky Mountains, and the Upper Great Lakes-Northern New England area. Outside the mountain areas the average snowfall reaches one hundred inches in Northern Michigan and Northern Maine. The Gulf States, Southern New Mexico, Arizona, and California receive only a few inches at best while the Middle tier of states average about 25". The amounts along the Canadian border contribute about one-third of the total annual precipitation observed there. This snowfall does contribute to water storage but usually its greatest hydrologic significance comes in the Spring when excessive snowfalls followed by sudden warming can contribute to disastrous flood situations such as those in the spring of 1969 in the Mississippi basin.

The situation is much more confused in mountainous terrain. Here snow varies greatly with elevation and mean snowfall figures are only representative, if that, of the immediate surroundings. Some examples, taken from the Alps where long term statistics are available, should illuminate this. The variability indicated would also be found in the Northwest.

In one thirty-five mile stretch of the Austrian Alps the annual precipitation varies from 47" at a height 1900 feet up to 72" at an elevation of 5900 feet and down to 22" at 2600 feet on the other side of the ridge. Intermediate values are found at intermediate points. Table I gives some other data, also from the Alps, showing the variability of snowfall with elevation. This makes extremely difficult the hydrologist's task of estimating snow amounts in a broad region.

TABLE I

Changing Proportions of Snow with Altitude in the Eastern Alps

Elevation in feet	Number of Days of Snowfall per year	Maximum Depth of Snow in inches	Number Days Snow on Ground
650	27	8	38
1300	32	12	55
2600	45	29	109
3940	62	47	138
5250	85	56	169
6560	113	79	212
7880	143	119	270
9840	188	215	354

With this forewarning some mean statistics for the West Coast might be interesting. In Washington State, at levels of 4000-5500 feet, normal wintertime snows may vary from 400 to 600 inches. In Oregon between 300 and 550 inches normally falls from 4500 to 6000 feet and in California mean amounts are about 450 inches at levels between 6000 and 8000 feet. In the winter of 1955-56 the Mt. Rainier Paradise Ranger Station (el. 5500') recorded 1000" (over 83 feet). As an example of what can happen in extreme cases a small valley in the Colorado Rockies, Northwest of Denver, once recorded 87 inches (over 7 feet) of new snow in 27 hours.

Errors in the actual measurement of snowfall (as distinct from measuring the snow on the ground) are easy to make. The gauges used to measure rain can produce errors of ± 5% even if well cared for. With windblown snow errors as high as ± 20% are easily made. Furthermore, the representativeness of a given measurement is particularly difficult to ascertain. Variations in forest cover, exposure to the wind, local terrain, etc., can all reduce the area over which a given sample is a valid estimate. It should be stressed that these statements apply to measurements of snowfall. Other speakers will discuss the problems of measuring the water equivalent stored in the snow pack.

As a final word of caution concerning snow statistics I wish to illustrate the dangers involved in interpreting mean snowfall data. Almost all statistics on mean precipitation are subject to the same sorts of problems and the more variable the quantity, the more one is likely to have the difficulty illustrated below.

I have taken these statistics from the records of precipitation at Corvallis in January. The 31-year average precipitation for January in Corvallis is about 6.5" but if we examine the distribution of rainfall in the various months of January which made up this average we find the following:

TABLE II

Distribution of January Precipitation in Corvallis*

Inches of Rain	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	>10
Number of Januarys with indicated rainfall	0	3	2	3	10	3	1	4	2	0	6

*For the years 1931 - 1964.

Here we see that only one January out of 31 came within 1/2" of the "normal". In fact, the best "forecast" for January would be 4" - 5". We can also see that about 2/3 of all Januarys are below normal. The answer lies, of course, in the six Januarys above 10". These exceptionally large amounts of rain boost the average up. But note again that the average value of 6-7" is one of the least likely to occur.

An even more striking example of biasing the average by extremes comes in the snowfall record for January for Corvallis. (These data do not include the excessive snow of January 1969). The 25-year January average snowfall is given as 4.9". This means that a total of 122.5" of snow fell in these 25 years. But in January 1952, a total of 52" of snow fell in Corvallis and are included in this average. This leaves 70" for the other 24 years, or an average of 3" per January

These types of distribution are not unique to Corvallis (altogether the 1952 snowfall was quite dramatic). Similar problems are found in all precipitation statistics.

This means that attempts to base long-range plans on <u>average</u> conditions must be looked at with considerable care. The possible errors in the measurements of snowfall are large, the representativeness of snowfall data in mountain areas somewhat under question. But even with good data, good areal representativeness, and long-term records, the average snowfall (or average precipitation) can be quite deceptive. The average is not necessarily the most probable value by any means. In fact, it is likely to over-estimate the most probable value for a given year, season, or month.

I'll close with a useful piece of advice. You can bet that the rainfall in Corvallis next January will be below normal. You have about a 65% chance of winning.

Presented April 10, 1969 by DR. GARY MAYKUT, Department of Atmospheric Sciences, University of Washington, Seattle, Washington.

The Properties of Deposited Snow

Snow is generally regarded as one of the most complex substances in nature. Although the physical and mechanical properties of deposited snow have been the subject of an increasing number of scientific investigations, many of the processes affecting these properties are not yet clearly understood. Snow is a transient material, ultimately being transformed into ice or converted into liquid water. Because of its inherent thermodynamic instability and proximity to its melting point, snow undergoes continual changes in structure and texture during its existence, with corresponding changes in its physical and mechanical properties.

Snow is especially sensitive to temperature, but mechanical stresses also alter its properties. Variations in meteorological conditions create discrete layers within the snow cover, each layer possessing an essentially independent set of characteristics. Snow thus tends to be inhomogeneous and many of its properties exhibit anisotropy.

Snow is a mixture of ice crystals, air, water vapor, and occasionally liquid water. Since it is permeable, air and water vapor are free to diffuse and convect throughout the body of the snow. Because its characteristics are such a complex function of its thermal and mechanical history, an individual snow sample is unique, and it is not surprising that measurements of snow properties show a large scatter.

Despite the difficulties in obtaining representative data, many of the gross features of fallen snow are well determined. Enough is known about the factors influencing snow on a large-scale that accurate forecasts of avalanches and runoff are now routinely made. In this lecture, we shall review some of the current knowledge pertaining to the physics of deposited snow.

METAMORPHISM

Newly deposited snow is a porous aggregate of hexagonal crystals whose form depends on the atmospheric conditions during their formation. The pores between the crystals are filled with air and water vapor. Immediately after deposition, the individual snow crystals undergo changes in shape which, after a few days, result in rounded, irregular grains of uniform size. This process is called destructive (equi-temperature) metamorphism. Figure 1 shows typical effects of destructive metamorphism on a single crystal stored at -2.5° C.

Initially, there is a rapid rounding of all sharp angles and spikes of the crystal. This is followed by the separation of the branches from the main body of the crystal, eventually resulting in a number of quasi-spherical particles. The smallest particles then vanish as the larger ones grow. The rate at which these changes occur increases with increasing temperature, being very rapid near the freezing point and essentially undetectable below about -40° C.

Various authors have attributed the cause of destructive metamorphism to differential evaporation and sublimation, migration of molecules along the surface of the crystal (surface diffusion), migration of molecules within the crystal (volume diffusion), plastic flow, or some combination of these processes. If a crystal is embedded in an oil or some other nonsolving liquid, transfer of mass through the vapor phase (and possibly along the surface) is eliminated. Single crystals have been preserved for as long as 3.5 years under such conditions, with almost no noticeable changes in form (Yosida et al., 1955). It thus appears that the changes associated with destructive metamorphism are predominantly the result of water vapor transport.

The saturation vapor pressure is greater over surfaces with a small radius of curvature than over those with larger or negative radii. Thus gradients of vapor pressure exist over the crystal and molecules diffuse from higher to lower vapor pressure. This produces a supersaturation and subsequent sublimation on those parts of the crystal with relatively less curvature. This mechanism explains the changes observed in Figure 1, however it has been pointed out that the rate of vapor diffusion is too slow to account for the speed with which these changes occur in nature (Yosida et al., 1955). It is thought that thermal gradients, convection in the pores, surface diffusion, or mechanical stresses may accelerate the transformation.

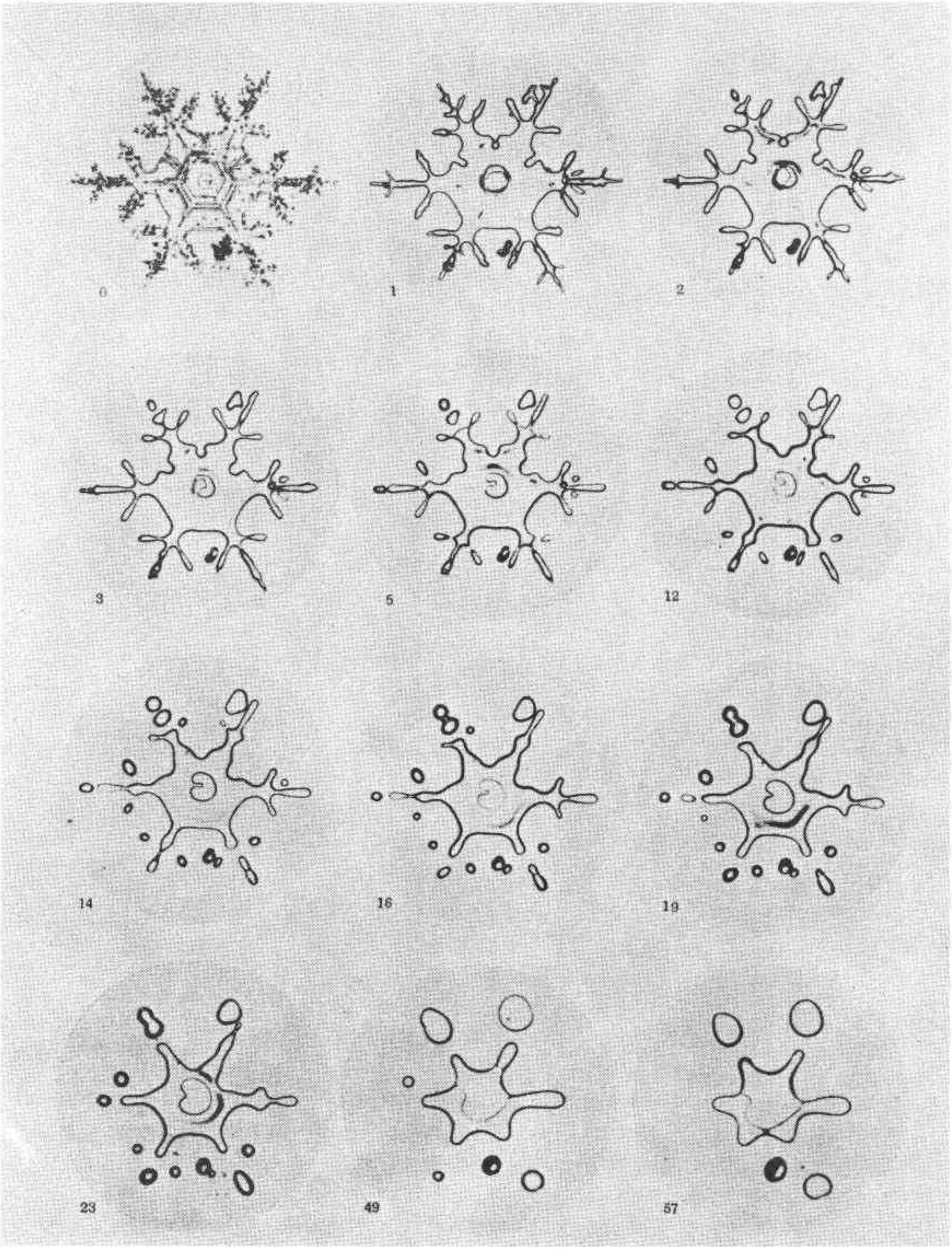

Figure 1. Metamorphism of a snow crystal in a closed atmosphere, temperature below -2.5 °C. Magnification 15X. Numbers to the left of the pictures indicate the age in days(from Bader, 1962).

The large temperature gradient which sometimes exists in a natural snow cover (Figure 2) gives rise to a second type of change, constructive, or temperature-gradient, metamorphism. Generally, temperatures in the snow increase with depth, reaching 0° C at the bottom of temperate snow fields. Because the saturation vapor pressure increases with increasing temperature, there is an upward flux of water vapor in the snow. Evaporation thus takes place on the warmer grains and sublimation on the nearby colder ones. This induces the formation of new crystals, having a tendency for their major axis to be parallel to the vapor pressure gradient.

These crystals are more stable than those formed in the atmosphere and generally persist throughout the winter. Under ideal conditions (thin snow cover, steep temperature gradient), intense growth occurs in certain portions of the snow cover, forming cup-shaped crystals of depth hoar (Figure 3) up to 15 mm in size. Depth hoar has high compressive strength, yet low shear strength, and is recognized to be a major cause of avalanches.

The upper portion of the snow is often subject to diurnal changes in the direction of the temperature gradient (Figure 2). Because of this and because of the larger vapor pressure gradient in the lower portion of the snow, recrystallization by constructive metamorphism is usually only well-developed near the bottom. Only during prolonged cold, dry spells is constructive metamorphism evident in the upper layers.

With the onset of spring melting, water begins to percolate into the snow, initiating melt metamorphism. As the snow becomes saturated, temperature gradients and their effects rapidly vanish, and the snow becomes isothermal. Heat is then transported only by the penetration of short-wave radiation and melt water.

Any remaining crystalline forms are destroyed and there is a loss of mechanical strength. The ice grains become even more spherical and tend to enlarge to a maximum size of about 3mm. Often the individual grains coalesce into polycrystalline grains, occasionally as large as 15mm across (Bader, 1962). As melt water penetrates the snow, it quickly forms drainage channels, rather than continuing to diffuse randomly between the grains. After the snow becomes saturated, the drainage channels formed, and melt metamorphism well advanced, the snow is considered to be "ripe". Subsequent melting of the snow then results in the discharge of water from the snow pack.

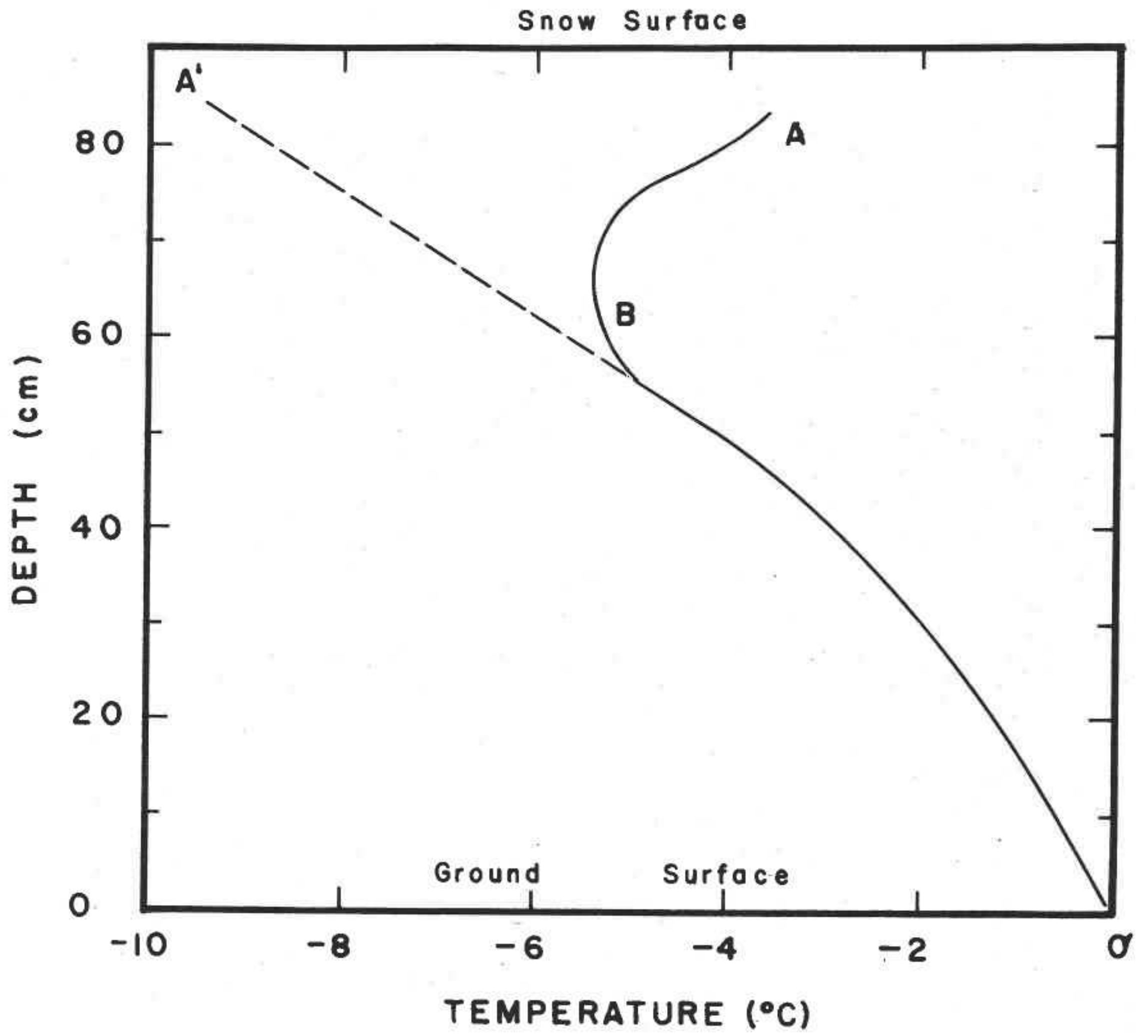

Figure 2. Typical vertical temperature distribution in a a natural snow cover. In the upper layers the distribution has the form AB during the day and A'B during the night (after Yosida et al., 1955).

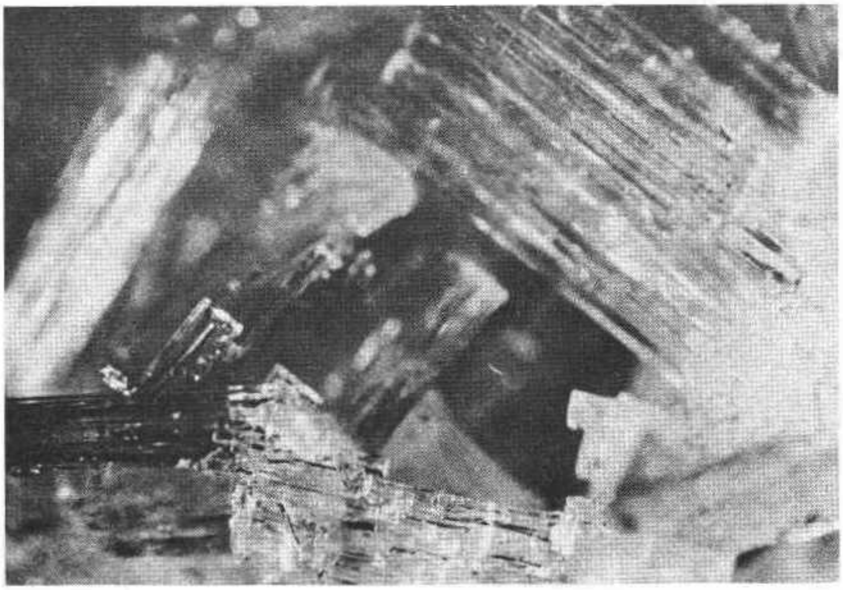

Figure 3a. Cup-shaped crystals of mature depth hoar(E. LaChapelle).

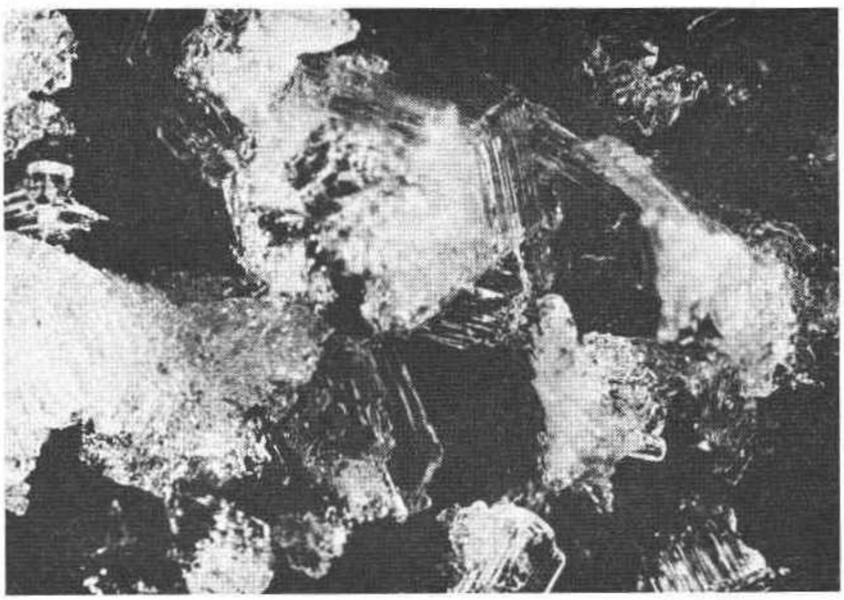

Figure 3b. Depth hoar in situ, Bertha Pass, Colorado(E. LaChapelle).

DENSIFICATION

Density is one of the key indicators of the physical state of the snow, as its value is related to grain size, thermal history, and mechanical properties. During the metamorphism process, density continually changes, but there is a trend toward higher values as the snow cover ages. Freshly fallen snow may have a density as low as 0.004 gm/cm^3 or as high as 0.3 gm/cm^3, depending on air temperature, crystal form, wind speed, and the rate of deposition; the average density being about 0.1 gm/cm^3.

As destructive metamorphism progresses, the large dendritic crystals break up and form small grains. Reduction in grain size causes a closer packing of the grains by gravitational settlement and an increase in density. Loading from above, through the accumulation of fresh snow, produces compaction and densification.

Large temperature gradients within the snow cover retard the rate of densification because of the effects of constructive metamorphism. Constructive metamorphism generally augments average grain size and gives the snow a high viscosity, which hampers densification by loading and settlement. After the initial settlement of the snow pack, intense thermal gradients may actually reduce the average density of the snow, especially in the lowermost layers.

Following the early stages of destructive metamorphism, it has been observed that grains which are in contact begin to form ice bonds or necks (Figure 4), even when the temperature is considerably below the melting point. The size of these necks increases with time. This process is known as sintering. The mechanisms responsible for sintering are probably the same as for destructive metamorphism: vapor transport, surface diffusion, volume diffusion, and plastic flow. From laboratory experiments with sintering spheres in an isothermal environment, it appears that vapor transport from the convex spheres to the concave necks is the most efficient growth process (Hobbs and Mason, 1964); however, it has been shown that volume diffusion may account for as much as 10% of the observed growth (Hobbs and Radke, 1967). Yosida (1969) feels that a thermal gradient is necessary to explain the sintering rates observed in natural dry snow.

As densification continues, the snow cover gains strength through sintering, and the grain size becomes more uniform. By the end of the winter, the density achieves values of 0.3-0.4 gm/cm^3.

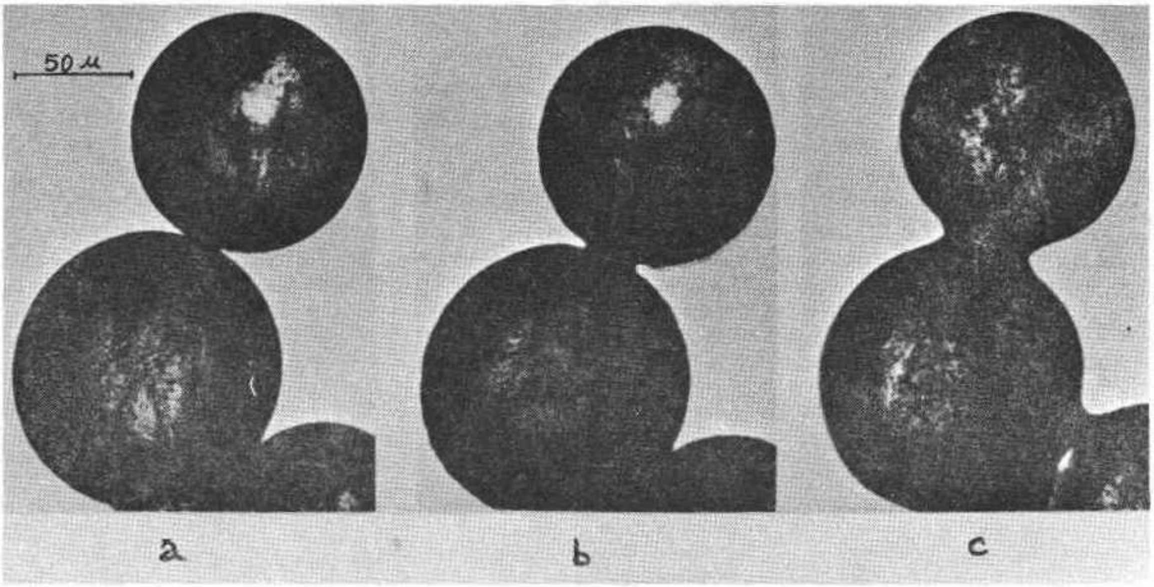

Figure 4. Sintering of two ice spheres in ice-saturated air at a temperature of - 5°C. (a) shows the initial contact, (b) was taken after 33 minutes, and (c) was taken after 64 minutes (From Kuroiwa, 1962).

With the introduction of melt metamorphism, sintering and densification proceeds at a rapid rate, until the density reaches about 0.5 gm/cm^3 in the early summer. The exact cause of some of the observed changes is not understood. Percolating water weakens the bonds between the grains and lubricates them, possibly allowing greater mobility and a more efficient packing of the grains. It is thought that the surface tension at the ice-water interface may promote sintering of the isothermal grains. The formation of the polycrystalline grains is most likely due to melting on convex surfaces and solidification on the concave ones, although other processes may contribute (Yoshida, 1969).

In polar and certain alpine regions, a perennial snow cover exists, consisting of a series of annual accumulation layers. The principal difference between these two regions is that the alpine snow is subject to melt metamorphism, while the polar snow remains dry. As snow accumulates at the surface, the lower layers are slowly compressed until they are converted to ice. Snow is defined to be ice when its permeability reaches zero (at a density of about 0.8 gm/cm^3). If density profiles are taken through a perennial snow cover, an abrupt discontinuity is observed at a density of about 0.58 gm/cm^3 (Figure 5).

This density is called the critical density. The discontinuity is believed to be the result of changes in the dominant mechanism of densification. The critical density corresponds to the close random packing of spheres and a density increase above this value cannot be achieved without deformation of the spheres. Thus, in the snow, vapor transport and surface diffusion cannot increase the density above about 0.58 gm/cm^3. Although volume diffusion may be important in the region near the critical density, ultimately the increasing load will cause visco-plastic flow to complete the transformation to ice (Hobbs and Radke, 1967).

It should be noted in Figure 5 that the overall densification rates for polar (dry) snow are less than half the rates for alpine (wet) snows, illustrating the importance of melt metamorphism in the densification process.

Anderson and Benson (1963) have used the concept of critical density to make a physical distinction between firn and névé. Firn is snow which has been wetted and survived at least one summer, but whose density is below the critical value. Névé is snow above the critical density, but which is less dense than ice.

MECHANICAL CHARACTERISTICS

Snow mechanics, as a science, is still in the developmental stage and a number of fundamental aspects are ill defined. The field is especially complex for several reasons: the properties of snow are highly temperature dependent, yet temperature exhibits large variations under natural conditions; the mechanical properties also have a strong dependence on density and grain size, both of which vary over a wide range; the snow cover is inhomogeneous and its properties appear to change with the direction of measurement; the individual grains may move in response to stresses; finally, the character of the snow is altered by the testing techniques and many of the results are not reproducible.

Determinations of such basic parameters as viscosity, strength, and Young's modulus show a broad scatter and these quantities are not precisely known. We shall avoid these complexities here and, instead, present a qualitative review of some of the most important mechanical characteristics of deposited snow.

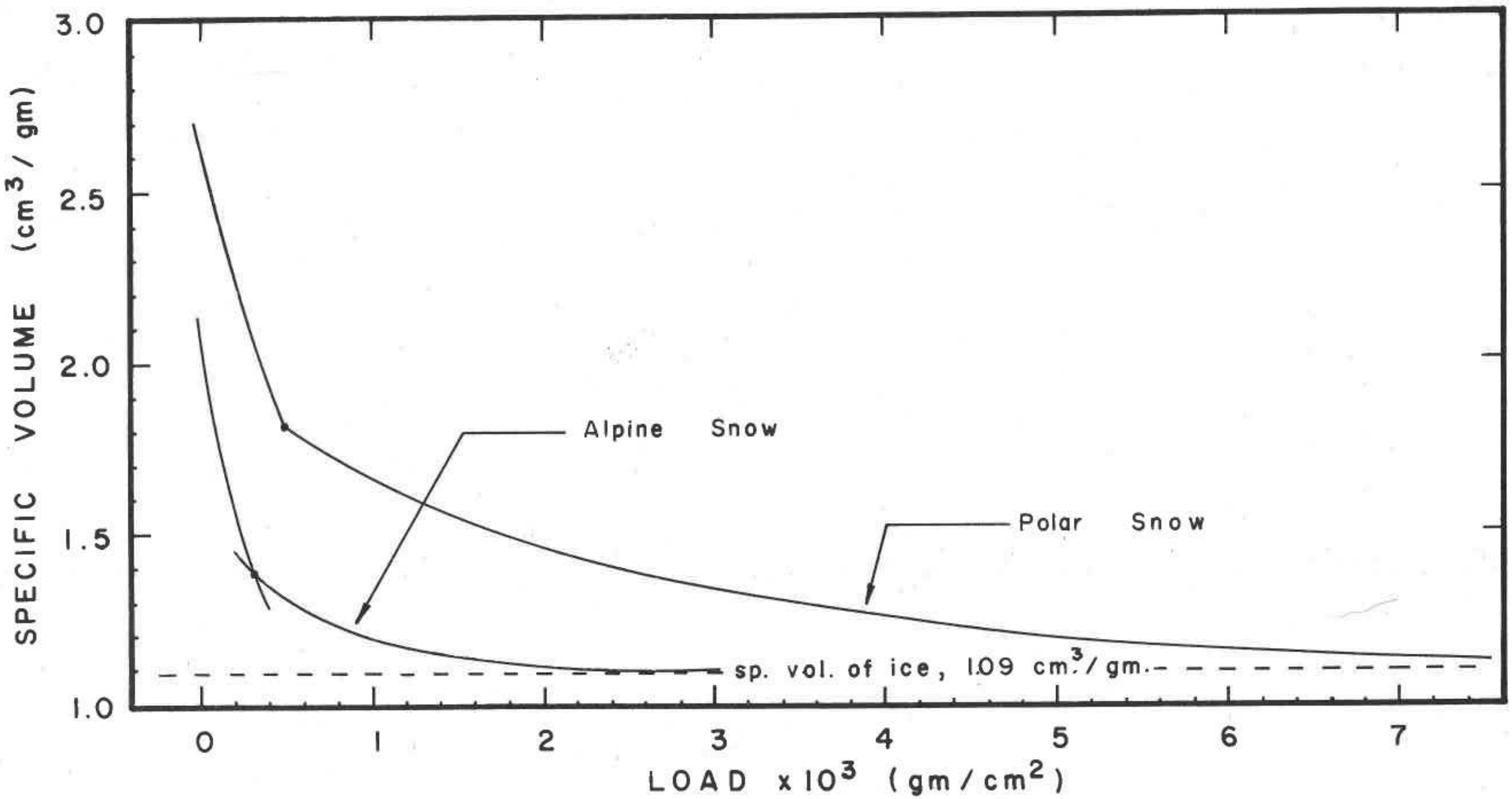

Figure 5. Specific volume of snow as a function of load. The upper curve results from observations of dry Polar snow in Greenland; the lower curve results from observations of wetted alpine snow (after Anderson and Benson, 1963).

Newly fallen snow consisting largely of stellar crystals, possesses a small, but definite, mechanical strength due to interlocking of the branched crystals and the presence of very weak bonds. After sintering begins, the grains become bonded into a coherent mass and the snow acquires an appreciable mechanical strength. If a beam is cut out of this sintered snow and suspended at its ends, the beam will slowly bend under the influence of gravity, i.e., it exhibits viscosity.

If a sudden stress were applied to the beam, it would simply break. Because its response appears to be viscous under some circumstances and elastic under others, snow is considered to be a visco-elastic substance. A simple experiment serves to illustrate how these two properties interact. A small weight is placed on a cylindrical sample of snow and the strain measured for a period of time; the weight is then removed (Figure 6). An elastic substance would show an initial contraction as the

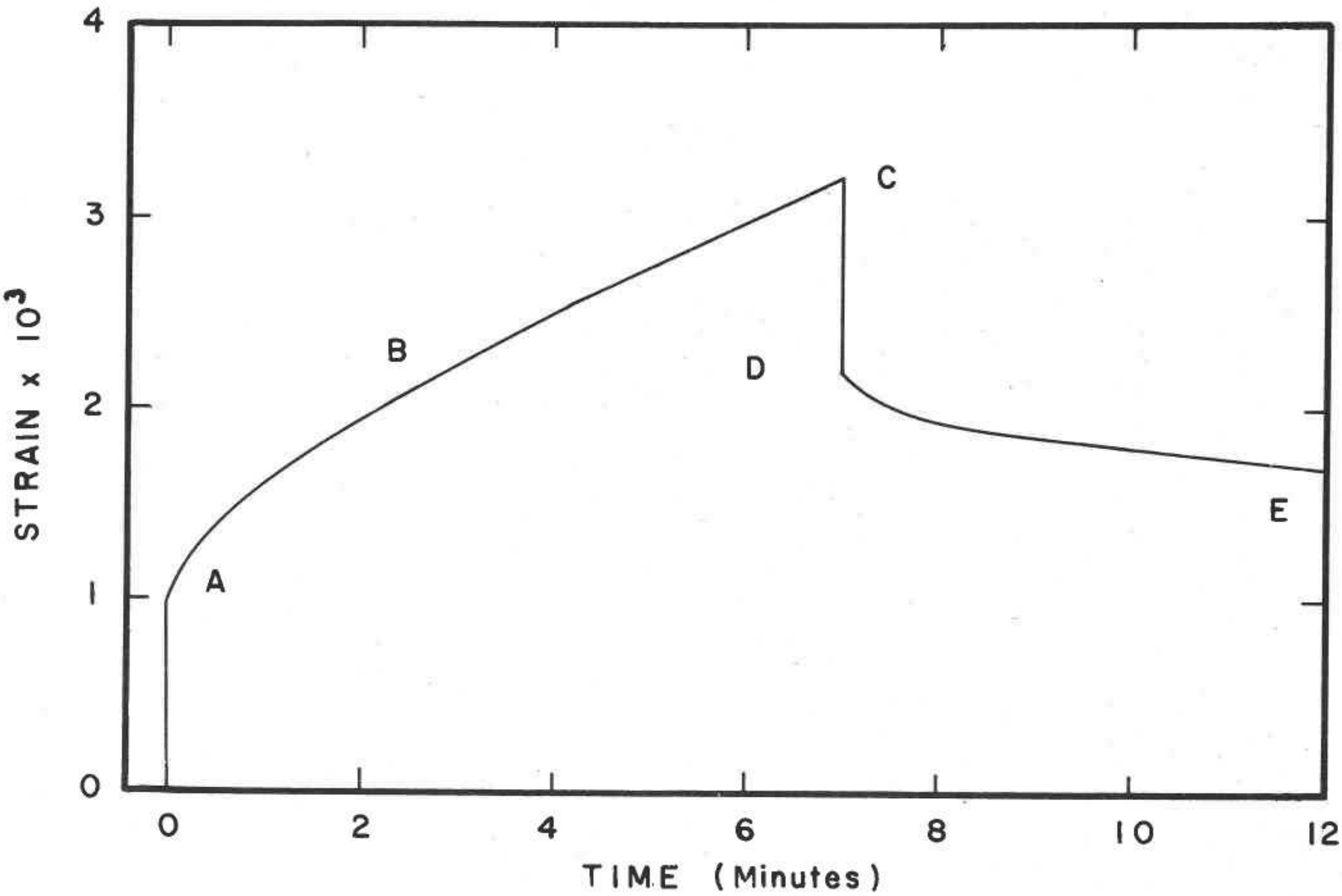

Figure 6. Strain (parallel to uniaxially applied constant stress) of a cylindrical snow sample as a function of time. The stress is removed after 7 minutes. Snow density is 0.19 gm/cm^3 and the temperature is -9° C (Yosida et al., 1956).

load is applied, but would regain its original length upon removal of the load. A viscous material would contract continuously as the stress is applied and would stop contracting when the stress is removed.

Figure 6 shows an immediate elastic contraction (OA), followed by a gradual viscous and elastic contraction (AB), and finally a linear, viscous contraction (BC). Removal of the load produces immediate recovery (CD) of the initial elastic strain (OA) and slow recovery (DE) of the part of the strain (AB) due to elastic contraction. There remains, however, a permanent deformation due to the viscous component of the strain.

For stresses less than about 600 gm/cm^2, the strain rate is a linear function of stress and the snow is said to be a Newtonian fluid. For larger stresses or high density snow, the linear relationship no longer holds and the snow behaves in a non-Newtonian manner. The region of Newtonian behavior tends to enlarge as temperature approaches the freezing point. Because snow is viscous it tends to flow or "creep" downhill and may, in addition, glide slowly along the ground under certain favorable conditions. In a deep snow pack, the combination of creep and glide may generate forces up to several $tons/m^2$ and must be considered in the design of structures in regions where snow creep occurs.

Theoretical models have been developed that describe the mechanical response of elastic solids which possess fluidity. These theories assume, however, that the material is incompressible and hence cannot be applied to snow. So far, little progress has been made in the development of a theory applicable to snow.

From an engineering standpoint, strength is one of the most important properties of snow. Snow strength is studied by measuring the resistance to tensile, compressive, or shear stresses. It was pointed out earlier that snow is weakened by constructive metamorphism and by the early stages of melt metamorphism, but is strengthened by sintering and densification.

Once the snow is compacted and grain movement eliminated (at a density of about 0.4 gm/cm^3 for polar snow and 0.5 gm/cm^3 for alpine snow), the mechanical properties become more predictable because sintering assumes the dominant role in determining snow behavior. Strength, for example, becomes a linear function of density in this region (Figure 7).

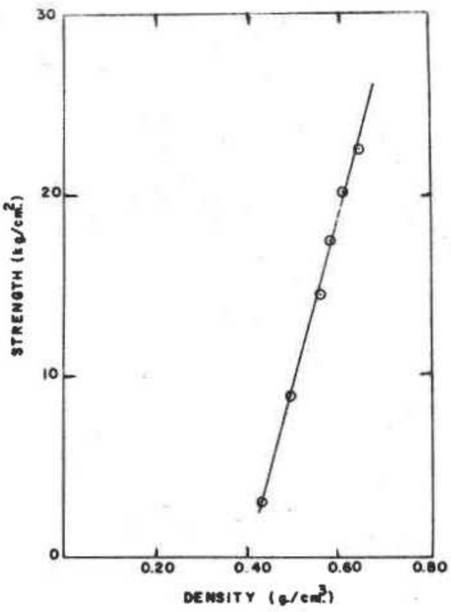

Figure 7. Strength of well-compacted Polar snow as a function of its density (after Butkovich, 1958).

If a sample of old compacted snow is kept at a constant temperature, many of its mechanical properties are observed to change with time. Hobbs (1965) has shown theoretically that if these changes result only from bond growth (sintering), the rate of change should be proportional to time to the 2/5 power. Compressive strength, work of disaggregation, hardness, and Young's modulus do, in fact, approximate a power law of this form and it follows that sintering must be the principal cause of the observed changes.

THERMAL AND RADIATIVE PROPERTIES

Because the properties of snow are so greatly influenced by temperature, it is important to understand the processes which transfer heat in the snow cover. In most solids heat is transferred by molecular conduction alone. In snow, heat is transported not only by conduction in the ice network and air in the pores, but also by convection of heat in the pores, convection and diffusion of water vapor through the pores, and, as snow is a translucent medium, by internal heating due to penetration and absorption of short-wave radiation.

Many of these processes are at least as important as conduction. The transport of water vapor carries with it a latent heat of sublimation of 676 cal/gm and the heat flux from this source has been observed to be of the same order of magnitude as from molecular conduction (Yosida et al., 1955). Calculations also indicate that convection in the upper few centimeters of the snow is several times more efficient at transporting heat than is conduction (Mantis, 1951). A substantial amount of heat can also be transferred by the refreezing of percolating water (80 cal/gm), if the snow is not isothermal.

Perhaps no single quantity better typifies the difficulties involved in measuring the parameters of snow than does the thermal conductivity. Not only does its value depend upon the density, texture, and structure of the snow, but it also must be determined in the presence of a temperature gradient.

Since the temperature gradient modifies the character of the snow, conductivity values traditionally vary during the period of observation. Also, the values which are measured must refer to "effective" conductivities as convection and diffusion are taking place along with the conduction. Figure 8 shows conductivity results obtained over the last 70 years. Few attempts have been made to relate conductivity to grain size or crystal structure. Due to its low conductivity, snow is an effective thermal insulator and benefits underlying vegetation by protecting them from winter temperature extremes.

Snow approximates a black-body in the infra-red. Since the long-wave emissivity is close to 1, snow absorbs nearly all incoming long-wave radiation and radiates according to the Stefan-Boltzmann Law. Snow, however, reflects much of the incoming radiation in the short-wave (visible) region. Albedos of 80-90% are common for fresh powder snow, but drop to 50-60% for melting snow. The absorption of short-wave radiation is complex and depends, among other things, on angle of incidence, grain size, density, and wavelength.

Certain wavelengths are absorbed strongly by the snow, while others (especially in the blue) penetrate to much greater depths. Although most of the short-wave radiation is absorbed within the first 20 cm, significant amounts may reach depths of 1 meter or more. Penetration of short-wave radiation is especially important in heat budget calculations. If a Beer's Law absorption is assumed, it is possible to calculate an extinction coefficient for snow. Extinction coefficients have been observed to vary between 0.03 and 1.5 cm^{-1}, according to the type of snow. More typical values are 0.1-0.3 cm^{-1}.

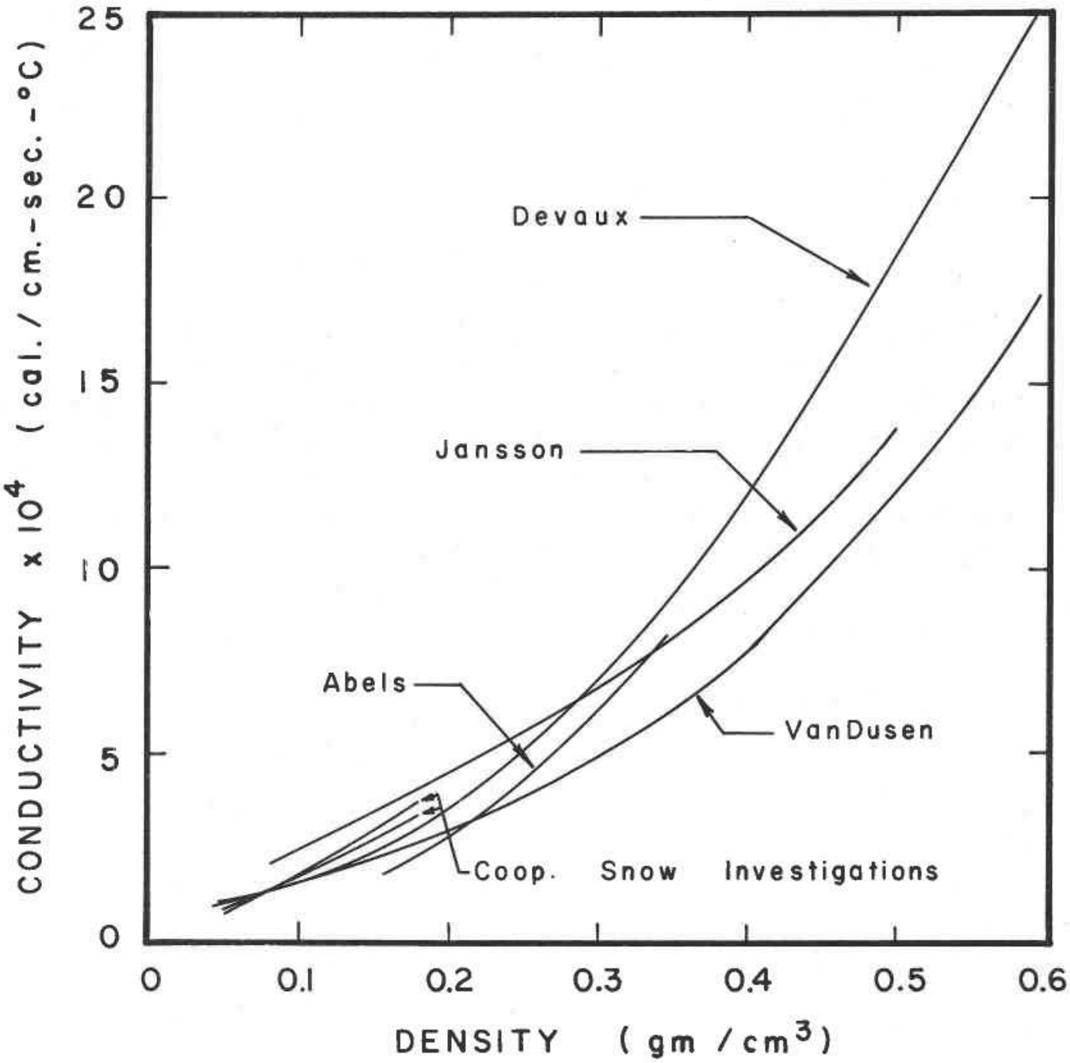

Figure 8. Thermal conductivity of snow vs. density as reported by various investigators (after Mantis, 1951).

HEAT BUDGET

Mass loss from the snow pack depends upon the energy balance at the surface (Figure 9). If all the energy fluxes are known, it is possible to predict ablation rates from the following balance equation:

$$(1-\alpha)F_r + F_L - \epsilon\sigma T_0^4 - I_0 + F_s + F_l + F_c = \begin{cases} 0 & , T_o < 0°C \\ -q\,\Delta H & , T_o = 0°C \end{cases}$$

where q is the latent heat of fusion for ice, ΔH is the ablation rate, and the other symbols are as in Figure 9. The convention is adopted that a flux is positive only if it adds heat to the surface. Although F_s and F_l may be in either direction, they are specified as being positive in the equation If the temperature at the surface is below the freezing point, any inbalance in the energy fluxes will be eliminated by a change in surface temperature and temperature gradients within the snow (F_c): if the temperature is at the freezing point, an increased energy input results in melting.

The net radiation balance $[(1-\alpha)F_r + F_L - \epsilon\sigma T_0^4 - I_0]$ depends upon latitude, cloudiness, albedo, and surface temperature, but usually is quite small or even negative. Since snow conductivity is low, the fluxes of sensible and latent heat therefore acquire significance in the energy budget of snow. These fluxes increase with increasing temperature and humidity gradients in the boundary layer, as well as with increasing wind speed.

At temperatures below the freezing point ablation may occur only through evaporation, however this is an inefficient mechanism. The heat required to evaporate 1 cm of snow would cause over 8 cm to melt if the surface temperature were at the melting point. Thus melting accounts for the principal part of spring and summer ablation. Unless there is a warm dry wind blowing over the snow, evaporation from snow is nearly negligible in terms of the energy budget. When the dew point is greater than the snow temperature, condensation occurs at the surface (with a release of about 600 cal/gm) and, if there is a vigorous wind, energy may be supplied at rates rivaling the radiation input. Rainfall adds little to the heat balance and is not a large factor in surface ablation.

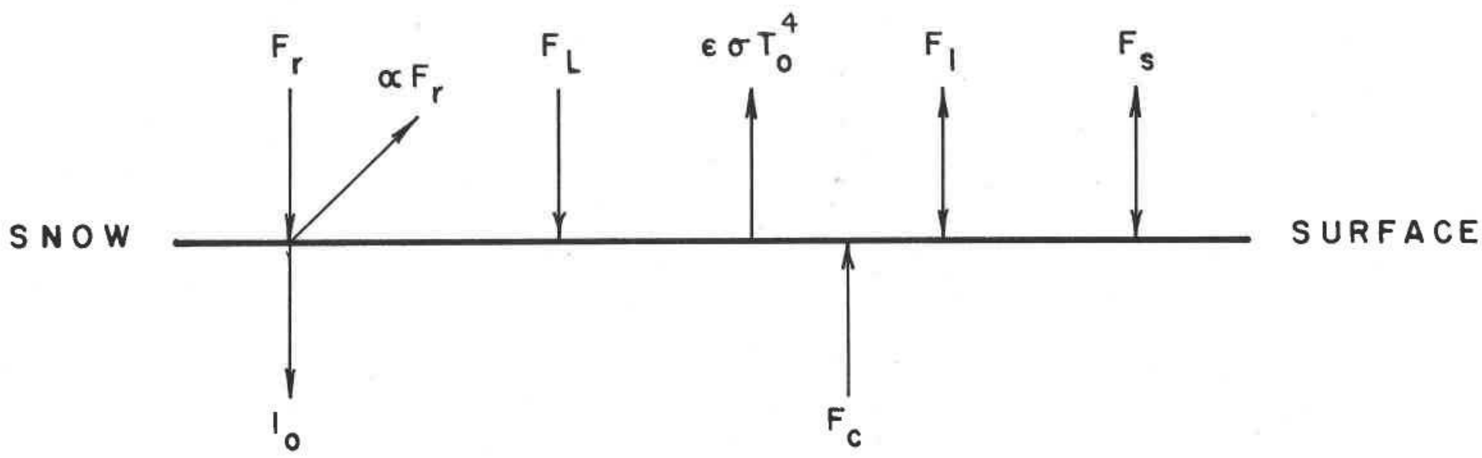

Figure 9. Components of the energy balance at the surface of the snow cover. F_r is the flux of incoming short-wave radiation, F_r the reflected short-wave radiation, F_L the incoming long-wave radiation, $\epsilon\sigma T_0^4$ the outgoing long-wave radiation, I_0 the amount of short-wave radiation which penetrates the surface but does not contribute to surface melting, F_l the flux of latent heat, F_s the flux of sensible heat, F_c the heat exchange with deeper layers of the snow, α the surface albedo, and T_0 the surface temperature.

Penetration and absorption of short-wave radiation is the only way in which energy may be added to the interior of an isothermal snow cover. A unique property of melting snow is that energy may be added to a snow layer which cannot be lost by conduction.

A physical demonstration of this is given by the formation of firnspiegel. With cold air temperatures and a small (or negative) radiation balance, there is little or no melting at the surface. However the radiation which passes through the surface (I_0) may melt cavities below the surface, leaving a thin ice layer over the cavities. Thus melting can occur (briefly) within the snow pack, without any visible surface indication.

CONCLUSIONS

As population increases, it is becoming increasingly critical that efficient use be made of our water resources. Snow is an important part of these resources. Even though we possess a great mass of observational data relating to snow, its properties cannot be completely determined from empirical evidence alone. The real need is for more basic research into the processes causing changes in the snow cover. When these mechanisms are more fully understood, we will be in a much better position to formulate theoretical models, allowing accurate predictions of snow behavior.

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Presented April 17, 1969 by HENRY W. ANDERSON, Project Leader, Hydrologic Analysis Methods, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, California.

Snowpack Management

Snowpacks throughout the West are increasingly being modified as high-elevation timber is harvested, roadways and power lines are cleared, brushfields are replanted, and fires, insects, disease, and gale winds devastate the forest. Research has provided some basis for estimating the impact of these changes on the West's water supply as well as for suggesting how we can manage snowpacks to improve water supply and control water.

In discussing the effects of snow management on water supply and water control, it will be necessary to consider not only the snowpack itself, but also the water from melting snow and the evaporative processes acting on snow water. First, I will summarize research results which have given quantitative expression to processes important to snowpack management. Then I will outline how we might cut forest, clear brushfields, and mechanically control snow accumulation in ways which will maximize water yield, modify snowmelt runoff, and control snow associated damages.

MANAGING FOREST SNOWPACKS

Results of research on managing forest snowpacks have indicated that forest cutting patterns and forest-terrain interaction have a major impact on snow accumulation, snowmelt, and water yield. I will discuss some of these impacts in terms of their effect on the distribution of falling snow, on the additions and losses from the snowpack caused by rain, evaporation, condensation, and drifting, and on the melting of snowpacks and the disposition of snowmelt waters.

Falling snow is almost a misnomer if we consider the complex path that snowflakes take from the free atmosphere to deposition in forests and forest openings. First, the forest and forest openings convert a nearly horizontal flowing stream of snowflakes to a turbulent mixture which only in a statistical sense is falling. Kuz'min (cited by Miller 1964) reported the average angle of falling snowflakes was only 4 degrees from the horizontal.

Rarely in the Sierra Nevada is wind not a factor during snowfall; Court (1957), for example, found that only 2 percent of the precipitation fell during calm periods.

Part of the falling snow is intercepted on the trees but only part of this is lost by evaporation. Many of the interception processes play an important role in the location and characteristics of snowpacks (Miller 1964, 1966). Without quantitative measurement of many of these complicated processes, any estimates of interception loss must be considered only approximate and tentative. However, the consistency of all estimates of interception loss as 10 percent or less of the precipitation probably suggests the proper emphasis which should be given to this evaporative loss in snowpack management (Rowe and Hendrix 1951, Anderson 1963, Anderson 1967).

Temporary storage of snow in trees has shown rather consistent maximum of about 0.2 inch (Goodell 1959, Miller 1964, Satterlund and Haupt 1967). However, for individual storm periods and for individual broken-top trees, snow platforms have built up with the equivalent of 5 to 10 times this ordinary maximum. Miller (1966) has described the transport of intercepted snow during snow storms, and Hoover (1960) has stressed the role of snow from trees in the build-up of snowpacks.

SNOW ACCUMULATION

How snow accumulates in various parts of forests and openings in forest under different conditions of topography and meteorology may explain the differences in snowpack between years and may serve as guides as to how snowpacks can be managed. Snow accumulation was studied at 250 individual points in the central Sierra Nevada of California (Anderson 1967).

I analysed snow accumulation during 16 periods from December 10, 1957 to March 28, 1958, which were characterized by wide differences in meteorological conditions. Points selected for analysis had maximum difference in topography and forest conditions, with a good distribution of points at openings in forests, within the forest margins near openings, and within continuous forest. Within continuous forest canopy points were selected in areas of uniform density of each of the following classes of canopy density: 20-50, 50-80, and 80-100 percent.

Openings within forests ranged from 1.7 to 7.5-tree heights across. Margins were the areas that surrounded forests equivalent in area to 1 1/2 times as great as the opening itself. The forests were largely of red fir and some lodgepole pine; trees averaged 88 feet tall, but in the analysis, the trees were characterized by their physical variables of shade and radiation rather than by species, or heights as such.

The relationship of snow accumulation to meteorological, topographical, and forest variables was obtained by reduced rank principal component analysis (Burket 1964, Wallis 1965). The analysis yielded interpretation of which physical variables were most important in explaining variation in snowpack accumulation and gave regression coefficients which allowed estimation of the quantitative effects of differences in forest under various terrain and meteorological conditions on snowpack accumulation. Detailed definition of variables and results are given in an earlier publication (Anderson 1967).

The differences in physical factors in explaining variation in forest openings, margins and continuous forest were:

Part of Forest	Storm Char.	Forest Shade	Solar Energy	Interception	Advec. Heat	Back Radiation	Total (R^2)	Std. Error
	-----	-----	-----	Percent	-----	-----	-----	Inches
Openings	86.6	0.0	3.4	0.3	2.1	0.5	92.9	3.4
Margins	75.3	0.7	6.4	0.2	1.7	1.1	85.5	4.1
Forest	80.1	0.7	0.3	0.5	3.3	0.2	85.1	5.2
All	82.1	1.1	1.6	0.1	1.3	0.8	86.1	4.1

The storm characteristics explain the largest part of the variation including both precipitation occurring during storms and storm wind. However, other variables contributed to the total explained variation which ranges from 85 to 93 percent. The standard error of estimates is also given; for example, the error estimate was 3.4 inches for forest openings, where average snow accumulation was 16.4 inches. Errors of estimates for margins and forests were somewhat higher.

In forest openings, forest margins, and areas within forest stands, the differences in snow accumulation associated with differences in variables during periods whose average precipitation was 19.6 inches were:

Variable	Opening	Margin	Forest
		inches	
Interception	0.5	1.7	2.1
Slope - North vs. South	3.0	3.0	(1/)
South winds	2.8	3.0	1.0
Shade			
South Slopes	3.8	0.8	1.1
North Slopes	1.9	4.9	2.1
Back Radiation			
South Slopes	-2.5	(1/)	(1/)
North Slopes	(1/)	(1/)	(1/)

1/ Negligible in these analyses.

These analyses suggest the wide contrast in snowpack accumulation which may be associated with two types of forest cutting -- uniformly removing trees within forest and cutting strips within the forest. If in both cases we cut 60 percent of the trees we see the average increases in snow accumulation (over that of 12.1 inches in a dense forest) were:

Types of cutting	Inches	Percent
Selection-cut	1.5	12
Strip-cut	5.3	43

Significantly about 30 percent of the increases in snow associated with the strip cutting was to be found in the margins of the cut areas. In another study, when one-quarter of a forest was cut in strips, the increase in snow accumulation was found to consist of 14 percent in the margins and 86 percent within the strip itself (Anderson 1963, p. 12). The results of analysis of 163 snow courses (Anderson and West 1965), when snow accumulation averaged 38 inches, showed increases in snow average equivalent of 7.2 inches in openings; however 40 percent of these increases was found to be in the margins.

The effect of dry years as contrasted with a wet year on forest and opening relations can be dramatic. The difference between the dry year of 1958 and the wet year of 1959 were:

	Snow at maximum pack 1958	1959
Snow Courses:	(inches of water)	
In forest near opening (area 1-1/2 times area of opening)	56.0	22.6
In opening (average, all sizes)	63.2	26.3
Within forest, 35% density	57.0	23.2
Within forest, 50% density	53.4	21.5
Within forest, 90% density	48.1	15.8
Opening associated snow (opening plus extra snow surrounding)	67.1	29.0

Note the greater percentage increase in snow in openings in the dry year, with the margins accounting for an even greater part of the snow increase associated with an opening in the forest.

We may conclude that forest openings and forest margins must be considered together in evaluating effects of cutting on snowpack accumulation. We may conclude further that many of the studies made in the past, when snow in forest openings was merely compared with snow in the adjacent forest, did not fully measure the total effect of the forest opening in increasing snow accumulation.

MELTING OF SNOWPACKS

Does it make any difference in how the snowpack melts if forests are cut or uncut and if forests are cut in different ways? Research results indicate that it does. Melt of the snowpack in dense forests, in large open areas, and in a cut strip under average conditions are shown in figure 1 (Anderson 1956). We found 12 inches more water in the snowpack at the time of maximum accumulation (April 1) in the cut strips than in the uncut forests.

Strips cut in the forest had only about one-inch more water than large unshaded areas. However, in the late spring (June 9), when all the snow was gone from large unshaded areas, 16 inches of water remained in the dense forest and 20 inches in the cut strip. The last snow disappeared from the dense forest and the cut strip about the same time--16 days later.

Recently a large-scale test of a strip cutting was made on the Tahoe National Forest near Yuba Pass, California (elevation 6,700 feet). Snow accumulation in the uncut forest was 19 inches; where one- quarter of the forest was cut in strips and another one-quarter thinned, snow accumulation increased by 4.7 inches (for the whole forest). Of this increase 70 percent persisted as delayed melt well into spring (May 21).

That test was intended to simulate the wall-and-step forest cutting pattern (figure 2) designed to maximize snow accumulation and delay melt. The pattern aims at maximizing the shade from the trees on one side of an opening cut in a forest and at the same time minimizing the back radiation from sunlit trees of the other side (Anderson, 1956). Elaborations of this cutting pattern for different slope exposures and management objectives are given in detail in a later publication (Anderson 1963, Appendix). Thus, forests may be harvested in ways which will not only increase snow accumulation but delay snowmelt. These differences in snow accumulation and melt may be expected to reflect in the amount and timing of water yield from watersheds.

EFFECTS OF LOGGING ON WATER YIELD

The effects of logging on water yield depend on both effects on snowpack accumulation and melt and on the losses from the snow and from the soil reservoir. Often, too, rain on snow and rain during non-snowpack seasons play a significant role in the water yield from watersheds whose primary yield is from melting snowpacks. Let us look first at some experimental results of harvesting of timber stands on water yield.

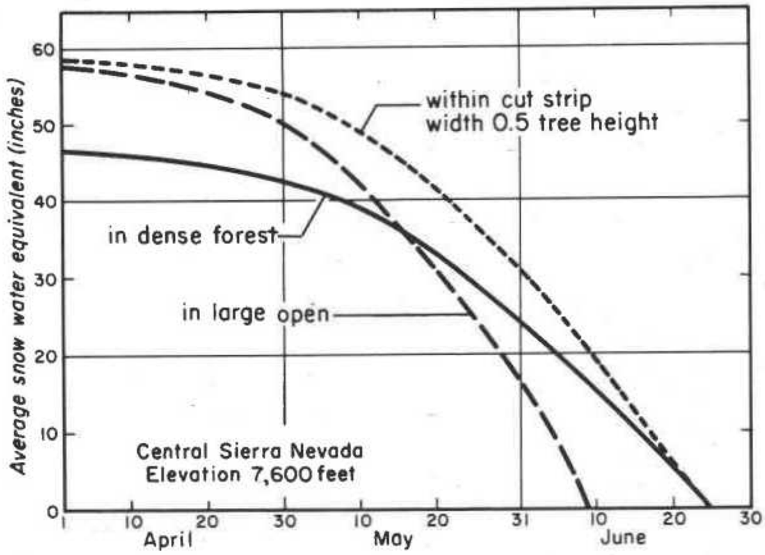

Figure 1. Snowpack water equivalent at various dates in an average year for two forest conditions and in the open.

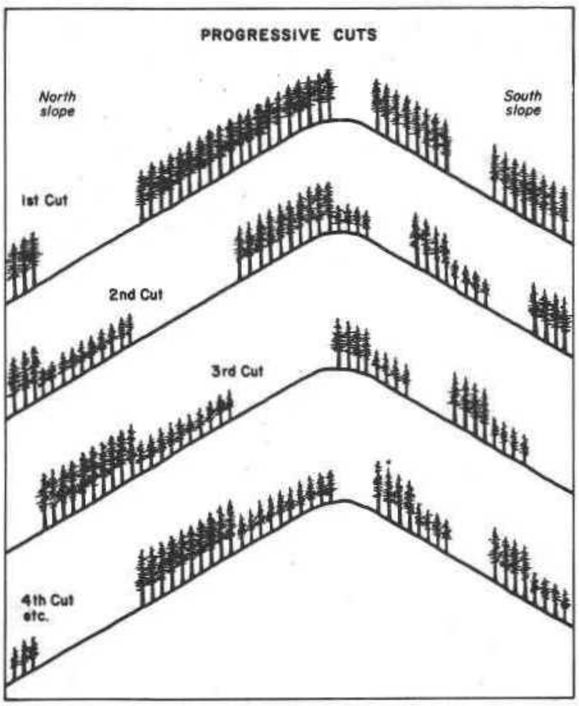

Figure 2. Progressive cuts establish wall-and-step forest in area rotation.

In Colorado, cuttings of 39 percent of lodgepole-spruce-fir forest strips of 1, 2, 3, and 6 chains width were begun in 1954 and completed in 1956. Goodell (1958) reported that streamflow from the watershed increased by 4 area-inches in 1956 and in 1957. Similar effects were found in a commercial selection cutting in California.

There, effects on streamflow of harvest of 2.8 million board feet from 1-square mile of a 4-square mile watershed in the Sierra Nevada were determined for the drought years of 1959 and 1960. Increase of streamflow for the logged area was equivalent to 7 inches deep or 400 acre-feet per year. In the California study, about one-half of the increased streamflow came in June.

CUTTING METHODS COMPARED

I have estimated the water available for streamflow under logged and unlogged conditions for commercial selection cutting, strip cutting, block cutting from results reported by Anderson and Gleason (1960). Results were obtained from a standard water balance equation -- yield equals precipitation minus interception, winter evapotranspiration, summer evapotranspiration, and fall evaporative losses. The method is useful in comparing relative effectiveness of different treatments but does not give exact values of yield. I have adjusted values previously reported in the light of more recent actual results of cutting on water yield so that the expected differences are as follows:

Forest Conditions:	Water Loss	Water Saved
	----------inches----------	
Unlogged	24	-
Strip-cut	12	12
Block-cut	15	9
Selection-cut	18	6

For the first year after logging, water yield increases under each logging method ranged from 6 to 12 inches. In the cut area itself, strip cut was most effective in saving water, the block-cut next, and the commercial least. About half the difference between commercial-cut savings and strip-and block-cut savings were in soil moisture losses -- water that is held over at the end of fall. That water will be yielded with the first winter melt or sometimes with late fall floods.

DURATION OF LOGGING EFFECTS

The duration of logging effects depends on the persistence of the effects of cutting on the snowpack accumulation and melt and the persistence of the logging effects on soil moisture and other evaporative losses.

Increases in snowpack accumulation have been found to persist for long periods after cutting of forests. In the study by the Rocky Mountain Forest and Range Experiment Station at Fraser, Colorado, (Rocky Mountain Forest and Range Experiment Station, 1956), increases in snow accumulation were found to persist 13 years after the initial cut. In a power-line clearing in California, the increases in snowpack diminished only about 20 percent after 10 years.

In contrast to the slow diminishing of snowpack accumulation with time after cutting forest, the saving in soil moisture tends to decrease quite rapidly -- especially under selection-type cutting. In a study in the Central Sierra, savings diminished by one-half in 4 years after a selection-type cutting (Anderson, 1963, p. 14). In the study of summer soil moisture losses in forest openings, Ziemer (1964) found that whereas logging saved 6.9 inches the first year of logging, this amount diminished to zero by the 16th year. Total saving in the cut strip for the 16-year period was estimated at 34 inches.

BRUSHLAND CONVERSION TO FORESTS

Brushlands may be converted to forests with some benefits to water supply during the conversion period and future benefits to snowpack accumulation and melt.

In a test in the Sierra Nevada of California, brushfields were cleared in strips by bulldozing manzanita and white thorn and windrowing the brush on contour (Anderson and Gleason 1960). Savings in soil moisture resulted. The initial field capacity storage of water in the soil was 18.5 inches of water. The final storage in the cleared and uncleared areas and water saving for soil 4-foot deep in each of the 4 years after clearing were:

	Final summer soil moisture			
	1958	1959	1960	1961
Treatment	------------inches------------			
Brush cleared	15.9	15.0	13.7	11.9
Natural brush	11.6	11.4	11.0	11.6
Saving	4.3	3.6	2.7	0.3

The savings in summer water losses were greater in deeper soils, less in shallower soils; in the shallower soils, the saving had diminished to zero by the fifth year.

Brushfields converted to forests may be also expected to delay yield of water through snowpack accumulation and delayed melt. For example, in 1959 at the elevation of 6,800 feet in the central Sierra (Nevada) area, melt in brushfields was 3 inches greater than in comparable large open areas bare of brush and 8 inches greater than from forested areas (Anderson 1963, p. 17). When all snow was gone from the brushfield, 7 inches more snow water remained in the forest. The quantitative results of brushfield conversion on streamflow must await experimental testing on watersheds.

However, small scale results promise at least temporary benefits in total water yield and long term benefits in delayed yield as well as increased timber values from the brushland conversion.

SNOW FENCES

Possibilities of using mechanical means of increasing late season snowmelt water yield through the use of fences near wind swept ridges have been demonstrated in experiments in Colorado. Lull and Orr (1950) reported that fences as well as natural tree screens helped pile snow into drifts, and thereby delayed melting. Martinelli (1966) reported that for each 100 to 125 feet of fence (8 feet high) he could expect 1 acre-foot extra water delayed for delivery after July 1.

MANAGEMENT EFFECTS ON FLOODS

Management effects on floods will depend on the kind of flood--snowmelt versus rain or rain-on-snow floods--the kind of management, and the time of water yield resulting from management. In one year, a management practice may increase the chance of floods, but in another, decrease floods.

Snowmelt floods periodically produce innundation in the great valleys of the West, usually in May and June. The amount of snowpack and its rate of melt are the prime cause variables. Alternate methods of forest management can affect snowmelt contribution to floods (figure 1). The synchronization of snowmelt from many parts of watersheds will determine the flood size from large watersheds. A different management practice in various parts of a watershed will augment or destroy such synchronization--and so affect floods.

Rain and rain-on-snow historically have produced large floods in California and Oregon. In contrast to snowmelt floods, these rain-on-snow floods are complex events with a dozen or more hydrologic processes combining to determine flood size from a particular watershed (Anderson 1962). Let us look at one of these processes operating on the snowpack itself during a rain event which produced the flood of December 21-24, 1964 in Oregon. For our example we will examine the contributions to the floods at the single point, Government Camp, Oregon (elevation 3900 feet) in December 1964. The snow storage, the melt by falling rain, the melt by advective heat associated with the air temperature, and the melt by the heat of condensation, produced these results.

Flood water sources:		Amount (inches)
Rain		11.5
Snowmelt		4.3
by rain	0.5	
by advection	1.4	
by condensation	2.4	
Condensate		0.3
Total		16.1

In the 3-day period (December 21-23, 1964) nearly 30 percent of the 16.1 inches of flood water was associated with snowmelt. Most of this was associated with advective and condensation melting of the snowpack, rather than melting by the rain itself. Studies of ablation of snowpack (Anderson 1956) suggest that the melt rate might have been reduced by forest shading by 40 percent. We might hypothesize that differences in ablation of snow in open areas versus shaded areas would have resulted, from this cause alone, in a difference in melt contribution of 1.6 inches or a difference in the flood runoff of 10 percent. Under other conditions, such as rain on soils with stored soil moisture, floods might be augmented by a particular type of forest management.

Maximum flood prevention can be expected to result from maintaining maximum use of water by vegetation, by maximizing the length of water flow paths, and by maximizing the diversity of snowmelt from parts of watersheds. Maintaining maximum use of water can be achieved, in order: by no cutting, selective cutting, or strip cutting on contour, and by maintaining deep rooted vegetation on deep soils and adjacent to channels.

Maximizing the length of waterflow paths can be achieved by restricting clear cutting to upper portions of slopes, by maintaining surface infiltration capacities and the opportunity for deep seepage of water, by prevention of soil freezing, and by draining roads away from channels to increase the water flow paths. Maximizing the diversity of snowmelt may be achieved by selective cutting on south slopes with no cutting or strip cutting on north slopes, or by drifting snow with natural or artificial barriers.

CONCLUSIONS

Research results have suggested how high-elevation snowpack forests can be managed for water production to meet such objectives as increasing water yield, delaying yield, and maintaining water control.

Snow accumulation and total water yield can be increased by cutting forests; interception and transpiration losses can be reduced without corresponding increases in evaporation from the snow and soil. Water yield can be delayed by cutting forests in patterns designed to slow snowmelt --retaining the shade of trees and minimizing back radiation of trees to the snowpack. Streamflow has increased after commercial timber harvesting and experimental cuttings.

Clearing brushland in converting to forest will increase water yield during the conversion period by reducing interception and transpiration losses. The pattern of the new forest can be designed and managed to delay water yield later than yield from the original brushland.

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Presented April 24, 1969 by TOM GEORGE, Snow Survey Supervisor, Soil Conservation Service, Portland, Oregon.

Snow Surveys and Water Supply Forecasting

In the western United States and Canada much of the spring and summer streamflow comes from the melting snowpack on the high mountain water sheds. To estimate the amount of spring and summer streamflow it is necessary to measure this snowpack. In 1909 Dr. James E. Church, a language instructor at the University of Nevada, first noticed this correlation between streamflow and the amount of winter-accumulated snow. He frequently determined the depth and water content of the deep snow on Mount Rose and related this data to the rise and fall of Lake Tahoe.

This started out as his hobby and in a few years became his full-time work. Gradually other organizations in other states began snow measurements so that they also could predict streamflow. By 1929 the state engineer was making regular surveys over a network of snow courses in Oregon. In 1936 the Soil Conservation Service was given the responsibility to coordinate the snow survey program in the western states.

Today there are more than 1500 snow courses in eleven western states. Forty-three different groups and agencies, such as irrigation districts and the U.S. Forest Service, cooperate to measure 180 snow courses in Oregon. Teams of at least two men travel by skis, snow-shoes, snowmobile, and helicopter each winter to find out the water content of the snow at these snow courses. Soil moisture and precipitation are also measured to be used in forecasting the snowmelt streamflow.

Advance knowledge of probable streamflow assists in the operation of flood reservoirs, power generation, and industrial and municipal water supply and tells the farmer how much water he will have for his thirsty crops.

SNOW MEASUREMENT TECHNIQUES

Since it is impractical to measure all the snow on a watershed, an index is obtained by selecting several different locations as snow-measuring sites. These sites are called snow courses. A snow course is usually 500 to 1000 feet long with predetermined sampling points at 50 to 100-foot intervals. Snow courses are located high on the watershed in an area that is protected from drifting winds and yet open so that the snow is not intercepted by trees. Each snow course is measured several times each winter by trained snow surveyors.

A snow surveyor is competent in measurement methods and trained in first-aid, avalanche hazards, and survival in the snow. These abilities are necessary because the snow survey team sometimes travels many miles in remote mountain areas under adverse winter conditions. Shelter cabins are provided in some areas for overnight stops and emergencies.

In addition to his survival "gear" a snow surveyor takes along a backpack of snow sampling equipment. The equipment consists of 30-inch sections of aluminum tubing. Enough sections are screwed together to reach through the snowpack to the ground below. On the outside of the tube there is an inch scale that indicates the depth of the snow. The bottom section has a serrated tooth cutter to cut through the ice layers in hard-packed snow. The backpack also contains a driving wrench and a weighing scale. The wrench is used to help drive the tube through the snow. The weighing scale is calibrated to weigh the snow core directly in inches of water. The value so obtained is the water content.

The depth of snow and water content is measured at each sampling point. Average depth, water content, and density are then algebraically determined.

If the location of a snow course is too hazardous, costly, or remote to reach on foot or by over-snow vehicles, snow surveyors record snow depth by reading graduated snow depth aerial markers from an airplane. The snow surveyors fly by at a safe distance above the ground and count the number of crossarms showing above the snow surface. The water content of the snow is then estimated by multiplying the observed snow depth by the snow density obtained from ground measurements at nearby snow courses.

Snow pressure pillows are used as water content sensors for the automatic-remote measurement of the snowpack. Snow pillows are made from pressure-sensitive materials such as sheet metal or rubber. The rubber snow pillows range from 6-12 feet in diameter. They are shaped like a "pillow" and are 2 to 4 inches thick if filled with an anti-freeze and water solution. The typical sheet metal ("tin") pillow is 4 feet by 6 feet by about 1 inch thick. The weight of the snow on the pillow creates a pressure which is changed to an electrical reading equivalent to the water content of the snow that can be radioed automatically from the snow course.

In Oregon the Soil Conservation Service has been testing a system of telemetered pillows for the past 3 years with some degree of success. This system consists of a base station located in Portland, two repeater stations, and four data sites.

The repeaters are located on Mt. Hood near Portland and Paulina Peak near Bend. The snow sites being telemetered are Peavine Ridge at the head of the Clackamas River, Irish and Taylor Lakes, Willamette Pass at the head of the Willamette River, and Cold Springs Camp on the Klamath River. The data sites can be automatically interrogated hourly or less frequently and manually at any time. The day of the year, time of day, station identification, and water content of the snow are printed out at the base station by a teletypewriter.

The information is also punched out on 8 channel paper tape which can be fed directly into a computer. Better and more frequent information on snow accumulation, peak accumulation, and snowmelt will be available as a result of snow pillows.

STREAMFLOW FORECASTING

Beginning in February and continuing through May and June the Soil Conservation Service issues water supply forecasts for 72 gaging stations in the State of Oregon. These forecasts provide farmers, ranchers, and other water users valuable advance information that is necessary in managing one of our most valuable resources--water. Water supply forecasting is a process that utilizes antecedent, current, and subsequent information for forecasting the seasonal (April- July) streamflow. Peak flows, date of peak, and the number of days until a certain stage occurs are other forecasts that are made.

The basic hydrologic equation used is: R = P-L; where R = runoff, P is precipitation and L is losses. Since it is impractical on large watersheds to quantitatively measure P and L, the following equation is then used: R = PI-LI; where

R = runoff

PI = precipitation index

LI = losses index

An algebraic example of a final equation after a detailed statistical analysis is:

$$Y = \pm K + b_{bf}BF + b_{fp}FP + b_{swe}S + b_{sp}SP$$

K is a constant.

b_{bf} is the base flow coefficient for weighting a base flow variable (BF).

b_{fp} is a fall precipitation coefficient for weighting a fall precipitation variable (FP).

b_{swe} is a snow water equivalent coeffiecient for a snow water equivalent variable (S).

b_{sp} is a spring precipitation coefficient for weighting a spring precipitation variable (SP).

Figure 1 (at end of article) illustrates the relationship between the April-July runoff of the Middle Fork of the John Day River at Ritter with a selected snow variable. The addition of more variables to the relationship, such as winter precipitation (Fig. 2) and spring precipitation (Fig. 3), shows the additional variability that can be explained by these parameters. The addition of base flow (Fig. 4) completes the equation. Because at the time of the forecasts in February, March, and April the spring precipitation is not known, average values are used in the equation at forecast time.

The relationship that has been illustrated is typical of eastern Oregon streams. Streams originating on the west flank of the Cascades are easier to forecast because their seasonal snowmelt runoff does not vary as much from minimum to maximum.

Peak forecasts can be made by plotting April-July volumes against their associated peaks (Fig. 5). Typically there is a close relationship between the volume and the peak. This type of information is valuable in flood forecasting.

Water users are often interested in the number of days a stream will stay above a certain stage and/or the date that it will fall below this level. This can be found out by developing the relationships previously mentioned and then plotting peaks against the number of days above a certain amount or stage (Graph - Fig. 5, 6 and 7).

Hydrograph forecasts are essentially a plotting of all the previously discussed forecasts. As runoff occurs the forecaster adjusts his hydrograph for the observed data.

BENEFITS OF THE WATER SUPPLY FORECAST

There are about 2 million irrigated acres of land in Oregon. Knowing what the water supply will be for the coming season is a real aid to the irrigator in planning his summer operations. How much water will he have ? Will he need supplemental water? What crops should he plant? These are all questions that are answered or partially answered by the water supply outlook information.

Advance forecasts of expected streamflow from snowmelt into reservoirs is a must for power production planning. Bonneville Power Administration estimates benefits of $350,000 per year on the average from water supply forecasts in the operation of three of their reservoirs, Hungry Horse, Libby, and Dworshak, in Montana and Idaho. Cities and towns are interested in potential water shortages as water restrictions are always unpopular.

Water supply forecasts are used as a guide in deciding when and how much water is to be released from flood control reservoirs in Oregon and throughout the West. Savings from flood damage by reservoir storage on the Columbia River and its tributaries was estimated at $93,000,000 during the 9-year period, 1956-64.

CONCLUSION

In Oregon and throughout the West water supply forecasts are necessary for the efficient use of one of our most important resources--water. Accurate and timely forecasts based on snow survey and other related hydrologic information help to promote the economy of any area depending on watershed snow for its water supply.

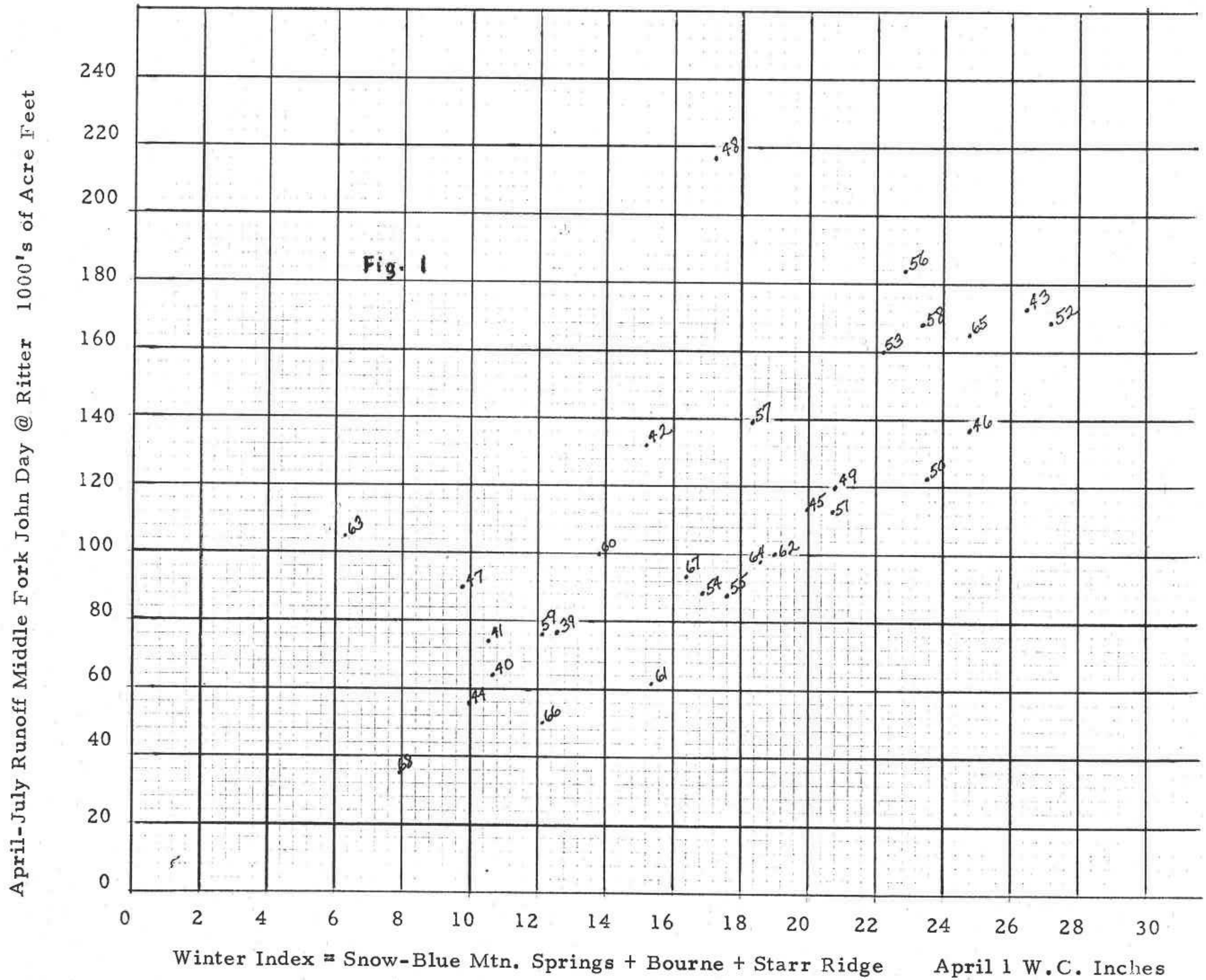


Fig. 1
240
220
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
April-July Runoff Middle Fork John Day @ Ritter 1000's of Acre Feet
Winter Index = Snow-Blue Mtn. Springs + Bourne + Starr Ridge April 1 W.C. Inches

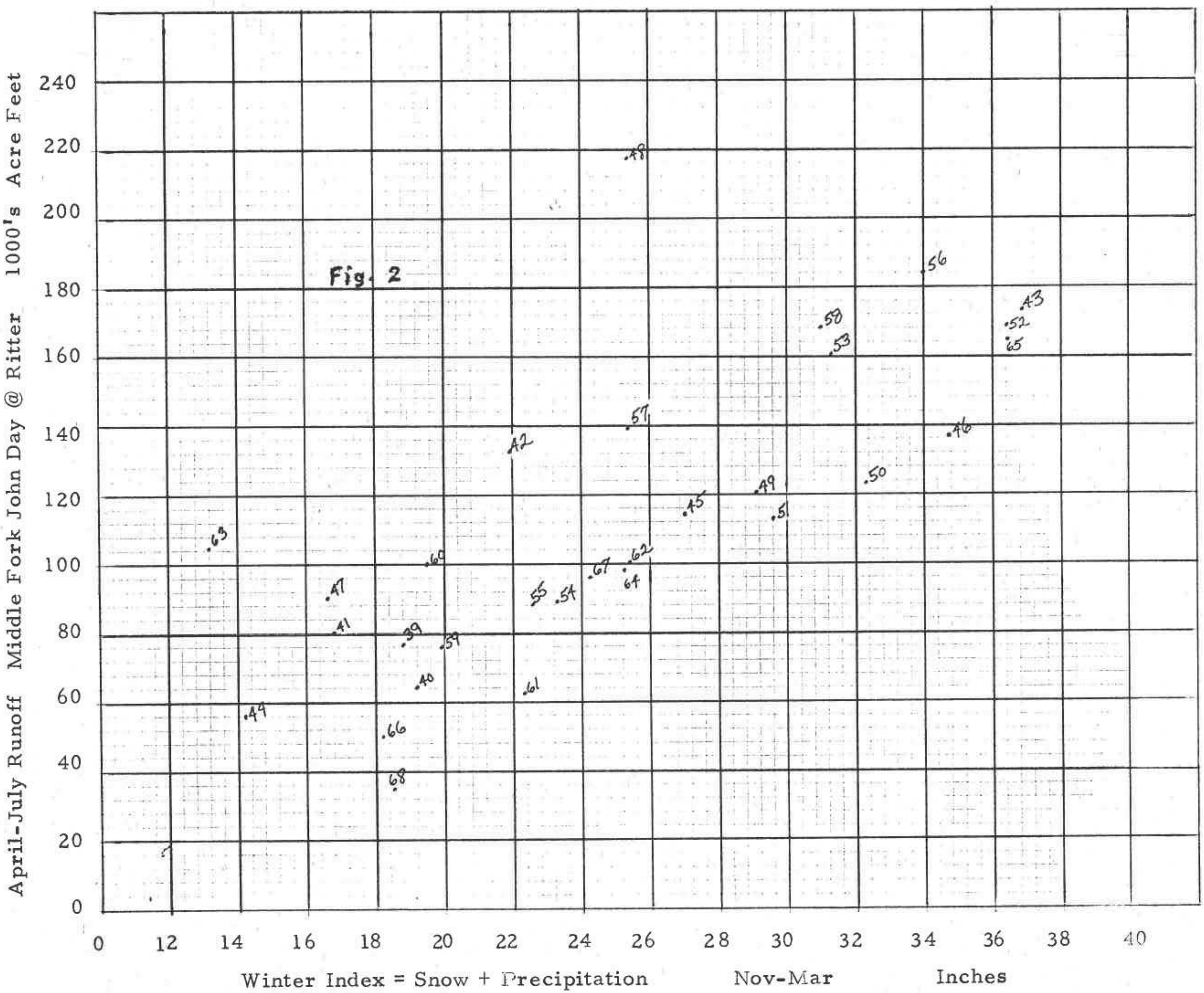


Fig. 2
April-July Runoff Middle Fork John Day @ Ritter 1000's Acre Feet
Winter Index = Snow + Precipitation Nov-Mar Inches
0 20 40 60 80 100 120 140 160 180 200 220 240
0 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40

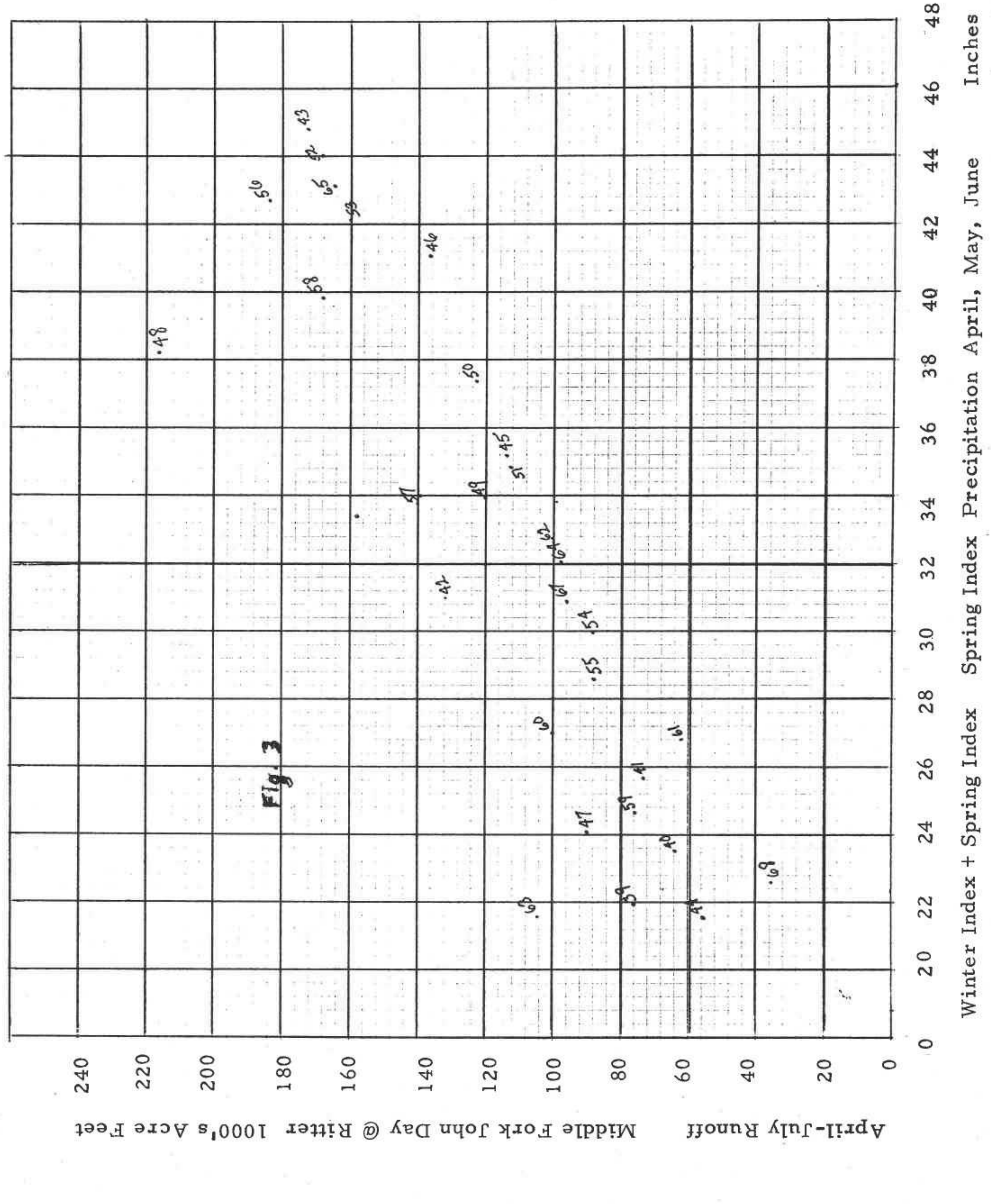


Fig. 3
Winter Index + Spring Index   Spring Index Precipitation April, May, June   Inches
0 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
April-July Runoff   Middle Fork John Day @ Ritter 1000's Acre Feet
0 20 40 60 80 100 120 140 160 180 200 220 240

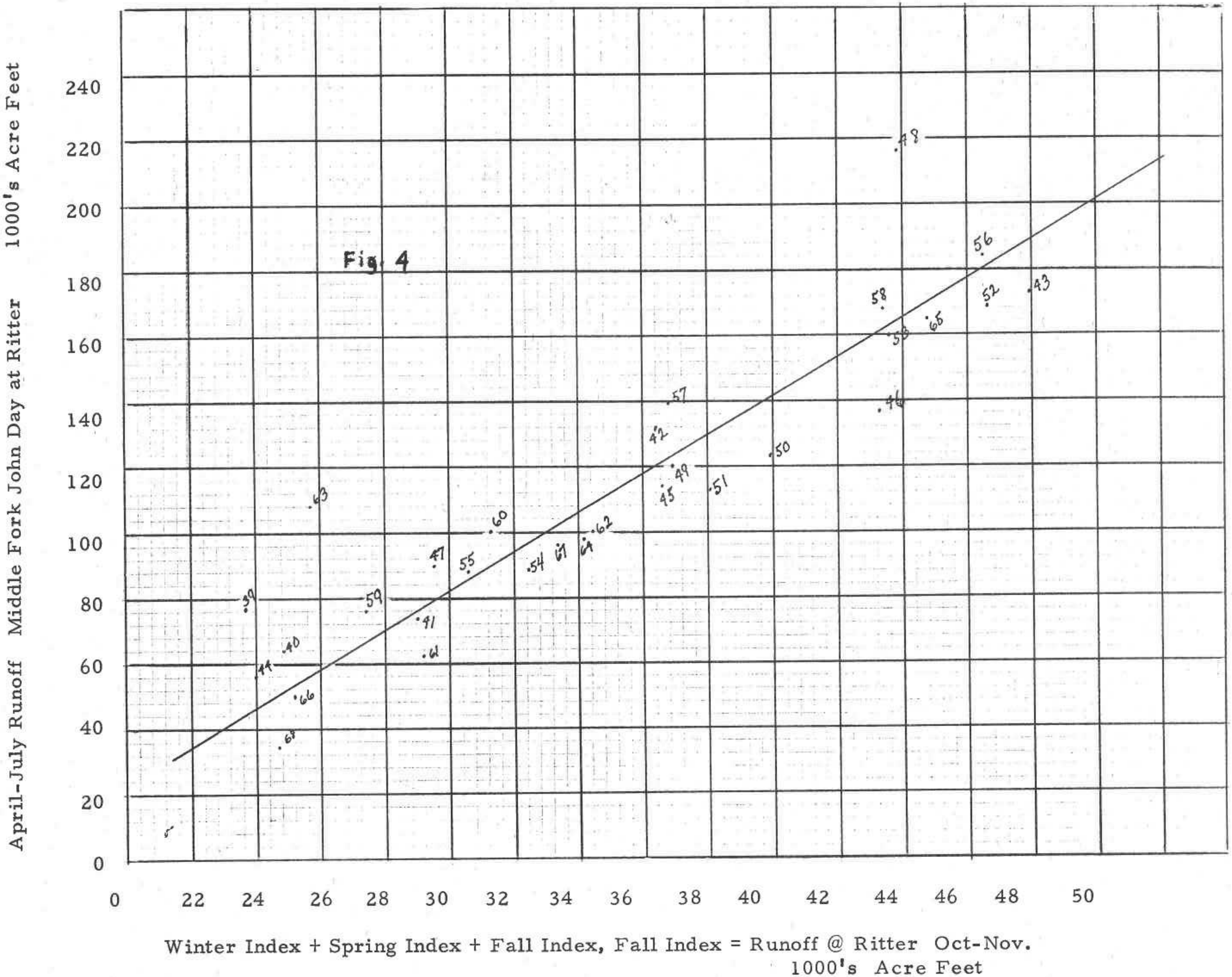
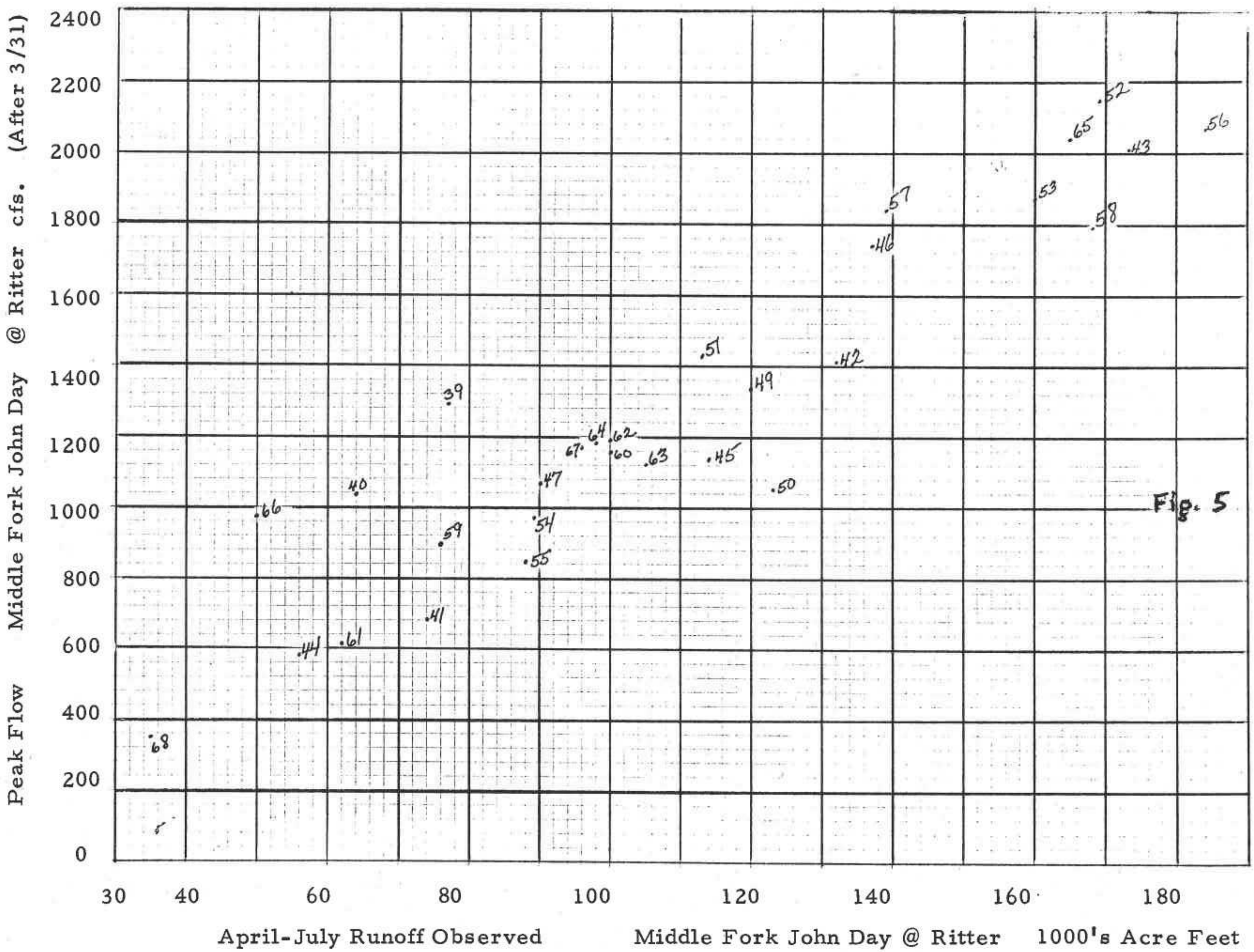
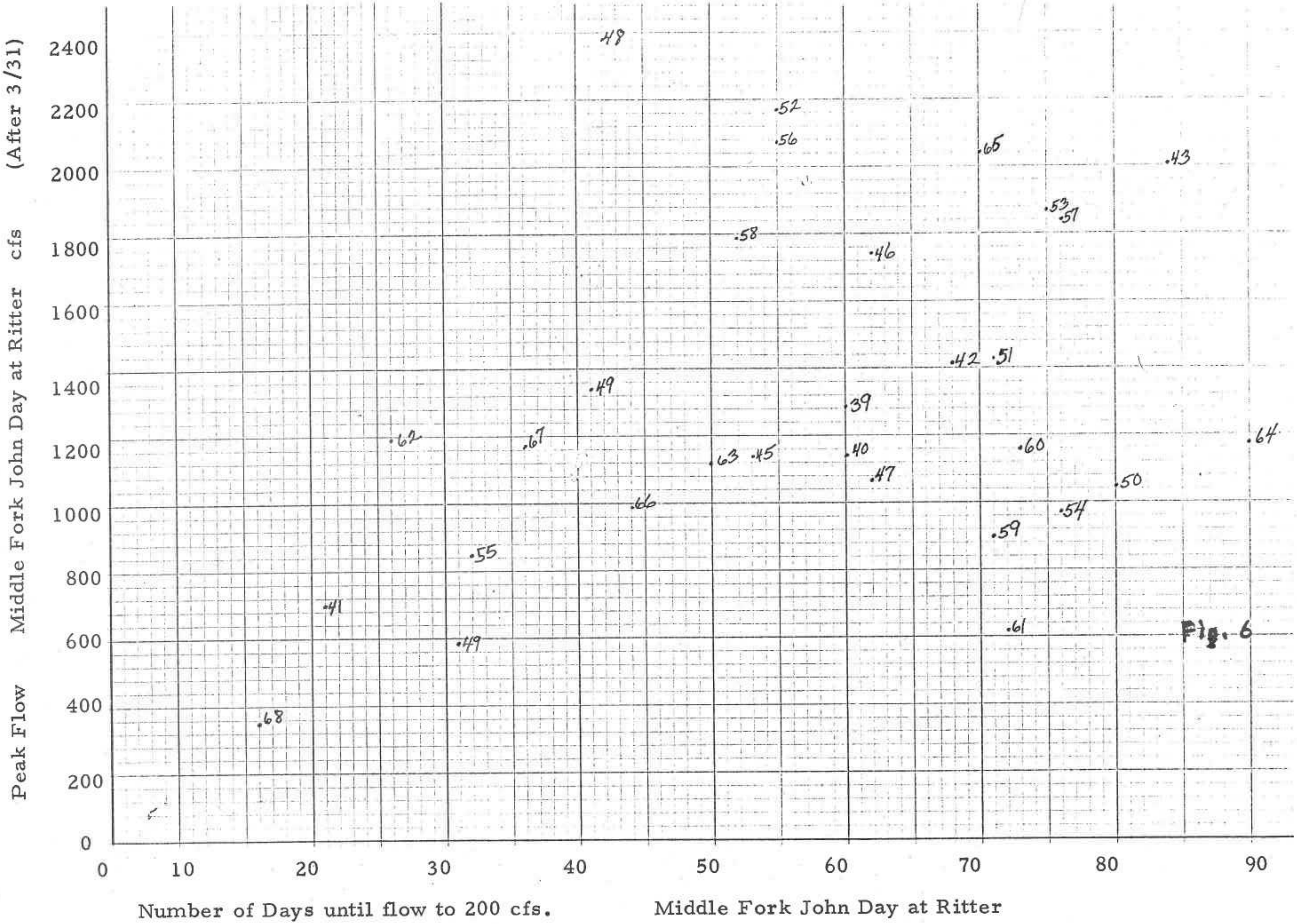


Fig. 4
April-July Runoff Middle Fork John Day at Ritter 1000's Acre Feet
240
220
200
180
160
140
120
100
80
60
40
20
0
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
Winter Index + Spring Index + Fall Index, Fall Index = Runoff @ Ritter Oct-Nov.
1000's Acre Feet
48
56
58
52
43
53
65
57
46
42
50
49
45
51
63
60
62
64
61
54
55
47
39
59
41
40
44
61
66
68


Peak Flow Middle Fork John Day @ Ritter cfs. (After 3/31)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
30
40
60
80
100
120
140
160
180
April-July Runoff Observed Middle Fork John Day @ Ritter 1000's Acre Feet
Fig. 5
.68
.44
.61
.66
.40
.41
.59
.39
.55
.54
.47
67.
.64
.62
.60
.63
.45
.50
.51
.49
.42
.46
.57
.53
.58
.65
.52
.43
56



Peak Flow Middle Fork John Day at Ritter cfs (After 3/31)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
0
10
20
30
40
50
60
70
80
90
Number of Days until flow to 200 cfs.
Middle Fork John Day at Ritter
Fig. 6

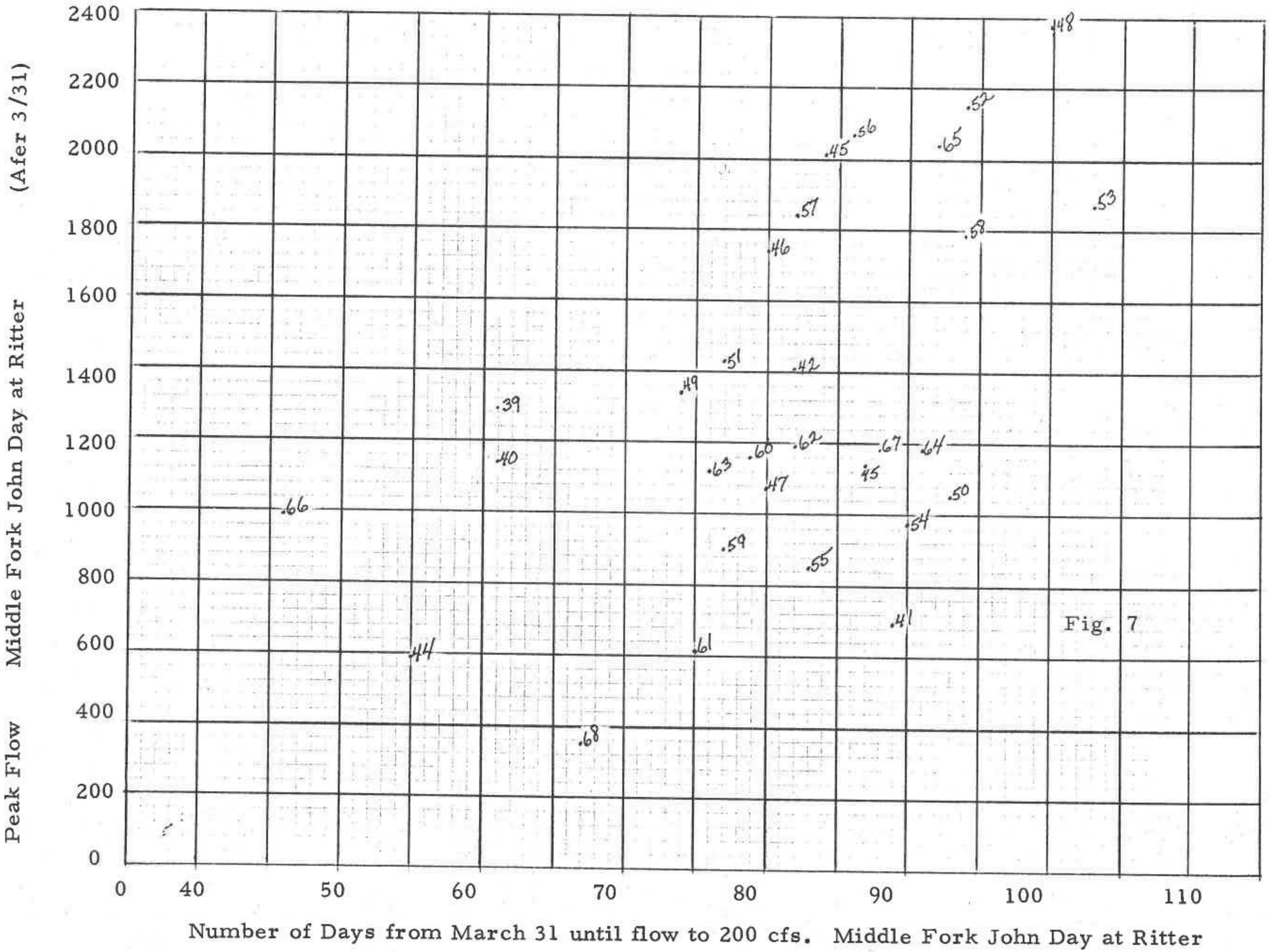

Peak Flow Middle Fork John Day at Ritter (Afer 3/31)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
40
50
60
70
80
90
100
110
Number of Days from March 31 until flow to 200 cfs. Middle Fork John Day at Ritter
.48
.52
.56
.45
.65
.53
.57
.58
.46
.51
.42
.49
.39
.40
.62
.67
.64
.63
.60
.45
.47
.50
.66
.54
.59
.55
.41
.44
.61
.68

Fig. 7

Presented May 1, 1969 by WILLIAM N. PARKE, Associate Professor, Forest Recreation, Oregon State University.

Snow as a Recreational Resource

This past winter the Pacific Northwest received a heavier, and more persistent snowfall than for many previous years. To the ranchers and fishermen this was most welcome. It meant that reservoirs would be filled in the spring and summer for irrigation, and there would be a better outlook for fishing. To others it meant better skiing conditions in the mountains, and to the youngsters in cities and communities it meant sledding on the streets and tobogganing on the hilly slopes nearby. To many adults it was unwelcome for it meant shovelling sidewalks and driveways, driving with chains and fighting snowbanks in order to park downtown.

Frankly, snow is a joy to some, and a headache to others -- depending upon what you do with it. One has the choice of staying indoors and brooding; or getting out with others and enjoying what an abundant snowfall offers in various snow sports.

Without fail, whenever an above-average snowfall hits Corvallis a lot of townspeople and University students glance up at nearby Mary's Peak and wishfully think of its development as a winter sports area. Mary's Peak has its potential for winter sports, but before we get into this let us look at the history of skiing here in Oregon, and the Pacific Northwest.

Skiing as a sport in the Pacific Northwest is only about forty years old. In the late twenties, and even the early thirties, there were no Willamette or Santiam Highways connecting the Willamette Valley with Central Oregon. The McKenzie Highway, and the Mt. Hood Loop Highway through Government Camp were summer routes only, and were open about five or six months each year. Ski touring in those early days was a genuine effort, and enjoyed only by residents of European descent, particularly Scandanavian, or those from the New England states. No uphill facilities existed in those times, and those ski-venturesome residents drove the Mt. Hood, or McKenzie Highways, as far as the highway was open, and took off from there for a day's outing -- or for whatever remained of the day.

COMPETITION HELPED

Skiing enthusiasm built up rapidly in the thirties and such ski clubs as the Cascade of Portland, the Skyliners of Bend, and the Ski Laufers of Eugene were organized. Competition in ski jumping, cross country and slalom events was much publicized and these ski clubs were largely responsible for this.

The ski jumping events in the 1930's at Multorpor, on Mt. Hood, and at Leavenworth, near Wenatchee, became nationally famous--and the annual Leavenworth jumping event continues to draw top competitors and large crowds of spectators.

It seems rather odd that skiing in the Pacific Northwest became such a popular sport during the depression years of the 1930's. The Civilian Conservation Corps had a lot to do with this.

In 1933, the CCC camps started to spring up in mountainous areas and road building, clearing fire breaks, and developing recreation sites of all kinds were important jobs of the crews. Some of the camps were hardpressed for winter work projects because of heavy snowfalls and many smaller communities took the examples set by such cities as Portland and Seattle, and worked with the U.S. Forest Service in selecting ski slopes to clear, and in building warming huts and sanitation facilities. The State highways aided in plowing snow and parking areas along the highways, and the CCC crews in many instances brought in bulldozers and cleared spur roads to the ski sites. Cooperation of government, both state and federal, and local ski clubs, chambers of commerce, and others exemplified the spirit of the times.

In the pre-World War II era, such well-known ski areas as Mt. Baker, Stevens Pass, Snoqualmie Pass and Mt. Rainier, in Washington, and Timberline Lodge and Multorpor in Oregon, became nationally known. Following World War II many ski areas were expanded and new ones developed such as White Pass, Crystal Mountain, Ski Acres, Mt. Spokane, Mt. Pilchuck and Mission Ridge in Washington, and Hoodoo, Spout Springs, Mt. Bachelor, Willamette Pass, Anthony Lakes, Mt. Hood Meadows and Mt. Ashland in Oregon.

It is interesting to note that the first snow tractor developed in the Pacific Northwest was used in the 1937 survey of Hoodoo. Since then a number of fine snow tractors have been manufactured and are standard equipment for transporting people and supplies, and plowing snow in many ski areas.

Corvallis people interested in the development of Mary's Peak might benefit by the fact that though local ski clubs in the Pacific Northwest provided the spark that touched off the growing interest in skiing, and in the initial development of many ski areas, a number of the areas actually were developed by a husband and wife partnership. Bruce and Virginia Kehr (Stevens Pass), Webb and Virginia Moffette (Snoqualmie Pass), Pete and Esther Eyraud (Spout Springs), Everett and Ida Darr (Multorpor and Government Camp), Carl and Mary Reynolds (Multorpor and Ski Bowl), and Ed and Ruth Thurston (Hoodoo) practically built their areas alone. All except the Thurstons are still operating their areas.

HIGH INITIAL COST

It is quite expensive to build ski areas to present-day standards and it is now rare to have a family finance such developments. The trend is for a group of local, well-known citizens to pool their financial and other efforts in providing their local communities with winter playgrounds. Mt. Bachelor, Anthony Lakes, Hood River Meadows, and Mt. Ashland in Oregon are good examples of this. A similar approach may offer the best chance of developing Mary's Peak.

The development and management of a ski area in the Pacific Northwest is filled with problems. Initial investment is high and of course interest rates on loans are anything but low. Since ski seasons are relatively short, and snow conditions unpredictable at best, it is difficult to find loan agencies willing to put up the money. Insurance rates for ski lifts are particularly high, even though the equipment is usually excellent and well maintained. Skiing use is heaviest on weekends, and only the larger areas are open on week days.

This presents problems of maintaining good personnel, and in supplying food and services. Access to some ski areas cannot be guaranteed at all times due to occasional storms on weekends and the fact that highway snow removal equipment must keep the highways open as a priority. Ski area access and parking areas are opened after the first priority is met.

The ski area operators in the Pacific Northwest on the average have the public interst at heart and my experience with them is that they are the best in our country. In no other region do we have such low ski lift rates, and our operators are keenly aware of the need for grooming the ski slopes -- and do a creditable job in this. This not only lowers the ski accidents, but helps to keep insurance rates within reason.

Our operators are constantly trying to add more and better ski lifts and other facilities. Many of them now offer night skiing - - particularly on weekends.

Winter sports use is considered one of the fastest growing recreational uses of the national forest (there are presently about 200 ski areas on national forest lands). Winter use has grown from 1,289,000 visits in 1939, when records were first started, to 1,712,000 visits in 1949, 4,600,000 in 1959, and in 1969 winter sports are expected to be over 7,000,000. In the Pacific Northwest there were 2,141,123 winter sports visits to national forest ski areas during the 1967-68 winter, of which 1,135,541 were to Washington areas and 1,005,582 to Oregon ski areas. Of course not all these visits were for skiing.

It is interesting to note that of the winter sports visits to Washington ski areas last year 17% were non-skiers, and in Oregon 33% were non-skiers. The non-skiers are spectators, snow players, including sledding and tobogganing. Of the 397,000 winter sports visits to Timberline Lodge in the 1967-68 season, only 77,020 were skiing visits. The rest were mostly sight-seers. Imagine the parking problem this means at Timberline Lodge with so many non-skiers. At Hoodoo, 83% of the winter sports visitors are skiers, and at Mt. Bachelor it is 82%.

RESULTS OF SURVEY

The economic benefits to a community in having a ski area nearby are many. There are so many subsidiary types of business that draw customers from among the winter sports users such as ski shops, hotels, motels, restaurants, service stations and others.

Dr. Arthur Stonehill of the School of Business and Technology, Oregon State University, conducted an economic study of a select group of nine Oregon Ski areas and found that the total spending in these areas amounted to $8.5 million during the 1967-68 season, excluding equipment and clothing. The average skier invested $262.69 in his ski equipment and clothing. During this same season the average skier spent $13.66 per day for his skiing, of which $8.21 was spent in the area. The balance was spent in travel and in the local community.

Dr. Stonehill and his students interviewed over 3000 winter sports visitors and to a question posed as to "why" they visited the Oregon areas the answers were:

- 28% because the area was close by
- 20% because of skiing conditions
- 13% because of friends in the area
- 39% gave minor considerations to weather, scenery, social life, etc.

Though skiing is the major snow sport, there are other activities that attract people. The East Side Commercial Club in Portland manages Snow Bunny Lodge near Government Camp, and thousands of youngsters who cannot ski--- or afford to --- spend many healthful and happy days tobogganing and sledding each year. There is a certain amount of this use in all ski areas.

A new snow sport has caught the public eye in many parts of our country, and particularly the Lake States. This is snowmobiling and it has made a phenomonal growth. There were 25,000 snowmobiles in this country in 1965. In the 1968-69 season we find 250,000 in existence - an increase of 1000% in four years. New models are offered on the market almost every day, selling from $600 to $2000 each.

Snowmobiling is a fascinating and exhilarating sport and much of it is done on federal lands. The U.S. Forest Service has recognized snowmobiling as a worthwhile use of national forest lands and in numerous areas has assisted in laying out and developing snowmobile trails for the guidance, safety, and enjoyment of the participants. Safety is a serious matter for equipment can break down and not all of the operators are able to keep the machines operating. A breakdown in a remote area places operators in a winter survival situation - and this can be fatal.

Safety "rules of the road" have been adopted by federal agencies, manufacturers and snowmobile clubs, and so far the results have been encouraging. Snowmobiles are used for transporting fishermen to isolated lakes where winter fishing is permitted--- and this is a popular sport in the Lake states. But the thrill of using these machines to observe big game animals in their winter habitat has led to some game harassment in some states and state laws regulating the use of snowmobiles are being passed, or considered, by several states.

The use of helicopters in transporting skiers to higher mountains or ridges from where excellent down-hill ski touring may be enjoyed is already a commercial business in some regions. It is bound to expand when the Vietnam war is over and surplus military helicopters will be on the market.

The use of dog teams pulling sleds is a sport that is gaining interest in some states. In Canada, New England, the Lake States, and even in Oregon, dog sled racing is quite a sport. Dog sled tours are a novelty, and are enjoyed at such places as Sun Valley, where horse-drawn sleds are also used. And for a rare sport, try ski-joring by having a horse pull you at a trot, or gallop, accross open fields. This is still being done at fashionable ski resorts where the snowfall is light.

Corvallis people will need to look into some of these items before getting too enthusiastic about developing a winter sports area on Mary's Peak. There is a mountain, it has snow and it is nearby. Now that the Siuslaw National Forest has purchased the summit of the peak from the City of Corvallis, and is in the process of improving the highway to the summer recreation development, there is bound to be a renewed interest by the Forest Service and Corvallis residents in exploring its potential for winter sports.

Presented May 1, 1969 by DR. BARD GLENNE, Assistant Professor, Department of Civil Engineering, Oregon State University, Corvallis.

As Seen by a Skier/Engineer

(Editor's Note: Dr. Glenne's presentation was accompanied by color slides of specific areas which were used to illustrate and develop the outline of significant points which he makes below.)

Before I present the essence of my argument, I would like to quote some statistics to show the relevance of the problem with which we are dealing:

- Recreation is a rapidly growing service industry. Wall Street is banking on it, undoubtedly since working hours are getting shorter.
- In 1968-1969 approximately 4,400,000 skiers spent about $1 billion outfitting themselves and going skiing.
- The number of skiers is increasing by about 12% per annum. Gross retail sales of ski goods, lodging, lift tickets, etc., is growing at about 3.5% per annum.
- In Oregon an estimated $14 million was spent on ski equipment and ski trips in 1968-1969. Of this amount, 20% was by non-residents.
- In Oregon there are eight real ski areas with a total of 19 chair lifts and 6 T-bars. All of these are essentially on National Forest Land. The areas have an average maximum vertical rise of 1200 ft. (Bachelor and Timberline have about 1800 ft). The average chair lift vertical rise is 760 ft.

And this is where the crux of my point lies. Today a skier wants to go to a major ski area and ski on longer and bigger hills. While the Forest Service is developing minor day areas, skiers and tourists are developing major ski areas with overnight accomodations. To illustrate this I have gathered some statistics on the twenty-four major ski areas in Switzerland. When averaged they show:

*** Average vertical rise: 4800'
*** Average number of ski lifts: 18
*** Average number of beds: 6280

I think that this proves that when a ski area is planned today one must earnestly consider that it will have an almost infinite life expectancy. This means almost unlimited expansion possibilities and attention to:

- Lodge, parking,condominium, and shopping areas which can serve the area 50 years from now.
- Lifts and gondola layouts.
- A vertical rise of at least 3000 ft.
- Careful layout of slopes and trails to optimize communication as the area grows.
- Coordination with possible skating rink, nightskiing, ski jumping, and other activities.
- Planning which allows summer utilization of facilities (sight-seeing, hiking, fishing, water skiing, conventions, festivals).
- Sound investment plan (opportunity for residents of the area to invest).

Bachelor Butte and Anthony Lake are examples in Oregon where some of these points have been ignored.

Expansion possibilities in Oregon are the best in the Western United States, according to a study by the U.S. Department of Agriculture. Near Joseph, Oregon two ski areas are possible --- one with a 2700 foot vertical rise and one with a 3800 foot vertical rise. These are probably Oregon's ski areas of the future.

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Presented May 8, 1969 by EDWARD R. LaCHAPELLE, Department of Atmospheric Sciences, University of Washington, Seattle, Washington.

Snow Avalanches

Avalanches fall into two major types, according to whether the snow at the area of origin is loose snow or a slab. Loose snow has little internal cohesion among the snow grains. Small disturbances at a point spread out as they propagate downhill in snow which for reasons prevailing at deposition or during metamorphism lies on a slope steeper than its natural angle of repose (Fig. 1, 2). Slabs are discrete snow layers with appreciable internal cohesion compared to layer attachment to underlying snow and surrounding anchor points. Snow slabs break away at a sharply defined fracture line and initially slide away as a coherent blanket. A large area of snow may be set in motion at the same time. Slabs are soft or hard according to whether they are composed primarily of new (low density) or old (high density) snow.

An avalanche is a surface avalanche if it slides on an underlying snow layer. It is a full-depth, or ground, avalanche if it slides on an earth surface. The snow may further be distinguished according to whether it contains much, little or no free water. These two criteria again apply at the area of origin. Many large avalanches display some evidence of free moisture as a result of frictional heating if they fall long distances. They may also remove snow down to the ground although they may have started as a surface avalanche.

The character of motion may be confined to sliding or flowing over the ground, may be air borne (dust cloud), or a combination of both. Type of motion dependes on terrain as well as snow conditions. Airborne or mixed motion is common to dry snow in winter, but even a wet avalanche may become airborne if it falls over a cliff. The dust cloud of dry snow (powder snow avalanche) may sometimes travel at very high velocity ahead of the ground component and inflict damage through wind blast.

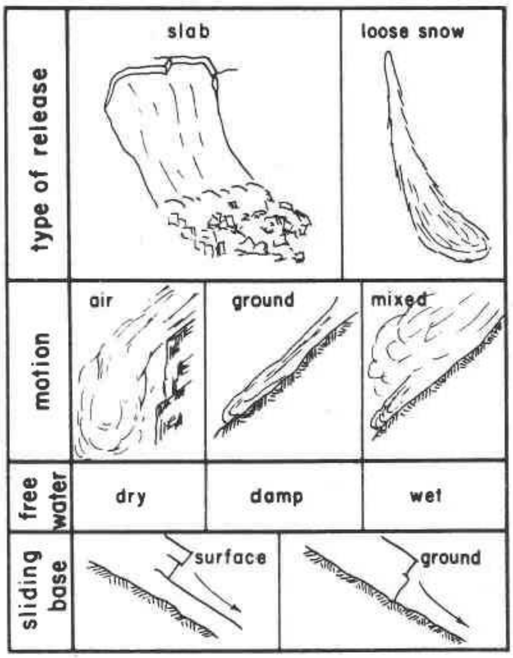


Fig. 1 The classification of snow avalanches

Fig. 2 The typical shape of a loose snow avalanche, which originates at a point and spreads out as it falls.. This one involves damp new snow.

According to the principal terrain characteristics in their path, avalanches are further distinguished as gulley or open-slope avalanches.

An avalanche path is divided into three zones: the release, or fracture zone, the fall zone, and the deposition zone, where the sliding snow comes to rest.

A direct-action avalanche falls as the immediate consequence of a new fall of snow. A climax avalanche, on the other hand, is caused by instability in the snow cover produced by a series of meteorological events extending over a larger period of time.

Although loose snow avalanches occur most frequently, many of them are small and harmless sluffs which actually stabilize the snow by allowing it to slide piecemeal from steep slopes. Most large avalanches and practically all of the avalanche hazard in mountainous terrain is generated by slab avalanches. (See Figs. 3 and 4)

THE FORMATION OF SLAB AVALANCHES

Snow is a visco-elastic substance of relatively high compressibility which is constantly deformed under the influence of gravity. In addition, metamorphism of the snow induces density changes which also find expression in external deformation. On level ground, the principal deformation is settlement, or compaction, of the snow.

On sloping ground, additional components of deformation are present (Fig. 5a). Creep is the internal, plastic deformation of the snow downslope. Glide is the slip of the entire snow cover along the ground. The total motion vector, sometimes loosely called snow creep, is the sum of the creep, glide and settlement vectors.

Both creep and glide depend strongly on temperature. They are fastest when the snow cover is isothermal at 0° C and free water is present. These deformations become less prominent as temperature falls. Glide is severely inhibited when the snow-ground interface temperature falls below 0°C. It is most pronounced when deep snow accumulates early in winter following a warm autumn. Fine-grained snow creeps much more readily than coarse-grained snow; the viscosity of snow varies approximately with the fourth power of grain size.

Snow deposition in nature always varies in depth from place to place in mountainous terrain, and this terrain itself exhibits highly variable slope angle and curvature. As a result, the total motion vector of snow deformation differs in both magnitude and direction from one

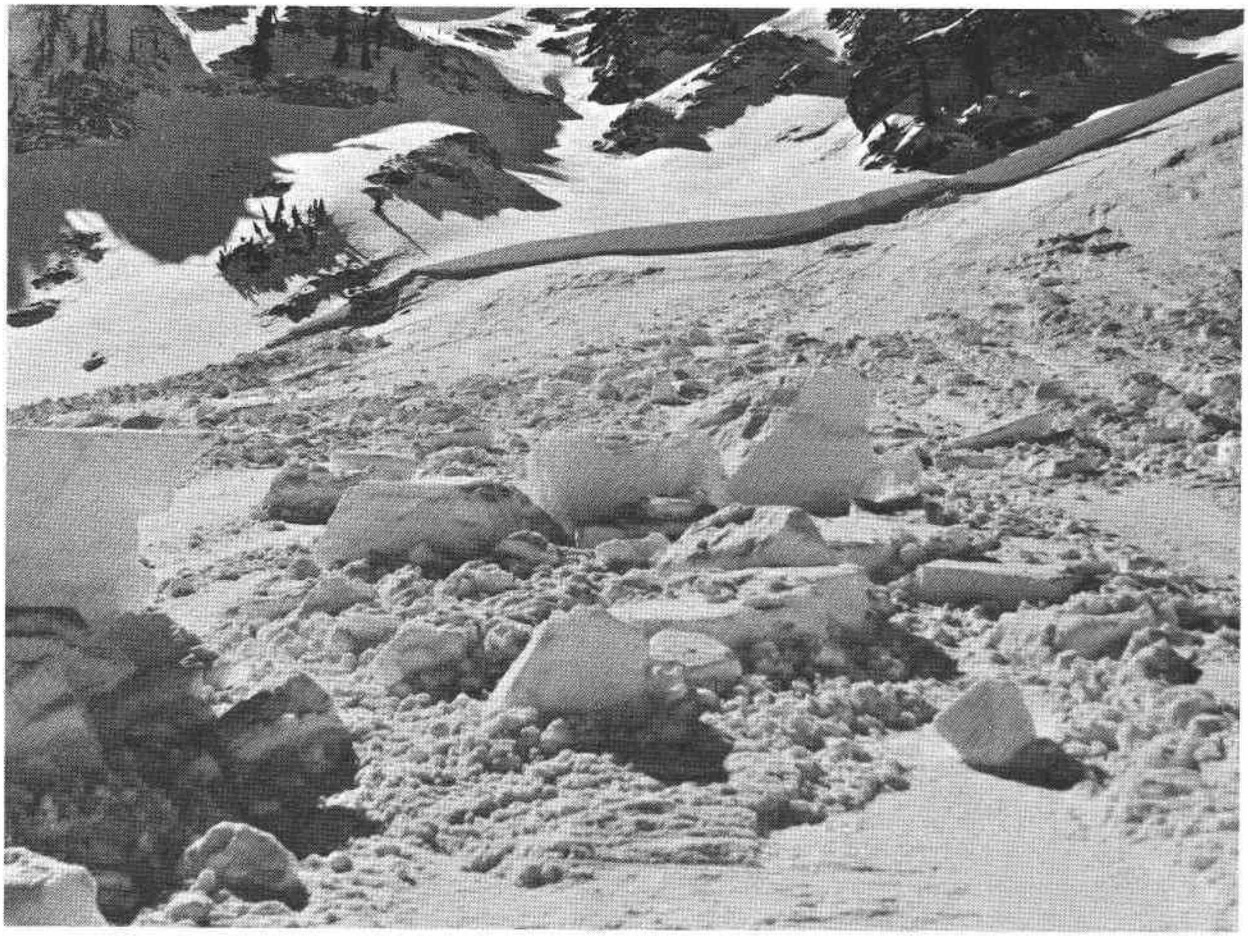


Fig. 3 A large slab avalanche of hard snow with sufficient internal cohesion to remain in blocks even after sliding down a long slope. The fracture line where the slab broke away is visible across the top of the slope.

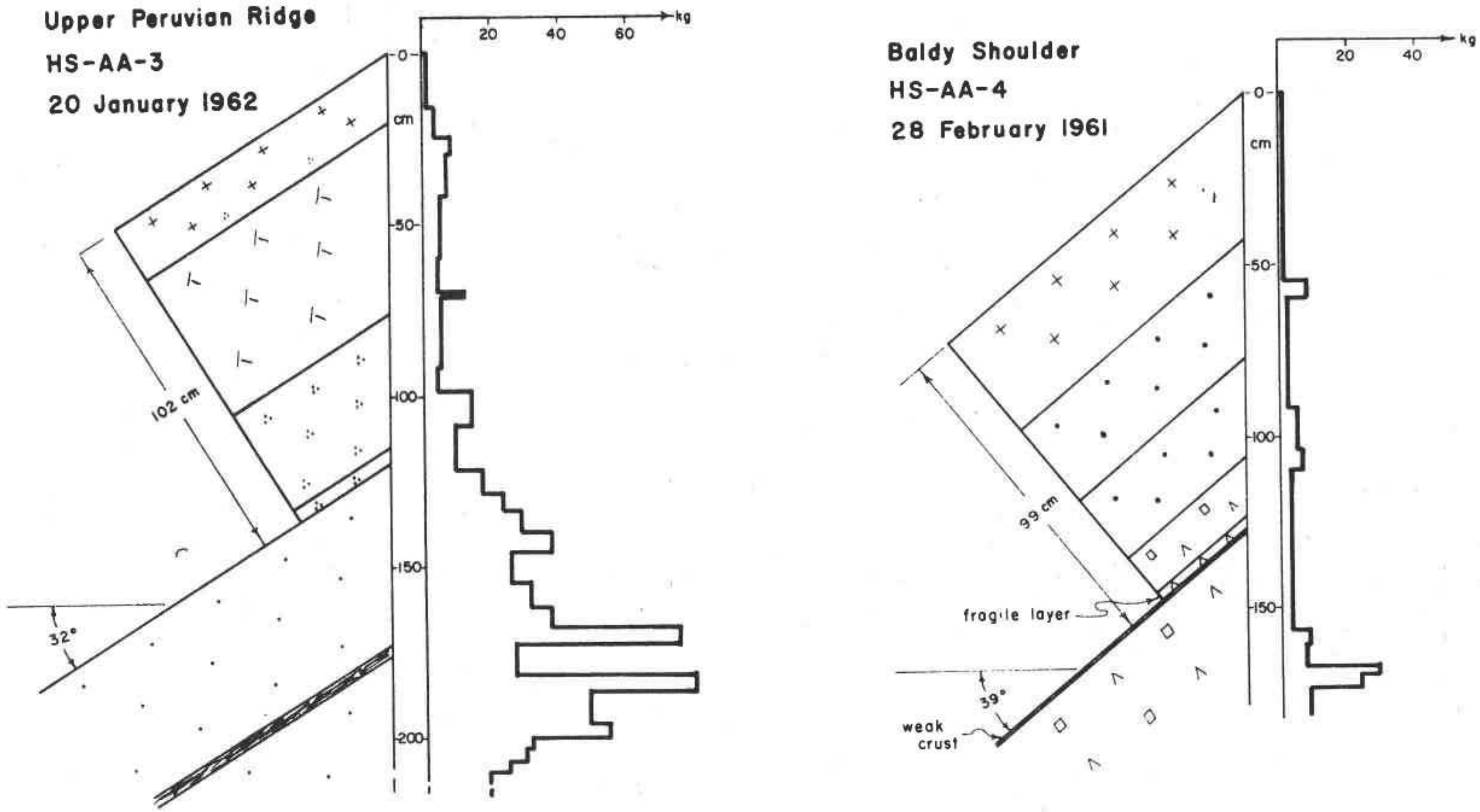


Fig. 4 Typical fracture line profiles of slab avalanches.
The Peruvian Ridge profile shows a slab which was composed of new, partly metamorphosed and graupel-type snow. It slid on a base of old snow, with a thin layer of poorly bonded graupel as lubricating layer.
The Baldy Shoulder slab consisted of both old and new snow which slid on a thin crust with a layer of fragile crystals, probably old surface hoar, as lubricant.

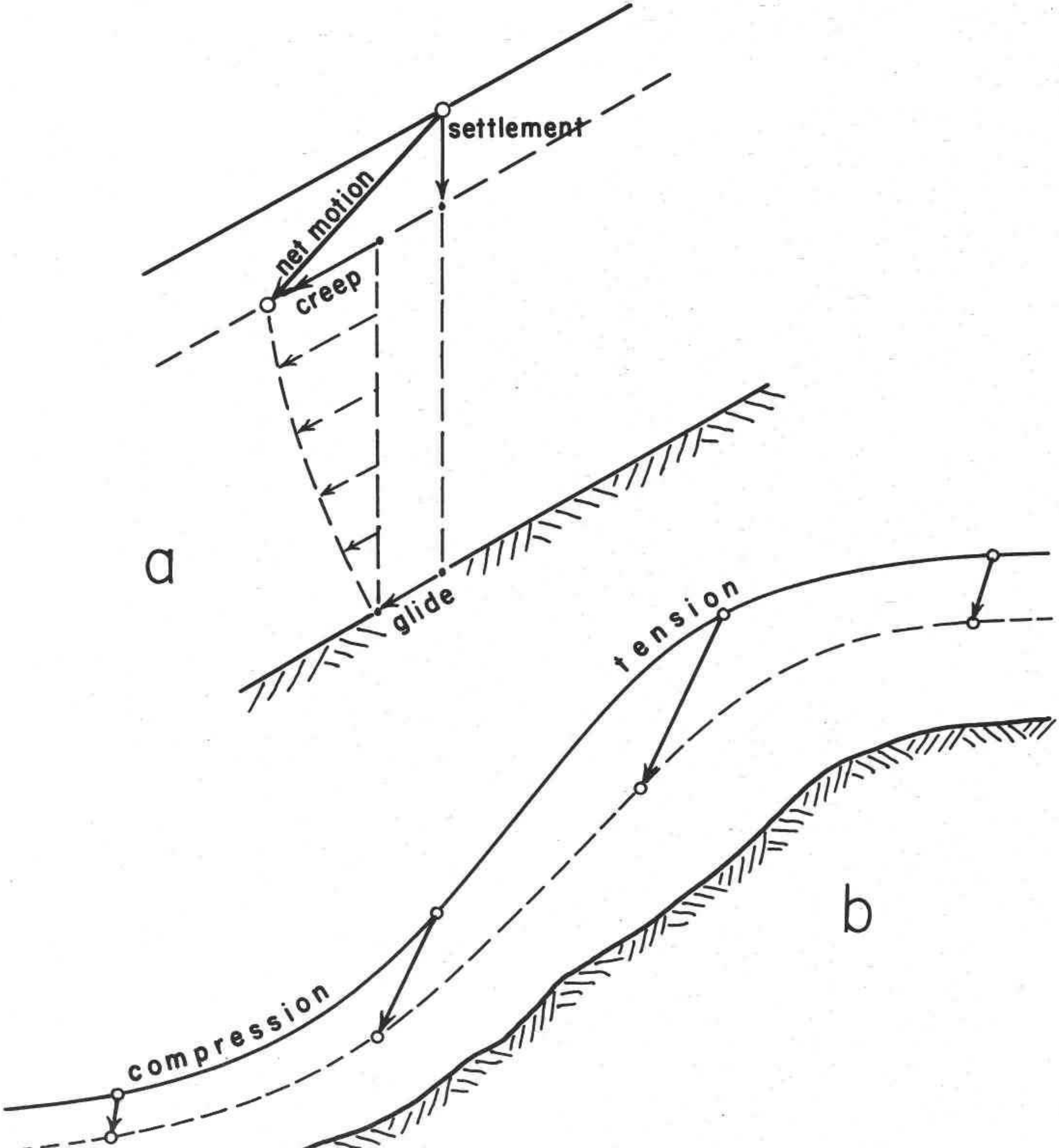


Fig. 5. Deformation within the snow cover (settlement and creep), plus slip of the snow cover along the ground (glide), cause stresses to develop in the snow when snow thickness varies or the terrain is uneven.

point to another. These differences exert both compressive and tensile stresses on the snow. These stresses further deform the snow, both viscously and elastically.

While snow behaves approximately as a Newtonion liquid close to the freezing point, the elastic component of behavior becomes more prominent as temperature falls. Even very soft snow exhibits appreciable and recoverable elastic strain under the influence of deformation stresses. In short, the snow in a tension zone can be stretched like a rubber band. Stresses added by such events as a new snowfall are eventually relaxed by internal viscous flow, but the "stretched" state can persist for appreciable lengths of time, especially at low temperatures.

When any substance is deformed elastically, some of the work of deformation is stored as elastic strain energy. This energy is available to propagate fracturing or rupture of the substance. The phenomenon is most noticeable in brittle substances; the way a skilled glass worker breaks a sheet of glass scored in twisting lines is a good example of utilizing elastic strain energy.

Snow is definitely a brittle substance, even that which is soft enough for a skier to call powder snow. A surprising amount of elastic strain energy can be stored in a steep snow slope. If this slope incorporates a poorly anchored slab layer, fracturing initiated by some external trigger can propagate with explosive violence as the stored energy is released. A whole slope may shatter into blocks of snow as it suddenly erupts into motion. (See Fig. 6.)

It is this characteristic which makes the slab avalanche so unpredictable and dangerous. It also makes possible the release of very large avalanches, for they start large right at the mountain top, rather than gaining volume only as they fall.

AVALANCHE FORECASTING

The slab avalanche is the principal source of hazard, so forecasting techniques obviously must be oriented toward it. There are two major methods by which the formation of unstable slabs may be anticipated: the study of snow cover structure and the analysis of meteorological conditions.

Structural examination is most useful for predicting climax avalanches whose genesis is extended in time. The meteorological approach finds its best application in forecasting direct-action avalanches, very frequently soft slabs, which involve new snow during or immediately

Fig. 6 The fracturing of snow under tension is a common mid-winter phenomenon. When such fractures propagate across an open slope where the fractured layer has inadequate anchorages, a slab avalanche is released.

after storms. In theory, either method could be applied to either avalanche type, but the practical dictates of available time restrict structural investigations to slab conditions which develop slowly, while the interpretation of meteorological causes becomes increasingly difficult as the time lengthens between cause and effect.

The basic principles of the two methods are summarized in Figure 7 and Table I.

The relative importance of structural and meteorological forecasting depends in large measure on climate. Colder climates lead to more emphasis on structure, while maritime climates with deep snowfalls are better suited to the meteorological approach. Usefulness of the latter method depends strongly on the accuracy of mountain weather forecasts.

In practice, the two methods are almost always combined to some degree. Many so-called avalanche forecasts are in fact evaluations of current hazard; prognostications of future snow behavior are at the mercy of the many uncertainties of mountain weather. Either forecasts or evaluations serve to estimate the probability that avalanches will fall in a given area. The prediction of the exact time and place a single avalanche will fall on a given slope in most cases is impossible.

In many field operations, such as the protection of mountain highways or of large ski areas, the formal avalanche forecast is checked by field tests of snow stability on known avalanche paths. Most commonly this is done by test skiing, but explosives or even artillary may also be employed for this purpose. The key evidence of instability is the propagation of fractures when the snow is disturbed (See Fig. 6). This evidence of stress build-up often precedes actual avalanche release and is a reliable sign of developing slab avalanche hazard.

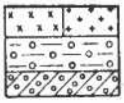
AVALANCHE CONTROL

The purpose of avalanche control is to reduce or eliminate the hazard to life and property from sliding snow. There are four basic ways in which this can be done:

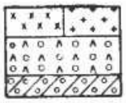
1) Restriction or closure of hazardous areas.

2) Artificial release at a controlled time and place. This is normally accompanied by temporary application of 1).

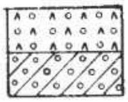
3) Diversion or arrest of sliding snow after the avalanche has occurred naturally (passive defense).



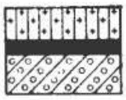
a) A heavy layer of wild snow or powder snow lies upon a hard underlayer. Danger of loose snow or soft slab avalanches on steep slopes. The danger increases with an increase in snow depth.



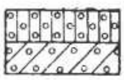
b) Deep layer of wild snow or powder snow on a loose, coarse-grained layer, which can also slide with the loose-snow or soft slab avalanche.



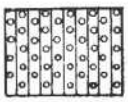
c) Coarse-grained, cohesionless snow (under some conditions Scwimmschnee) on a hard underlayer. Formation of many small loose-snow slides.



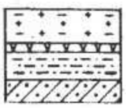
d) Fresh, wet snow on a crust. Formation of rolling snow-balls which may cause loose-snow or wet slab avalanches.



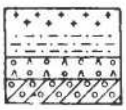
e) Coarse-grained, wet snow on hard underlayer. Loose-snow or wet slab avalanches very easily set in motion.



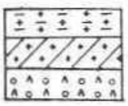
f) The entire snow cover consists of wet, coarse-grained snow. Danger of wet loose-snow avalanches or wet slab sliding clear to the ground.



g) Windpacked new snow is separated from a hard underlayer by a thin layer of surface hoar. Very favorable for slab avalanche formation.

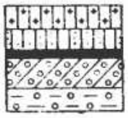


h) Older snow layers separated by a layer of Schwimmschnee are covered by a new fall of snow. Danger of slab avalanche.

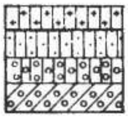


i) Medium-hard (windpacked) and hard new snow rest on Schwimmschnee. Danger of slab avalanches which may slide clear to the ground.

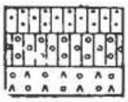
Fig. 7a Typical stratigraphic patterns which lead to avalanche formation. (After Mellor)



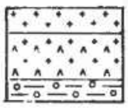
j) Windpacked new snow and solid older layers have been wet through. Above the ice lamination a water saturated area is found which can act as a lubricating layer for a slab avalanche.



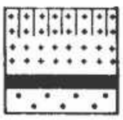
k) Wet new and old layers are separated from the more solid underlayer by wet, coarse-grained snow. This coarse-grained layer can act as lubrication for an avalanche.



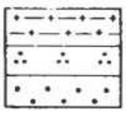
l) Damp, but solid, layers rest upon coarse-grained loose snow. Slab avalanches may slide clear to the ground.



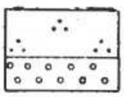
m) A new fall of warm, high-density snow follows immediately the deposition of cold, dry new snow on a firm base. Excellent for soft slabs.



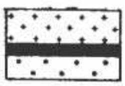
n) A deep layer of fluffy new snow is rapidly wet from the top by rain. The underlying ice layer increases instability, but is not necessary to form an avalanche. Soft slab (damp or wet).



o) A new fall of soft snow (or wind-blown slab) is separated from a firm base by dry, loose graupel, which serves as a lubricating layer. Soft or hard slab.



p) A sufficiently deep layer of dense, heavy graupel, forming a stiff slab on a hard, smooth old snow surface.



q) A deep fall of new snow, even quite soft and fluffy, on a smooth crust. Rain crusts tend to form avalanches this way more readily than sun crusts. Soft slabs.

Fig. 7b Typical stratigraphic patterns which lead to avalanche formation. (after Mellor)

TABLE 1

Meteorological Factors Contributing to Formation of Direct-Action Avalanches:

1. Old snow deep enough to smooth local terrain features.

2. Old snow surface favorable to poor bonding of new snow--rain crust, surface hoar, etc.

3. Over 30 cm of new snow. In some circumstances, as little as 15 cm of new snow can avalanche if other factors are strongly favorable.

4. New snow density which departs widely from long-term climatological mean. High density snow especially favors slab avalanche.

5. New snow consisting of rimed, fragmented or needle crystals.

6. Wind velocity persistently above 7 meters per second during snowfall.

7. Snowfall intensity above 2.5 cm per hour prolonged over several hours.

8. Precipitation intensity above 2.5 millimeters per hour prolonged over several hours, especially while wind remains above critical levels.

9. Less than 15-20% settlement in new snow during deposition.

10. Rising temperature during a storm, especially if snowfall is followed by rain.

4) Prevention of avalanche release (active defense) by

   a. modification of snow (temporary)
   b. modification of terrain (permanent)

Restriction or closure of hazardous areas can offer protection only to mobile targets of avalanche damage such as skiers or vehicles. It is most effective when applied to ski areas or highways only for short periods of time during very high hazard. Prolonged closure during marginal hazard quickly engenders public resistance and effort to circumvent it. Application of restrictive measures is primarily an administrative rather than a technical problem.

Artificial release of avalanches is a well-developed control technique which is widely used to protect ski areas and highways. Like restrictive measures, it is useful only for protection of people or vehicles which can be removed from the danger zone while avalanches are triggered and allowed to fall. Regular artificial release, properly applied, increases avalanche frequency on a given slope, but reduces the probability of snow conditions building up to form large climax avalanches.

Triggering agents for artificial release are designed to initiate fracturing in snow slabs. An active mechanical disturbance is required; practical use is made of everything from skis to bulldozers. The most commonly used trigger is a charge of high explosive. Empirical evidence shows that explosive energy equivalent to one kilogram of TNT is required to assure positive release in most types of snow.

Such charges are often thrown onto avalanche slopes by hand, but delivery via artillery shell is far more rapid, safe and efficient. Recoilless rifles and mountain howitzers are used in the United States for this purpose. Mortars are preferred in Europe. Permanently-mounted artillery weapons (Fig. 8) are now widely used for avalanche control.

BARRIERS ARE USED

Diversion barriers are historically the oldest type of avalanche defense. Heavy masonry walls or wedges above isolated dwellings have been employed for centuries in the Alps. Various adaptions of this principle are still used today to protect individual structures, such as a transmission line tower, from sliding snow. Large earth-fill or masonry walls are also used to deflect the flow direction of avalanches. In some instances, dams or catchment basins are used to arrest the falling snow. Arrays of earth mounds are a recent adaption of this principle. All of these structures are relatively simple to build and are effective

Fig. 8. Recoilless rifles are commonly used in the United States for avalanche control. The artificial release of avalanche and the stabilization of slopes with explosives is greatly facilitated if artillery fire can be used to deliver the explosive charges in the form of high-explosive shells. Fixed mount on a tower such as this permits blind firing during storms.

if large enough, but lose their effectiveness if repeated avalanches fill them up with deposited snow.

One of the commonest types of diversion barriers is the snowshed (Fig. 9), which is used extensively to protect highways and railroads in mountainous terrain.

The simplest way to prevent avalanche release is to modify the snow during or after deposition in such a way that the formation of slabs is inhibited. On a small scale, this is done by compacting the snow by walking back and forth on it. This breaks up continuity of the slabs and augments snow strength by compaction and sintering. Explosive charges used for artificial release also have a similar stabilizing effect even when no avalanche falls. Experiments have been made with application of certain organic chemicals in trace quantitites. These alter the metamorphism, inhibit depth hoar formation, and insure a much higher ultimate strength of the snow.

Modification of the terrain to limit or prevent avalanche formation demands more sophisticated engineering and often is expensive. This method of avalanche control is more commonly used to protect extensive fixed installations such as power plants, villages, or mines. A variety of designs has been utilized for supporting structures (Fig. 10) which are intended to break up slab continuity on a slope and provide actual physical support for the snow to prevent it from sliding.

These structures have to be very strong, for they are continually subjected to forces exerted by the creeping and gliding snow cover. Such forces may be as high as several tons per square meter, increasing with the square of snow depth. To design structures which can resist these forces and still be economically feasible to transport, erect and anchor on a steep mountainside is a challenging problem. A wide variety of materials - steel, aluminum, wood, concrete, and combination of these- has been used.

Numerous experiments have been made with a different type of terrain modification, wind baffles (Fig. 11), which are designed to alter patterns of snow deposition and thus limit slab formation. Because they are not required to support large snow pressures, they are much cheaper to construct than the type of structures shown in Fig. 10. They are also less reliable in assuring avalanche suppression.

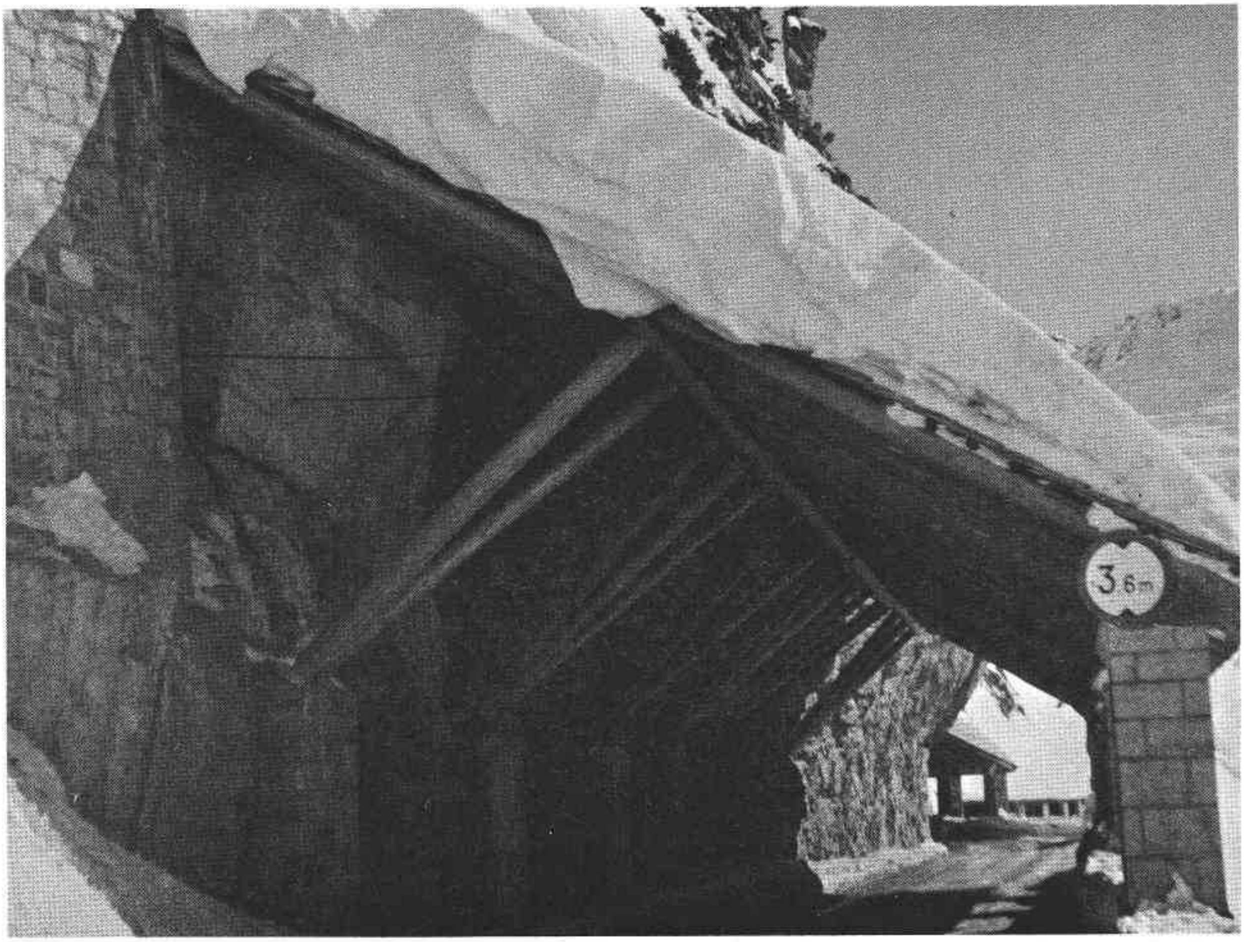


Fig. 9 Snowsheds are used to deflect sliding snow over highways and railroads. If the road bed is narrow, heavy timber construction, or a combination of timber and masonry, is adequate. For wider road beds, reinforced concrete is normally employed. Large snowsheds offer permanent protection from avalanches, but are very expensive to construct.

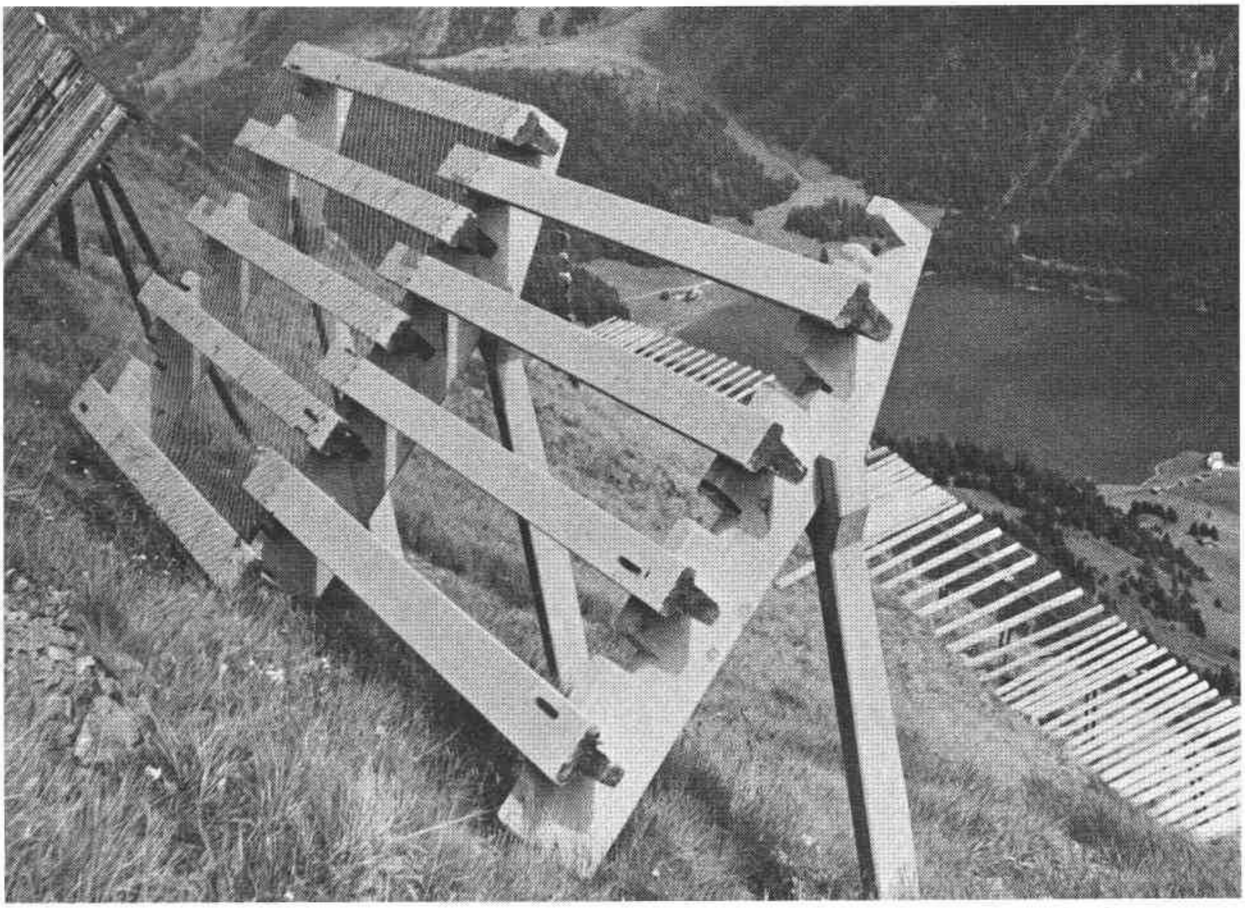


Fig. 10 Supporting structures are used to anchor the snow to a mountainside and prevent avalanches from falling. In the foreground is a bridge made of prestressed concrete. Below and behind it is a rake built from round timbers supported on a steel framework.

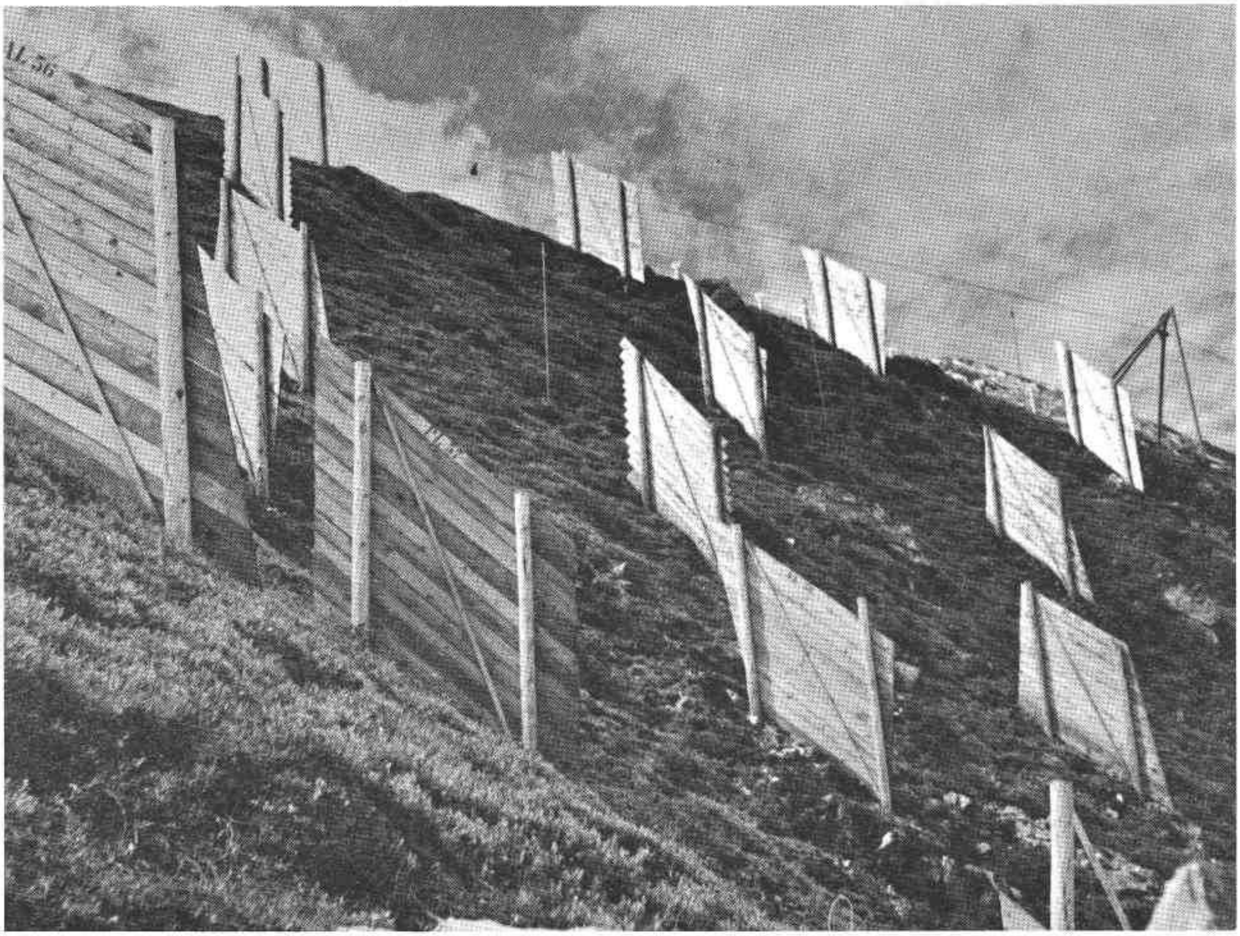


Fig. 11. Wind baffles can be used to create uneven deposition pattern for snow and thus inhibit the formation of slab avalanches over a large area of a slope. Baffles are not as reliably effective as supporting structures, but are much cheaper to construct because they do not have to bear large snow pressures.

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Presented May 15, 1969 by MARK L. NELSON, Chief, Water Control Branch, U.S. Army, Corps of Engineers, North Pacific Division, Portland, Oregon

Snowmelt Floods

It is my pleasure to be asked to participate in the Water Resources Research Institute's Spring Seminar on Snow. Up to this point in time speakers have dealt primarily with the theoretical aspects of snow physics, snowpack management, volumetric snow runoff forecasting, and also the subject of snow avalanches and recreation. As a representative of the U.S. Army Corps of Engineers, I will develop the subject of snowmelt floods, with particular emphasis on its engineering application to the design and operation of large water control projects. My purpose then, is to discuss the application of the principles of snow hydrology to design and operation of reservoirs here in the Pacific Northwest.

I will not dwell on the theory of snowmelt and snow runoff but rather how these results have been applied in actual practice in river regulation and project design. The main emphasis of what I will present will lie on the presentation of case studies of flood control and flood regulation as affected particularly by the contribution of snowmelt for both rain-on-snow and pure snowmelt floods as experienced here in the Pacific Northwest.

SNOW HYDROLOGY RESEARCH

I want to stress very briefly the work that the Corps of Engineers has done in the field of snow hydrology research. Some twenty-five years ago, the Corps along with the U.S. Weather Bureau and other government agencies embarked on a research program termed Cooperative Snow Investigations. This work proceeded along according to certain broad objectives as follows:

(1) The determination of a practical and reliable method of evaluating the maximum streamflow which may be produced by a watershed as the result of snowmelt or combined snowmelt and rain;

(2) Development of a practicable and reliable method of forecasting seasonal and short-term streamflow, including floods, resulting from snowmelt or combined snowmelt and rain;

(3) Expansion of basic knowledge of hydrodynamic and thermodynamic characteristics of snow through a program of fundamental scientific research;

(4) Advancement of knowledge of meteorological, climatological, and hydrological phenomena as they influence the above three objectives.

This program was actively pursued during the ten-year period from 1946 through 1956, and it largely accomplished the objectives which we had set out to perform. The investigations were completed by the North Pacific Division office of the Corps.

The work consisted basically of establishing, instrumenting and operating three snow laboratories in the rugged mountain areas of the West, representing three environments of snow accumulation and runoff. It also included the processing and analyzing of the data from the snow laboratories and the program carried out a large number of research investigations on problems related to snow hydrology. The culmination of the work was the publication of a comprehensive report on the theory and practice of snow hydrology which could be applied to problems of river forecasting, reservoir regulation and project design.

The program dealt principally with the evaluation of the hydrologic cycle in areas of snow accumulation and snowmelt. The large emphasis of the program was dealing with the evaluation of factors affecting snowmelt and the methods of application to snow flood hydrology.

I do not have the time to discuss with you the results of the program in detail, but I would like to refer you to the Summary Report of the Snow Investigations, entitled, "Snow Hydrology" which is still in print and summarizes the results of the program as a whole. This publication is available by writing to the North Pacific Division Office, Corps of Engineers, Portland, Oregon. It is available without cost to those who are associated with university programs or government agencies.

APPLICATION OF SNOW HYDROLOGY RESEARCH TO PROJECT DESIGN AND OPERATION

One of the major areas of hydrologic engineering and application is in the development of design floods for determining the capacity of spillways to insure the safety of structures involved. This type of flood derivation is of a theoretical nature and involves the reasonable maximization of the hydrologic factors which would produce a "Probable Maximum" or "Standard Project" flood, as developed by flood synthesis. In the Pacific Northwest, the development of the design floods involves snowmelt analysis.

The results of the Snow Investigations program have been used in recent years for developing design floods for many major projects which are now constructed, presently under construction, or in the planning phase. These include the Libby Project, Dworshak, Chief Joseph Modification, Bonneville Modification; the Rampart and Snettisham projects in the Alaska District; and many projects in the coastal regions of western Oregon and Washington, including the projects in the Willamette River Basin, the Rogue River Basin, and the Wynoochee Project in Western Washington. These floods were developed either for the case of rain-on-snow conditions of Western Oregon and Washington or for primarily snowmelt runoff conditions of the Columbia River and its major tributaries.

These floods are synthesized by the use of an appropriate streamflow synthesis model and consider all of the elements that are reflected in the development of the design flows in the particular river basins being considered. The development of these design floods is a major factor in safe and economical design for the major projects involved and has a large bearing on the design and costs of the projects in meeting the design criteria.

The application of snow hydrology to the operation of river systems is now becoming more important than even the project planning and design. Over the past thirty years the development of the Columbia and Willamette Rivers has proceeded in an orderly manner. We are now at a condition which represents near full development of the river systems as a whole. The Corps of Engineers major river control works presently operating or under construction in the Pacific Northwest represent an investment of public funds exceeding $2-1/2 billion. Other Federal or non-Federal investments for river developments and related facilities are estimated to be about $3 billion.

The optimum management of these facilities to meet the ever-changing meteorological, hydrological and project operational conditions calls for application of the most advanced methods of river control that are currently available in our technology. The application of advanced techniques in snow hydrology is one of the most important elements in the efficient management and regulation of the river system.

In the Columbia River system particularly, the project operation must be based on hydrologic evaluation involving forecasts. These forecasts may be categorized as follows:

(1) Long-range forecasts of seasonal runoff volume, made several months in advance of the runoff period. These forecasts determine the long-range application of reservoir operating rule curves in order to meet all project requirements and assure full use of reservoir storage on the basis of projected inflows on a seasonal basis.

(2) Day-to-day forecasts of streamflow rates for short-range periods (up to 5 days) and medium-range periods (5 to 30 days) in advance. These forecasts play an important part of reservoir regulation in that they supply rates of flow on the basis of projections of streamflows and reservoir conditions occurring as the function of the snowmelt and operational variables.

FORECASTING TECHNIQUES

As an outgrowth of the investigations carried on under the Snow Investigations program, specific techniques were developed for synthesizing streamflow resulting from snowmelt. These techniques were particularly applicable to the problems of river management and streamflow forecasting in accordance with the requirements for the operation of the Columbia River system during the hydrologically active period of April through August each year. The principle effort in carrying out the application has been in the form of simulation of streamflow and river regulation by means of the electronic digital computer.

The computer programs developed by the North Pacific Division Office of the Corps for performing the required simulations has been termed the "SSARR" model, as the abbreviation of Streamflow Synthesis And Reservoir Regulation. This model is a general purpose digital computer program. It is now in its third generation of development. It was originally designed in 1957 by Dave Rockwood for use on the IBM 650 Computer and he has directed its continued development since that time.

From its operational use on a multitude of streamflow simulations for planning, design and operational hydroelectric studies, the scope, techniques, and utility of the program for efficient utilization of today's high-speed computers have increased many-fold from the original design. The basic concept of the SSARR Model is to create a mathematical hydrological model of a river and reservoir system, whereby streamflows will be synthesized for evaluating the entire process of snowmelt and/or rainfall runoff, for all components throughout the system. Drainage basins can be separated into homogeneous hydrologic units of a size and character which may be used as a logical delineation of a major drainage into its component sub-drainages.

The program contains the ability to access three basic elements as follows: (1) generalized hydrologic watershed model for synthesizing water from snowmelt, rainfall or combination thereof; (2) river basin model for routing streamflows from upstream to downstream points, including the ability to route streamflows from multi-variable relationships involving backwaters from tides or reservoirs; and (3) reservoir regulation model whereby predetermined or synthesized reservoir inflows may be operated upon in accordance with several modes of reservoir regulation.

This model has been used operationally over the past ten to twelve years in connection with river regulations in the Columbia River system and, more recently, the Willamette system in order to achieve the optimum regulation based on simulated streamflows up to thiry days or more in advance. Papers describing the design and application of the SSARR Model are available.

COOPERATIVE COLUMBIA RIVER FORECASTING UNIT

In order to coordinate river forecasting activities, and to make full use of the SSARR Model for streamflow forecasting and reservoir regulation on an operational basis, the Cooperative Columbia River forecasting Unit was formed in 1963 at the Washington level of the agencies involved. This Unit is presently comprised of the river forecasting element of the U.S. Army Corps of Engineers, North Pacific Division, and the River Forecast Center of the U.S. Weather Bureau, ESSA. It provides the means of centralizing forecasting and river regulation activities to meet requirements of both agencies.

The overall objectives of the unit are: (1) to make the best use of available computer facilities and to train river forecasting specialists of the agencies involved; (2) to advance techniques in all phases of river forecasting related to river management; (3) to provide coordinated operational forecasts on a long, medium and a short-range basis for the common use of all Federal agencies in meeting their respective missions; and (4) to centralize the river intelligence in the river operation center for a daily briefing. Over the past 6 years of operation, the unit has largely achieved its goals. Operational forecasts made by the use of the SSARR Model have been the result of efforst by both the Corps of Engineers and Weather Bureau personnel working as a team in order to provide the necessary inputs to the program in acquiring the weather forecast, hydrological data and reservoir regulation data.

Continued development of the SSARR Model for utilizing more advanced hydrological data and techniques in computer systems has developed a team effort between the Corps of Engineers and the Weather Bureau personnel. A jointly operated briefing room was established for display of current and forecast hydrometeorological and reservoir regulation conditions throughout the basin. Through a period of years, this facility has become the focal point of river management activities. This year, a new and larger room has been constructed in the Custom House in Portland, in conjunction with Corps of Engineers Reservoir Control Center. Figure 1 is a photograph of the interior of the Briefing Room of the Cooperative Columbia River Forecasting Unit.

CASE STUDIES OF FLOOD REGULATIONS

The remainder of my time this afternoon will be spent in discussing two specific cases of flood regulations that have been accomplished in the past several years. The first is the major flood of December 1964, known locally in Western Oregon as the "Christmas Flood". This flood was predominately rain, with some additional effect of snowmelt which caused a flood of major proportions in Northern California, Western Oregon and even into part of Eastern Oregon, Idaho and Eastern Washington.

The second case study is the flood of the May-June 1967 in the Columbia River. This was a typical snowmelt flood occurring during the spring runoff typical of the Columbia. It was one which had the potential of a major flood disaster along the main Columbia and its tributaries, but by use of reservoir storage operated on the basis of some of the techniques I have been discussing earlier, the flood was controlled to moderate proportions and relatively minor damages were inflicted.

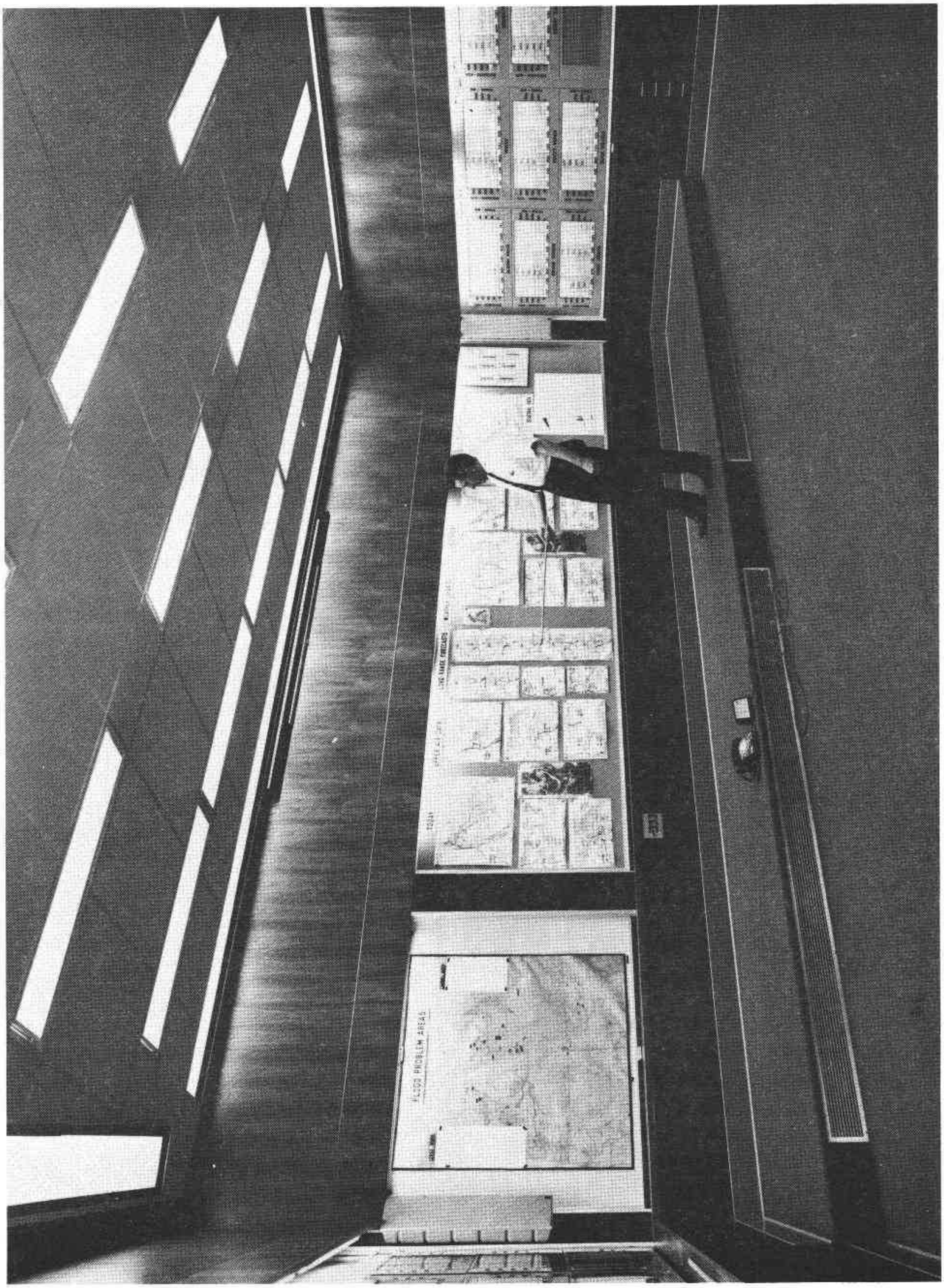


Figure 1

THE DECEMBER 1964 FLOOD

The December 1964 flood resulted primarily from the critical meteorological conditions which prevailed preceding and during the flood event. Figure 2 shows the general atmospheric circulation pattern preceding the December 1964 flood and the meteorological conditions which ultimately resulted in the flood. This chart first shows the general circulation pattern of the atmosphere at the 500 millibar level on 15 December, which was characterised by inflow of cold, moist air in the North Pacific as a result of the cold low lying to the north of the Columbia Basin in Canada.

This circulation pattern resulted in extremely cold temperatures in the whole Pacific Northwest and also an unseasonable early snowfall during this period. During the next few days the circulation gradually shifted westward and was as shown on the Chart for the 18th of December. The airflow was somewhat to the south of the former circulation and brought in moisture more directly from the Western Pacific.

Finally, culmination of the flood just before Christmas resulted in the circulation shown on the Chart for the period 21-25 December, in which atmospheric circulation was from the southwest. This pattern brought an inflow of very warm moist air from as far south as the Hawaiian Islands. Copious rainfalls occurred which together with the augmentation of snowmelt from the accumulated previous snow resulted in a flood of possibly one in a hundred years magnitude. Figure 3 shows the total storm precipitation for the period 19-23 December 1964. This shows total precipitation amounts as high as 20 inches along the coast range of Western Oregon and southern coastal regions in California. Along the Cascades as much as 18 inches fell during this period. Even in the Southwestern Idaho area precipitation amounted to as much as 8 inches during the storm period.

These amounts, together with the warm temperatures which helped to melt some of the accumulated snow, resulted in the major flood. Our best estimate of the relative proportion of snowmelt to rainfall contribution indicates that approximately 20 percent of this flood was a result of this snowmelt, while about 80 percent was due to rainfall.

The regulation of the December 1964 flood by the Willamette Basin projects prevented a major catastrophe for the region. To illustrate the control of this flood by the projects that were then existing in the Willamette Basin, Figure 4 shows the flood hydrograph for Detroit Project on the North Santiam River. The inflow hydrograph had a peak flow 80,000 cfs on the 22nd of December. The regulation by Detroit is

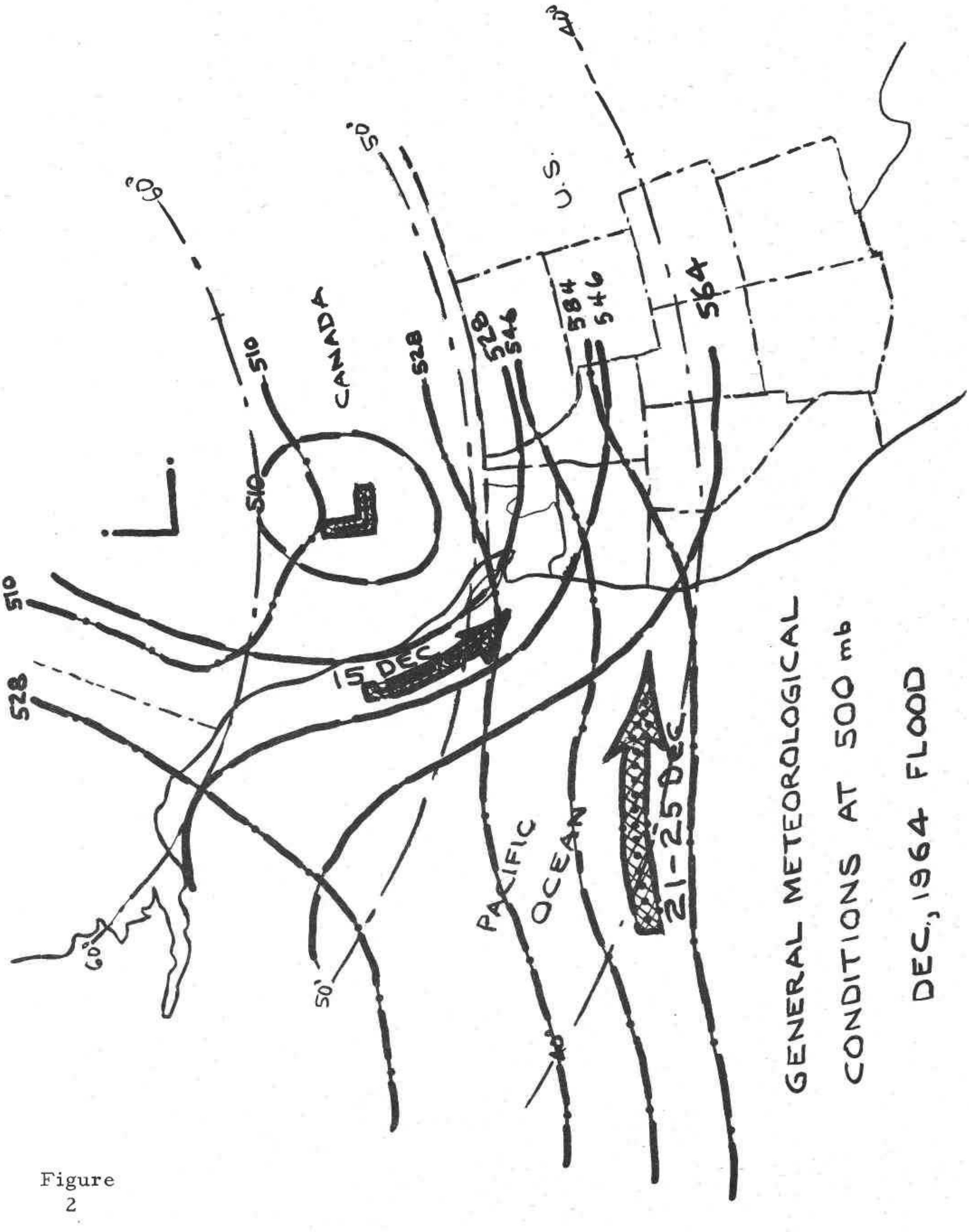

GENERAL METEOROLOGICAL
CONDITIONS AT 500 mb
DEC., 1964 FLOOD
CANADA
U.S.
PACIFIC
OCEAN
15 DEC
21-25 DEC
510
510
510
528
528
528
546
584
546
564
60°
60°
50°
50°
40°
40°

Figure
2

TOTAL STORM PRECIPITATION

19-23 DEC 1964

Figure
3

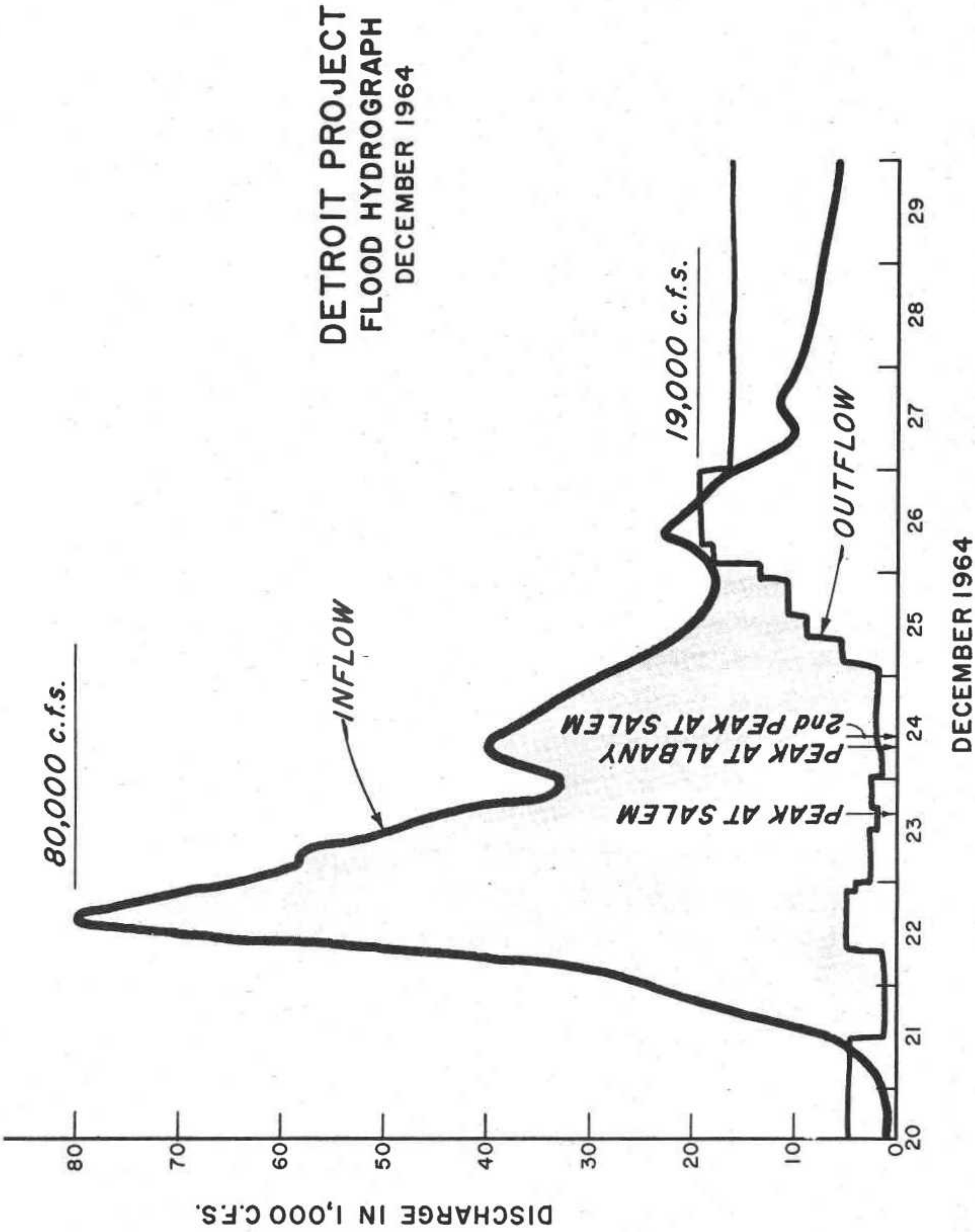

DETROIT PROJECT
FLOOD HYDROGRAPH
DECEMBER 1964
80,000 c.f.s.
19,000 c.f.s.
INFLOW
OUTFLOW
PEAK AT SALEM
PEAK AT ALBANY
2nd PEAK AT SALEM
DISCHARGE IN 1,000 C.F.S.
0
10
20
30
40
50
60
70
80
20
21
22
23
24
25
26
27
28
29
DECEMBER 1964

Figure
4

shown as the shaded area below the "outflow" line. The outflow of the projects was essentially reduced to zero during the height of the flood, but finally as the flows receded on the 25th the outflow was gradually increased to meet the inflow. This Chart shows the reservoir achieved its maximum effectiveness in the control of the flood at the project, and there was sufficient capacity to store the flood waters until flows had receded to safe limits downstream.

SIGNIFICANT RISES RECORDED

The combined effect of all Willamette reservoirs in existence in December 1964 is shown on Figure 5. This represents the flood discharges for the Willamette River at Salem. At this point, the major flood stage is 33 feet corresponding to a discharge of 230,000 cfs. The reduction in streamflow that was effected by the upstream reservoirs can be noted. It can be seen that without these reservoirs the peak discharge would have been 471,000 cfs corresponding to a peak stage of 45 feet or approximately 12 feet above major flood stage. With the regulation, however, the peak was 308,000 cfs corresponding to a peak stage of 37.8 feet. This shows the total reduction of more than 7 feet that can be credited to the reservoir control. The area shaded with diagonal lines represents the reduction that would have been effected by the projects which were under construction or authorized at that time. The combined effect of all existing, under construction, and authorized storage would have reduced the flood at Salem to 210,000 cfs corresponding to a river stage of 31 feet. This would have been 2 feet below major flood stage.

The December 1964 floods were very unusual in that because of the intense rain, even east of the Cascade range, there were significant rises in the streamflow in the main Columbia River. These rises came mainly from the contribution from the Lower Snake and the minor tributaries to the Columbia below the mouth of the Snake River.

Figure 6 shows the hydrograph for the Columbia River at Bonneville Dam. Here again, there was some degree of reservoir control by upstream storage. This included the effects of the projects in the Boise River System, the Owyhee and other irrigation reservoirs in the Snake River, Brownlee project and Round Butte project of the General Electric Dam on the Deschutes River. Also, there was a special effort made to control the flows from the Upper Columbia by regulation at Priest Rapids Dam whereby the flows were reduced at Priest Rapids by shifting of power loads to the rest of the hydro power system in the Pacific Northwest.

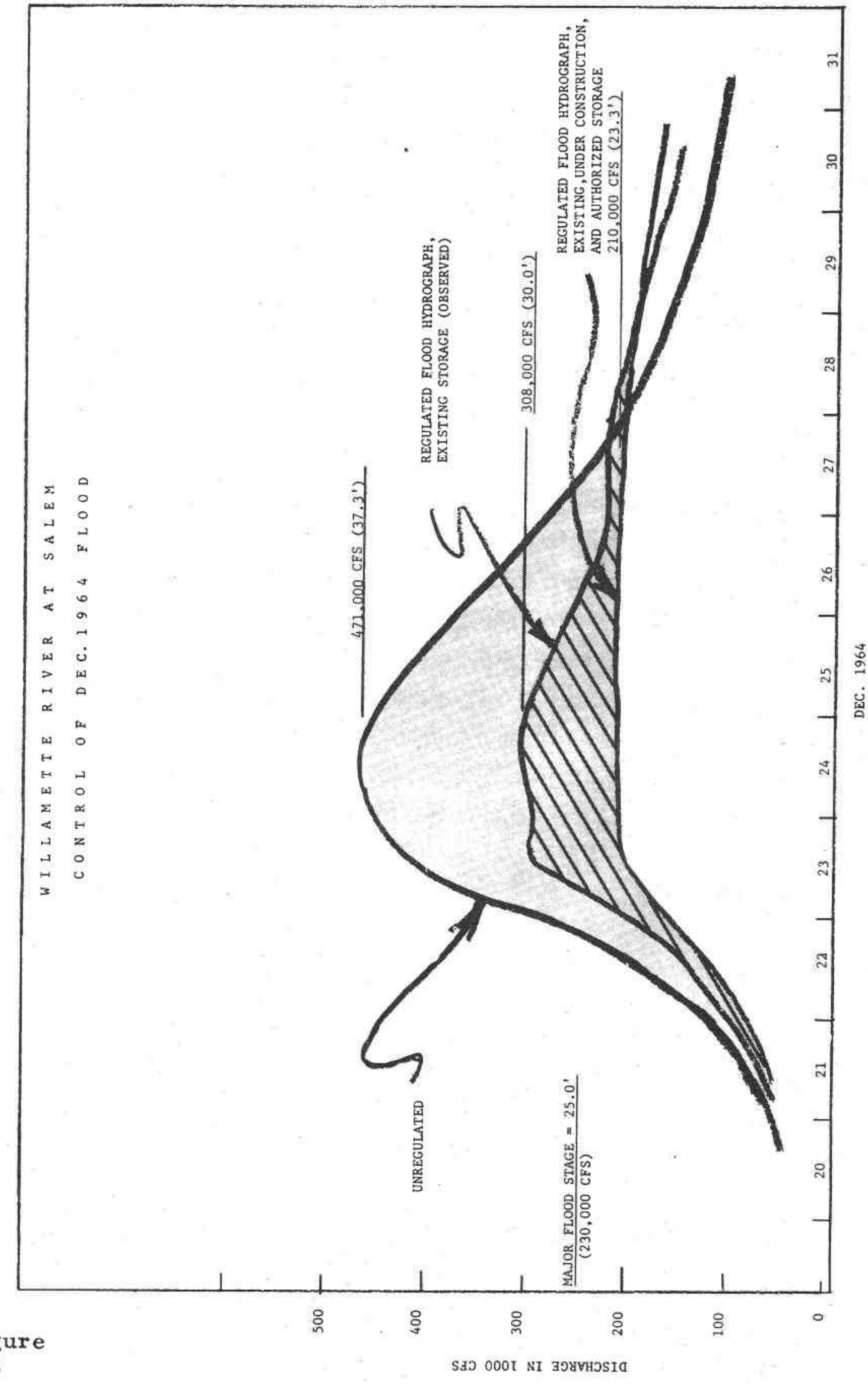
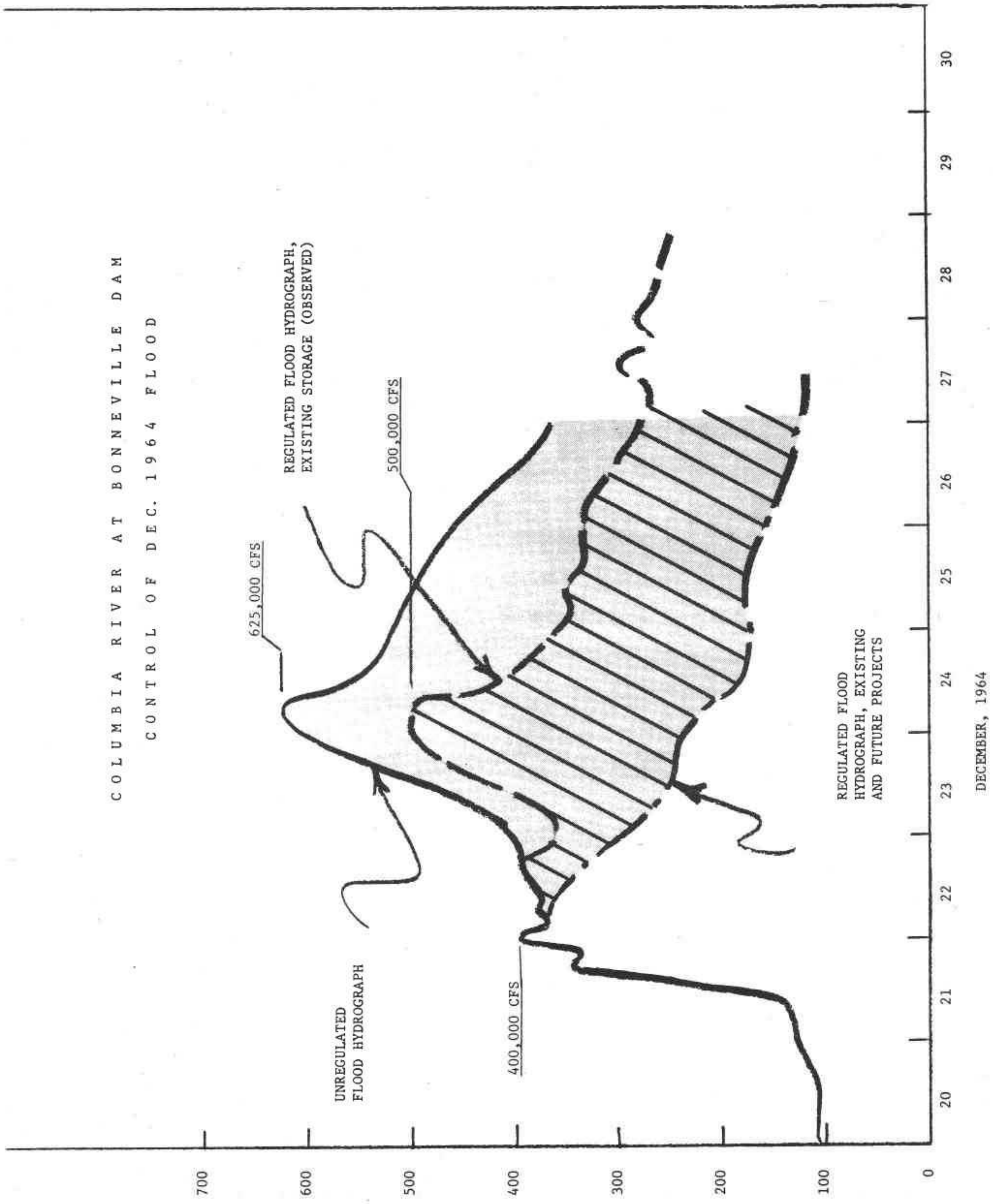

WILLAMETTE RIVER AT SALEM
CONTROL OF DEC. 1964 FLOOD
471,000 CFS (37.3')
REGULATED FLOOD HYDROGRAPH, EXISTING STORAGE (OBSERVED)
308,000 CFS (30.0')
REGULATED FLOOD HYDROGRAPH, EXISTING, UNDER CONSTRUCTION, AND AUTHORIZED STORAGE
210,000 CFS (23.3')
UNREGULATED
MAJOR FLOOD STAGE = 25.0'
(230,000 CFS)
DISCHARGE IN 1000 CFS
0
100
200
300
400
500
20
21
22
23
24
25
26
27
28
29
30
31
DEC. 1964

Figure 5



COLUMBIA RIVER AT BONNEVILLE DAM
CONTROL OF DEC. 1964 FLOOD
REGULATED FLOOD HYDROGRAPH, EXISTING STORAGE (OBSERVED)
500,000 CFS
625,000 CFS
UNREGULATED FLOOD HYDROGRAPH
400,000 CFS
REGULATED FLOOD HYDROGRAPH, EXISTING AND FUTURE PROJECTS
20
21
22
23
24
25
26
27
28
29
30
DECEMBER, 1964
0
100
200
300
400
500
600
700
DISCHARGE IN 1000 CFS

Figure 6

The effect of all of the control is shown by the shaded area at top which indicates a reduction in peak discharge of 625,000 cfs to 500,000 cfs. Again, on this chart, the projects which are existing and planned for the future, or the area indicated by diagonals, would have achieved the amount of reduction shown as the amount of reduction in the storage system now in the Division.

Figure 7 shows the total regulation for the combined Willamette and Columbia River flow as estimated just below the mouth of the Willamette River below Vancouver. Without regulation the peak discharge would have been 1,100,000 cfs, corresponding to the peak stage at Vancouver of 32.5 feet. With the combined effect of storage in both the Willamette and Columbia River systems the peak was reduced to 860,000 cfs corresponding to a stage at Vancouver of 27.7 feet. With all projects now envisioned in the system as a whole, the level would have been further reduced to river stage of 22.0 feet. The major flood stage at Vancouver is 26 feet.

Figures 8-11 show some of the flood effects, such items as debris showing the approach of flood, washing out of roads and highways, in controlled areas, urban damage in the Keiser area near Salem. It can readily be seen that while the December flood was a major flood for the Willamette and adjacent areas, the effect of upstream storage resulted in major benefits to the region.

As it turned out the river stages in the Portland Harbor area were barely within the limits of the so-called "seawall" which borders downtown Portland. If it had not been for the upstream reservoirs, the river stages would have been at least 5 feet higher in the lower river and this would have resulted in a major catastrophe by flooding downtown Portland and would have caused untold damage, not only from flooding but from other flood effects. It has been estimated that the savings effected by the reservoirs for this one occurrence represent a value greater than twice the cost of the existing reservoir system in the Willamette Basin.

Figure 12 shows a summary of flood damages and benefits from regulation and other flood protective works that were achieved during the control of the Christmas Flood.

COLUMBIA RIVER BELOW VANCOUVER, WN.

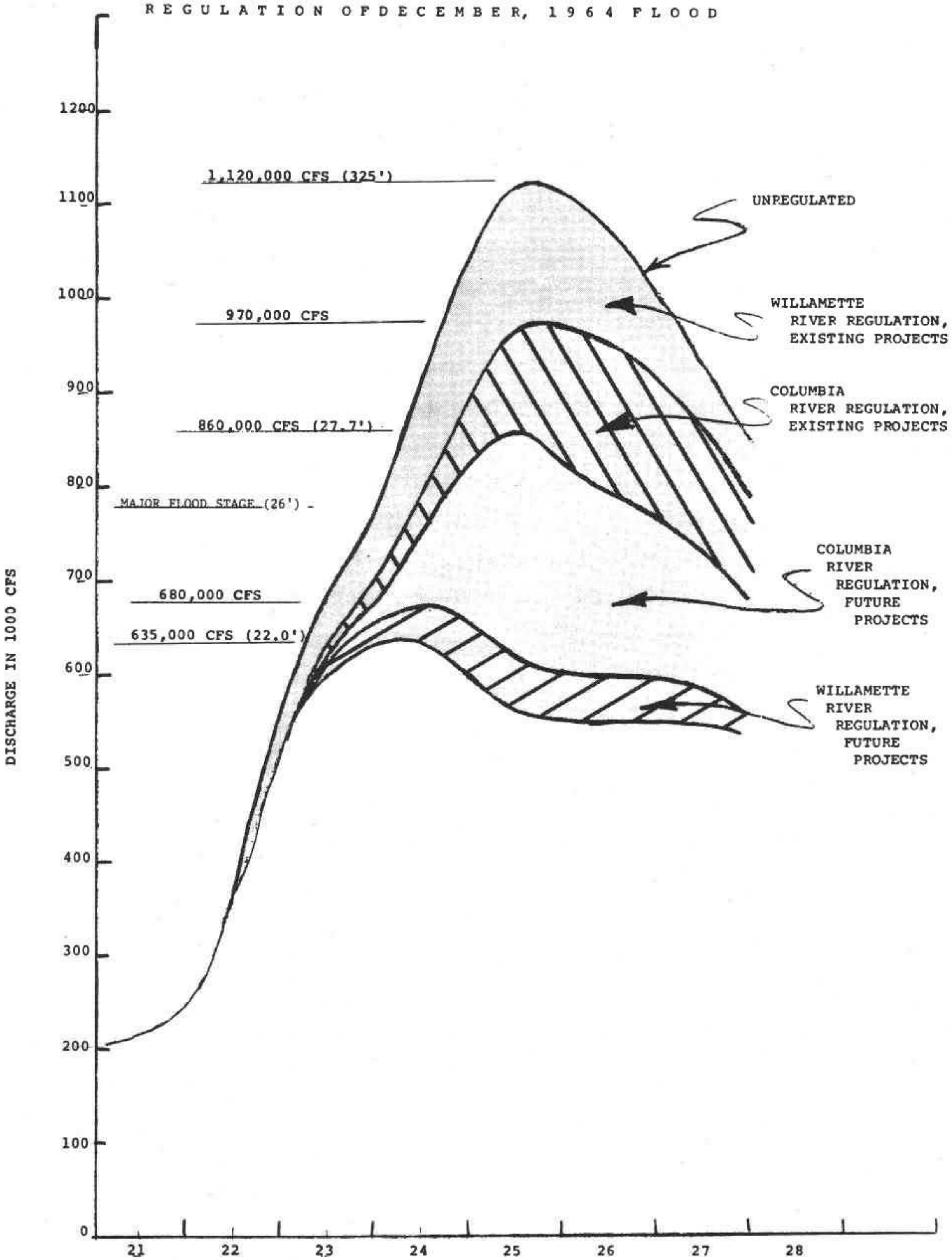


Figure 7

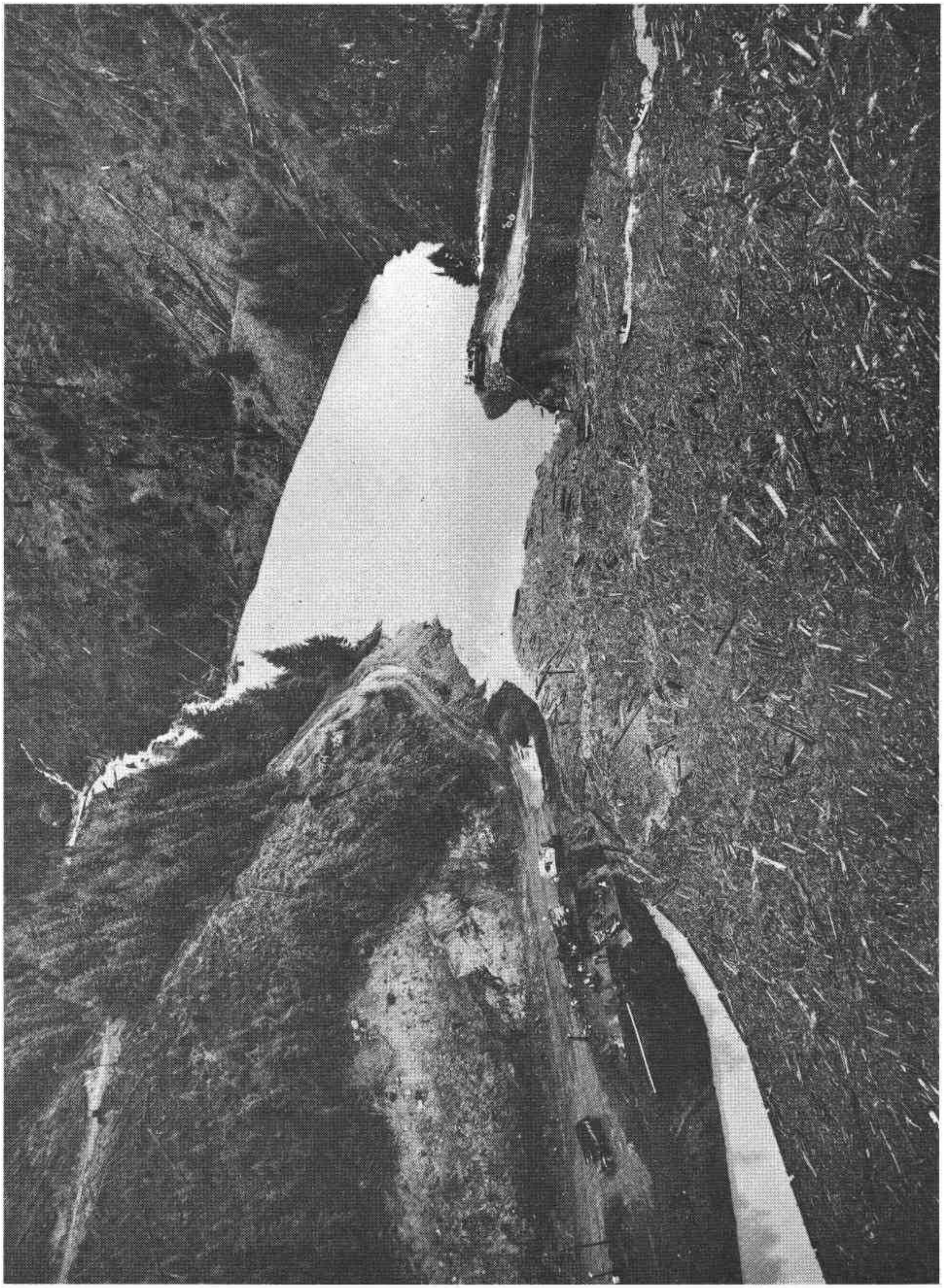


Figure 8

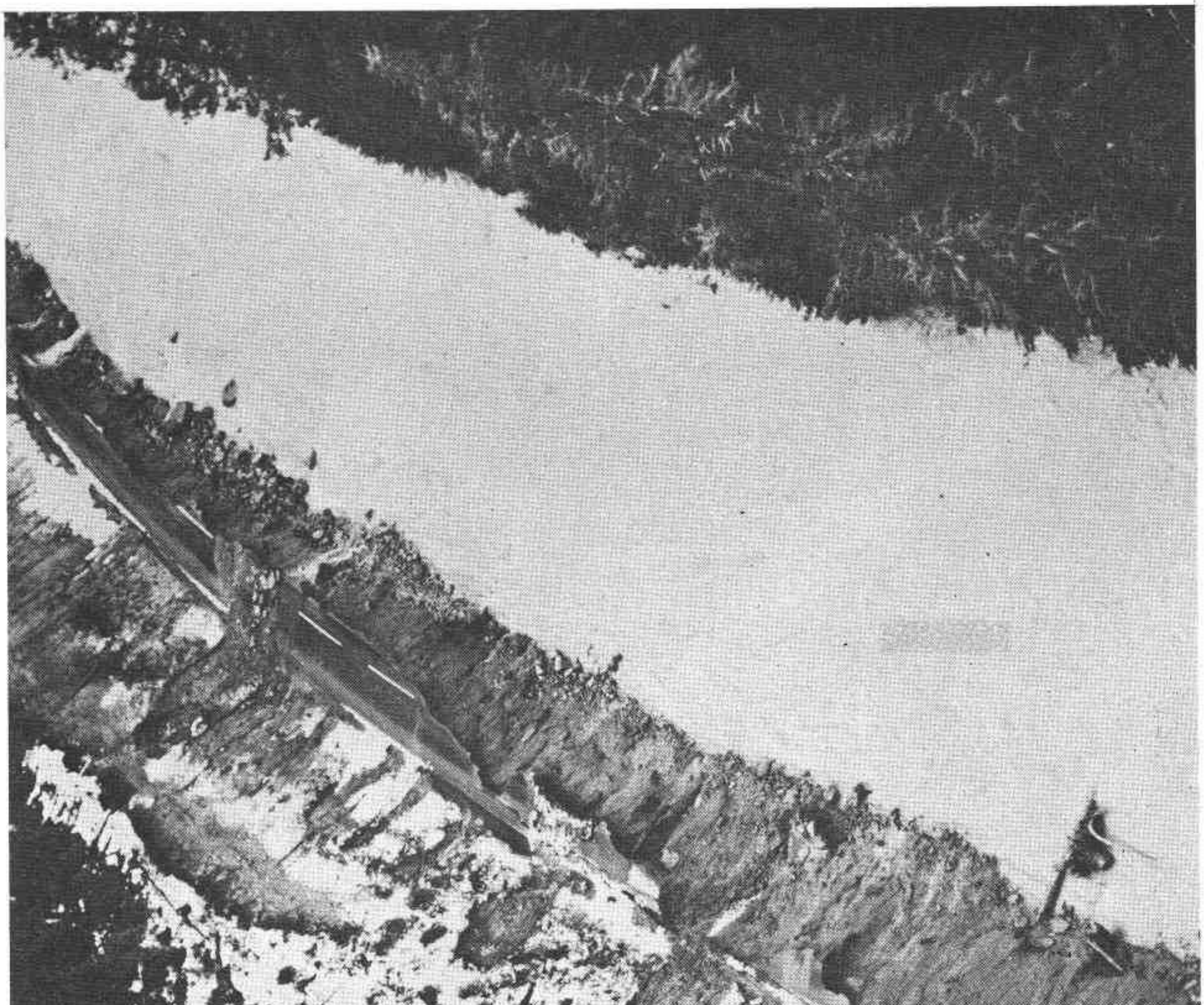


Figure 9

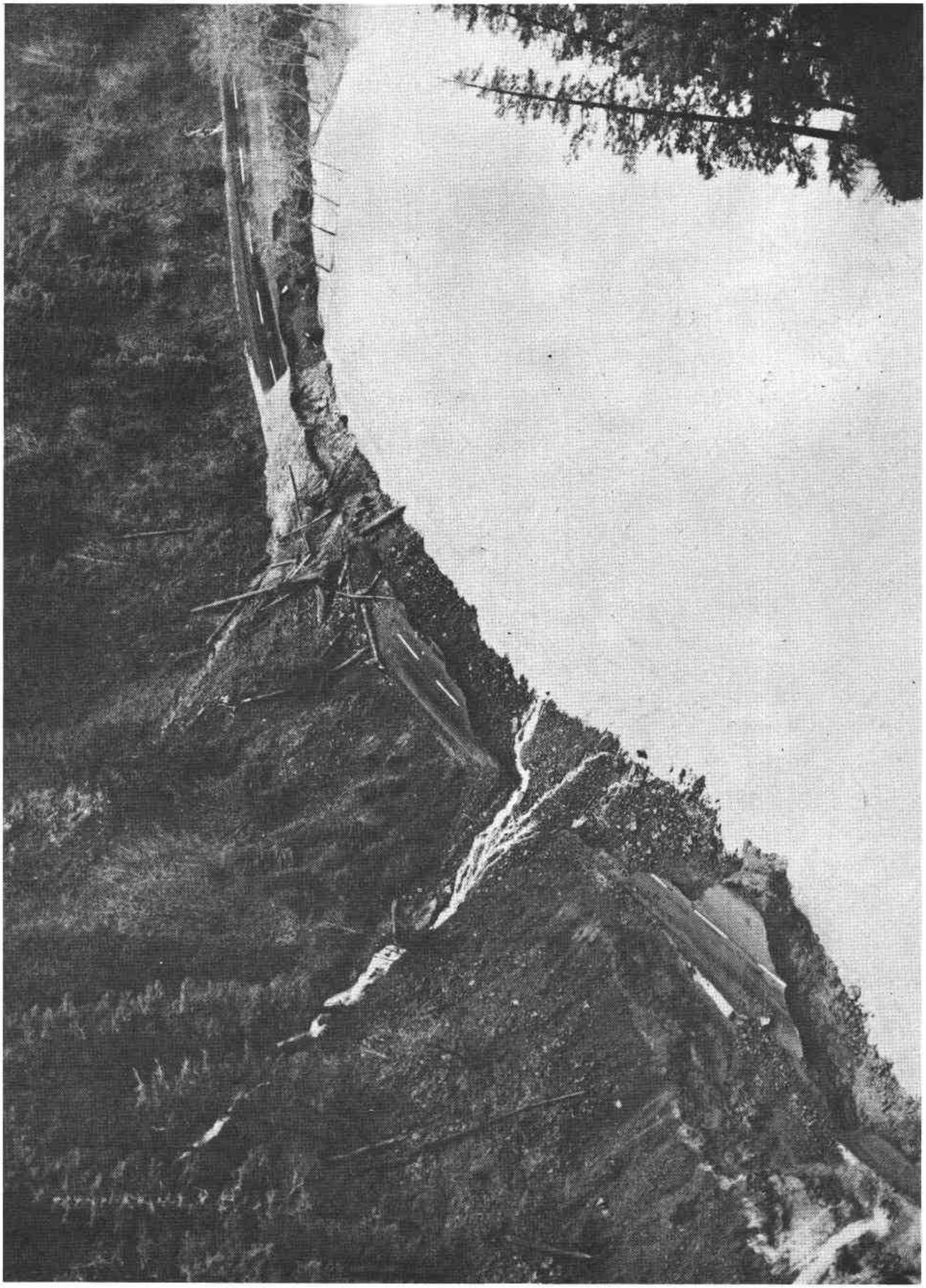


Figure 10

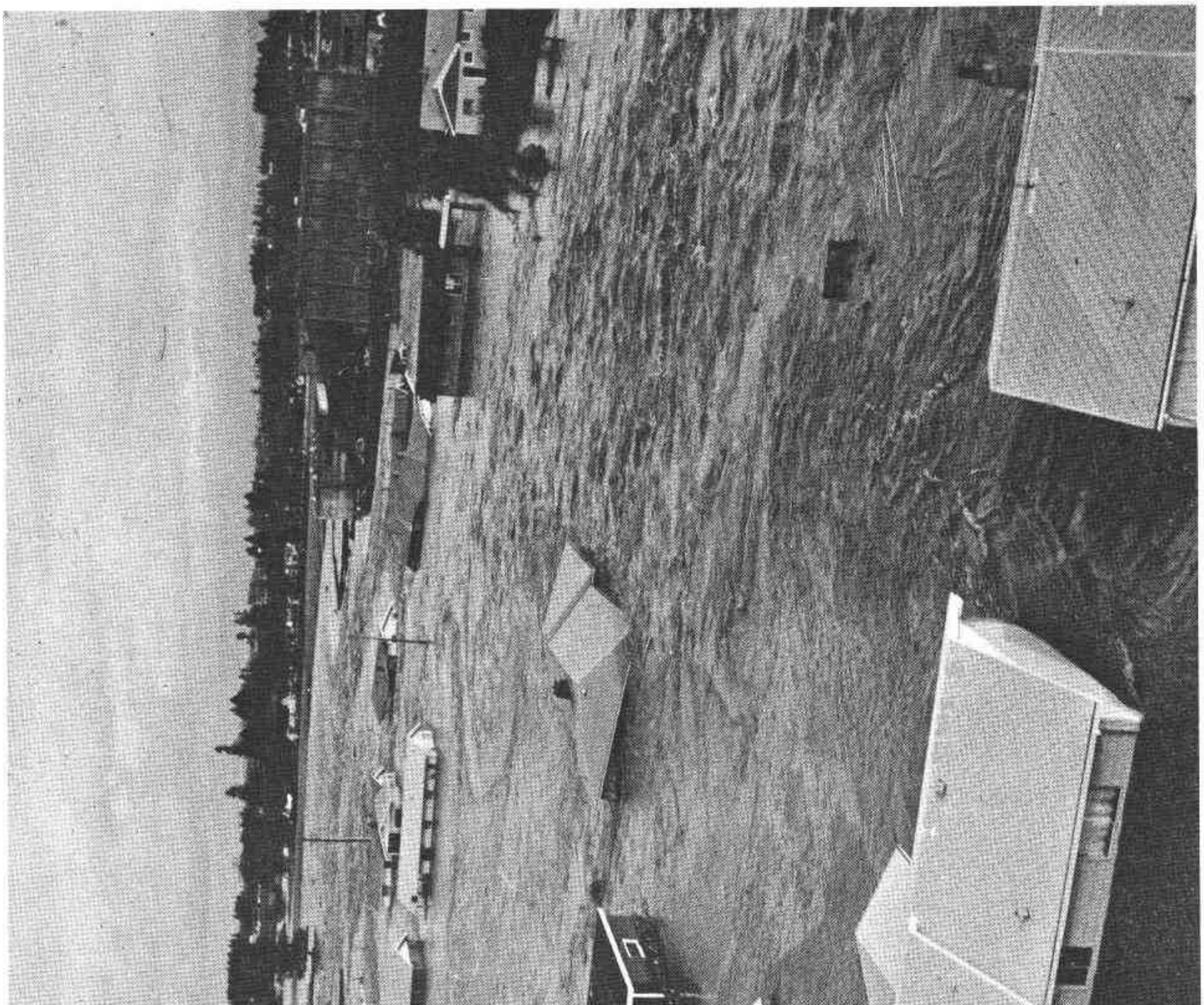


Figure 11

Figure 12

DECEMBER 1964 FLOOD

SUMMARY OF FLOOD DAMAGES AND FLOOD CONTROL BENEFITS

IN MILLIONS OF DOLLARS

RIVER BASIN	ACTUAL FLOOD DAMAGE	DAMAGES PREVENTED	
		RESERVOIR STORAGE	LEVEES
A. Principal drainages			
WILLAMETTE	109	572	
LOWER COLUMBIA	12	30	52
UMPQUA	31		
ROGUE	23		
PAYETTE	2.9	3.0	
BOISE	0.5	12.3	
WALLA WALLA	4.0	0.8	
SPOKANE	2.0		
JOHN DAY	10.8		
B. Grand total, Columbia and coastal drainages			
ALL AREAS	233	627	52

COLUMBIA RIVER SNOWMELT FLOODS

Finally, I want to touch very briefly on the flood regulation of the Columbia River Basin system during the annual high-water period which results from the melting of the mountain's snowpack.

Figure 13 is a pictorial representation of the Columbia River Basin. It shows the location of the major storage reservoirs in the system. It must be recognized that the amount of storage control is small in relation to the volume of runoff during the high-flow period and at the present time amounts to about 15% of the total runoff volume. Obviously, reservoir storage must be used judiciously in order to achieve effective flood regulation of the main stem of the Columbia.

This requires in a large measure the use of forecasts in day-to-day regulation of streamflow conditions, in order to detect unforeseen runoff potentials resulting either from excessive snowmelt or from augmentation of the snowmelt flood by rainfall. The so-called "shape factor" of the annual spring flood hydrograph cannot be forecast on a long-range basis. It must be dealt with, in day-to-day evaluations, in order to detect the changing runoff potential as the season progresses.

Figure 14 shows the differences that can be encountered by the effect of the weather pattern during the runoff period. This shows that for two months of the approximate runoff potential in normal years, as illustrated by the 1896 flood, a modest amount of storage is required in order to control the flood to a predetermined level. For the 1948 flood an exceptional amount of storage would be required.

1967 COLUMBIA RIVER FLOOD REGULATION

The 1967 Columbia River flood serves as an example of optimum reservoir regulation which was accomplished largely by the aid of the SSARR Model. In that year, only about 10,000,000 acre-feet of usable storage were available for downstream river control. Forecast of seasonal runoff volume made as of 1 April indicated about 108% of normal runoff for the basin as a whole. Furthermore, during the pre-flood condition of April and early May weather conditions were such that the potential for serious flooding increased. Precipitation was generally above normal and temperatures were below normal, so that a relatively larger proportion of the snowpack remained in the mountain areas in mid-May.

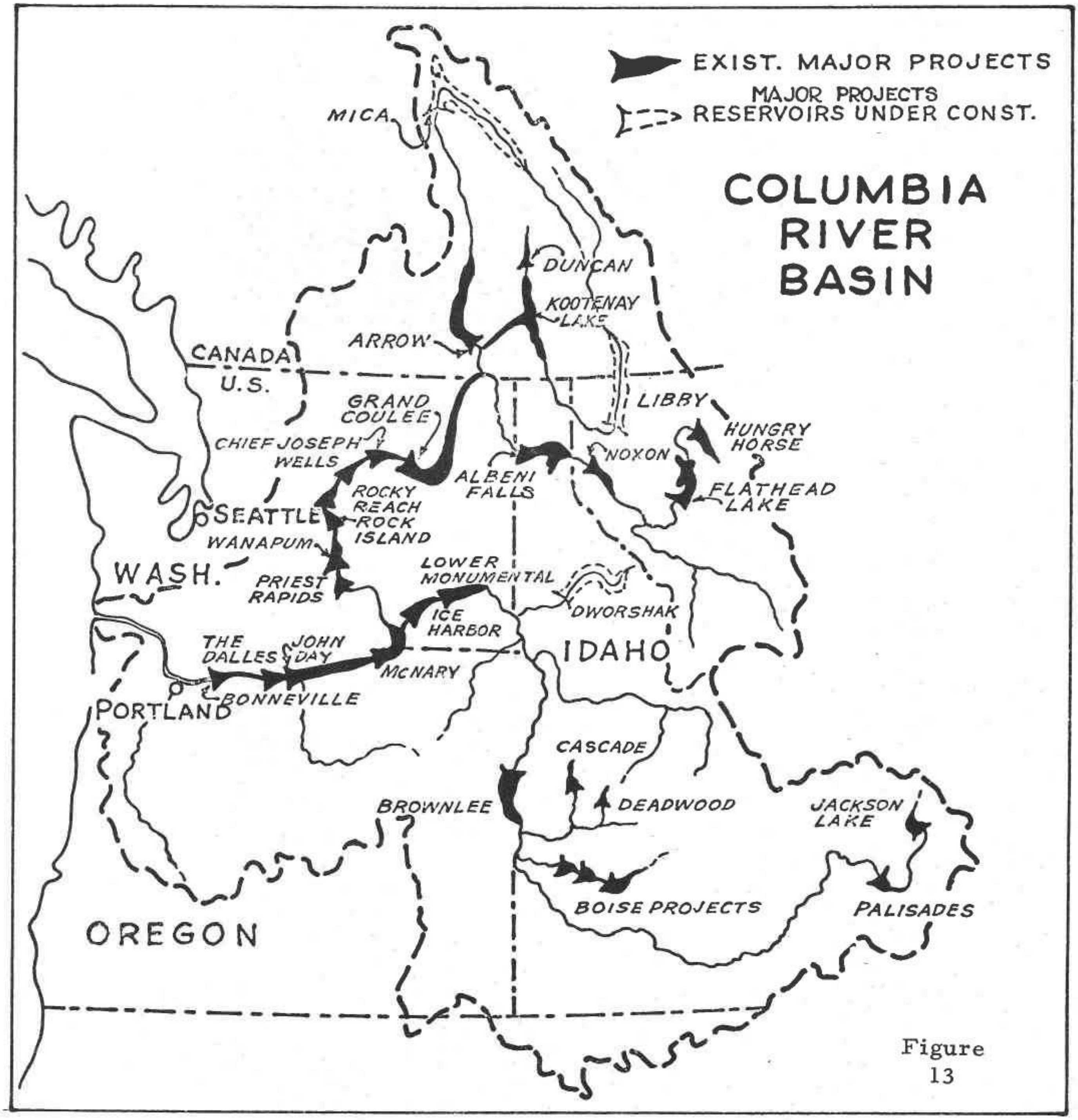

EXIST. MAJOR PROJECTS
MAJOR PROJECTS
RESERVOIRS UNDER CONST.
COLUMBIA
RIVER
BASIN
MICA
DUNCAN
KOOTENAY LAKE
ARROW
CANADA
U.S.
GRAND COULEE
LIBBY
HUNGRY HORSE
CHIEF JOSEPH
WELLS
NOXON
ALBENI FALLS
FLATHEAD LAKE
ROCKY REACH
SEATTLE
ROCK ISLAND
WANAPUM
WASH.
PRIEST RAPIDS
LOWER MONUMENTAL
DWORSHAK
ICE HARBOR
IDAHO
THE DALLES
JOHN DAY
McNARY
BONNEVILLE
PORTLAND
CASCADE
DEADWOOD
BROWNLEE
JACKSON LAKE
BOISE PROJECTS
PALISADES
OREGON

Figure 13

Storage Required for Flood Control

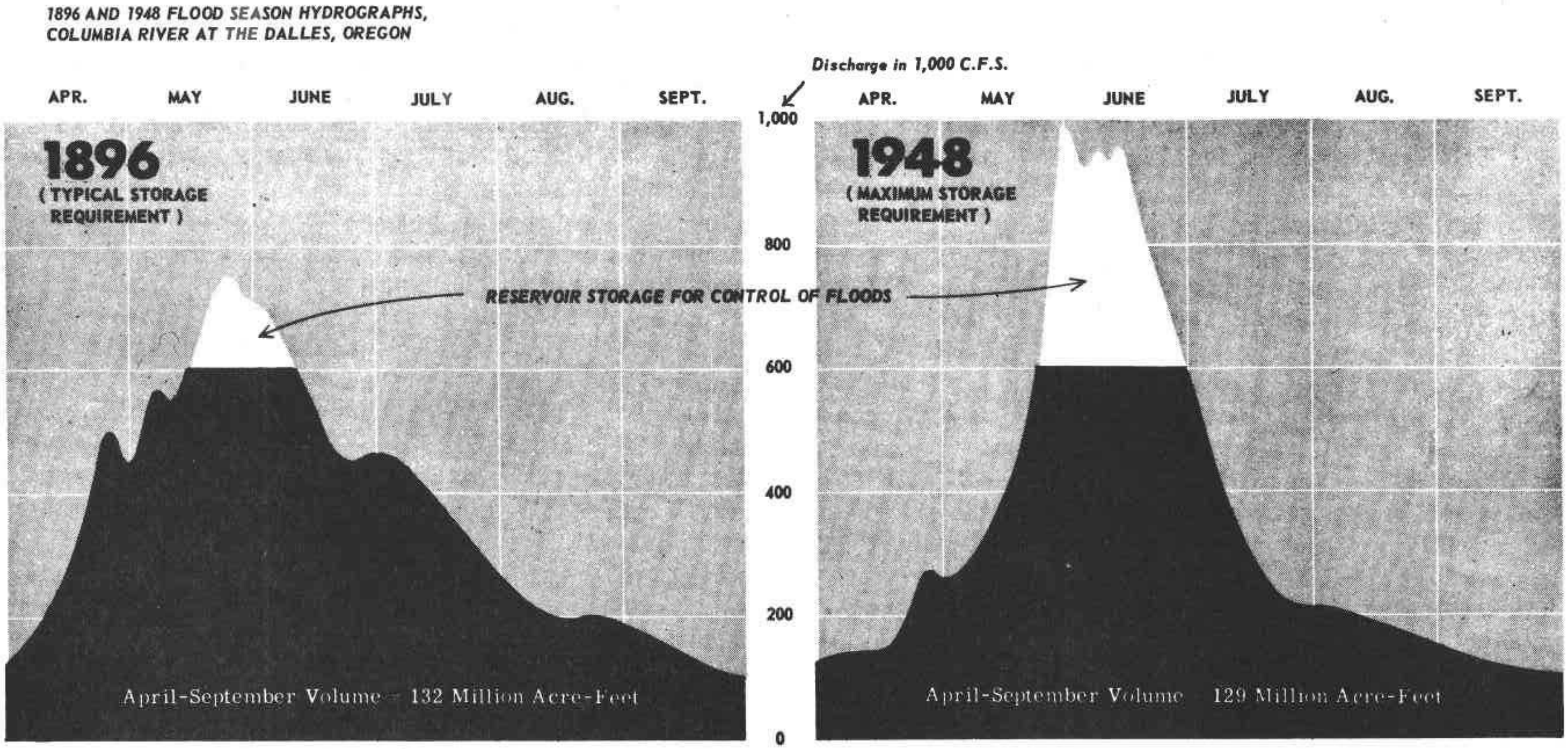


Figure
14

There was general concern in the lower Columbia River area of a possible major flood occurrence. Upstream reservoirs, including Hungry Horse, Jackson Lake, Palisades, three reservoirs on the Boise River, Cascade and Deadwood Reservoirs on the Payette River were regulated on the basis of fixed regulation criteria in a manner to store their share of the flood waters on the basis of seasonal volume forecast. The Bureau of Reclamation's Grand Coulee Project at that time provided the major downstream reservoir control and this storage on the Columbia River is operated on a day-to-day basis in response to flow increases during the major spring rise accompanying the peak of the flood. About 2,000,000 acre-feet of storage were available at Grand Coulee in mid-May 1967, and that was held for final regulation of the flood peak of June.

On 8 June the flow of the Columbia approached 600,000 cfs. From the computer simulations, it was possible to determine at that time, that the peak could be held so as not to exceed this value of discharge through the remainder of the flood even with adverse snowmelt conditions for the remainder of June. It was decided to regulate the flow so as not to exceed approximately 600,000 cfs.

As it turned out above normal snowmelt augmented by rainfall did occur in mid-June, but there was sufficient space in the reservoirs to control this level. All project purposes were met and the reservoirs were essentially filled by the end of June. Figure 15 shows the regulated and unregulated discharge for the Columbia River at The Dalles for the 1967 flood superimposed on the summary hydrograph for the spring flows at that location. This indicates the relative magnitude of the flood with respect to historic streamflow records by degree of regulation as achieved by reservoir storage.

Figure 16 is a similar chart showing the effect of regulation on the river levels as measured at Vancouver, Washington. Without regulation the peak would have been 26.6 feet which would have been over major flood stage at 26 feet. The reduction in river levels is indicated by the hatched area on this diagram and shows that the regulation reduced the peak to 21.5 feet, or a reduction of over 5 feet at Vancouver. The benefits resulting from this regulation amount to more than $14,000,000, by reduction of flood damages from the lower Columbia River.

Finally, Figure 17 shows the various components of reservoir storage that affected this reduction in river flow for the lower Columbia River. These results were obtained by "un-routing" the flood to show the storage effect in the Lower River of each project or group of projects. From this diagram, you may visualize proportional regulation that was achieved by the individual projects involved.

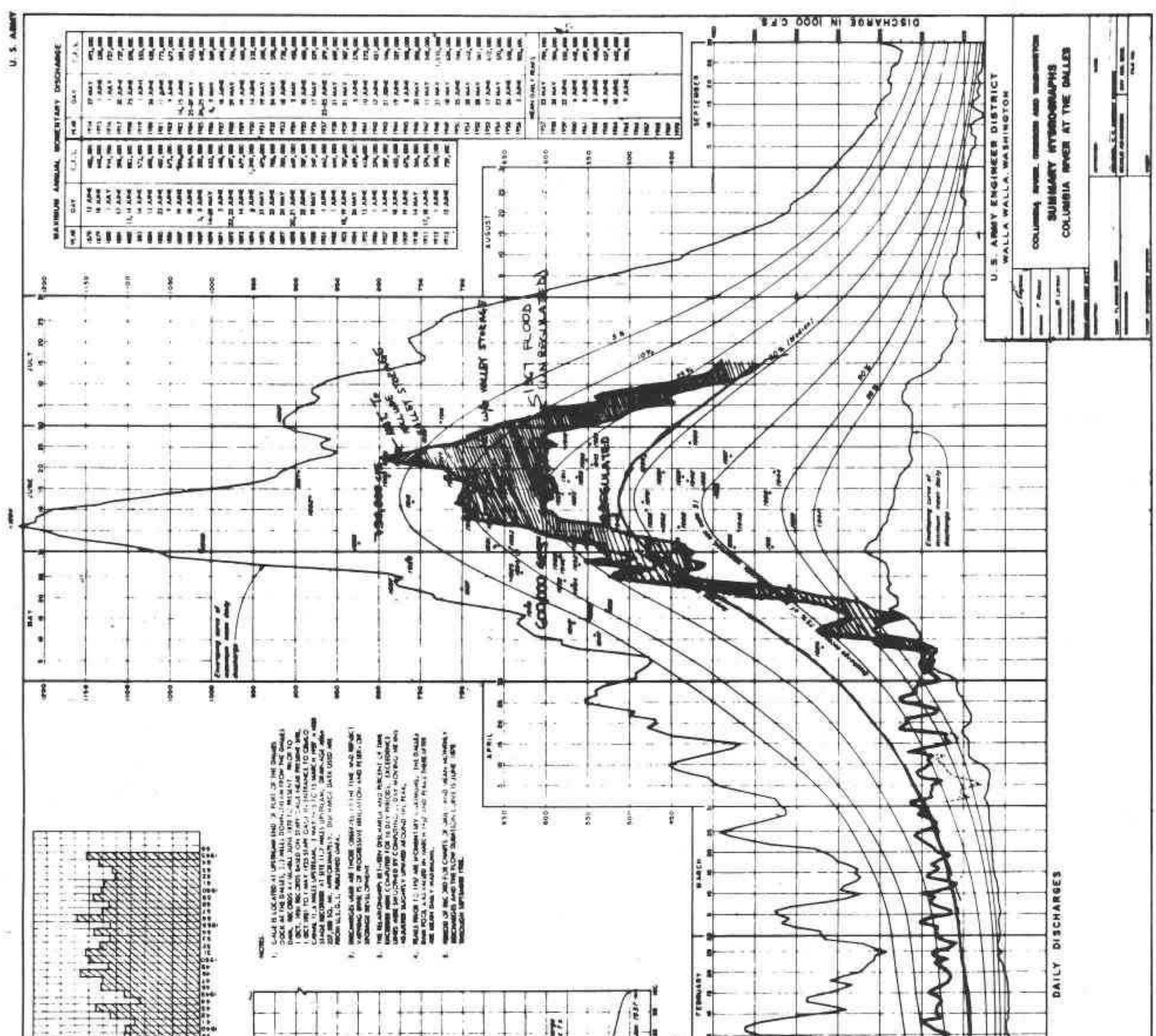

CORPS OF ENGINEERS
U. S. ARMY
U. S. ARMY ENGINEER DISTRICT
WALLA WALLA, WASHINGTON
SUMMARY HYDROGRAPHS
COLUMBIA RIVER AT THE DALLES
DAILY DISCHARGES
MEAN MONTHLY DISCHARGES
WATER YEAR RUNOFFS
FLOW DURATION CURVE

Figure 15

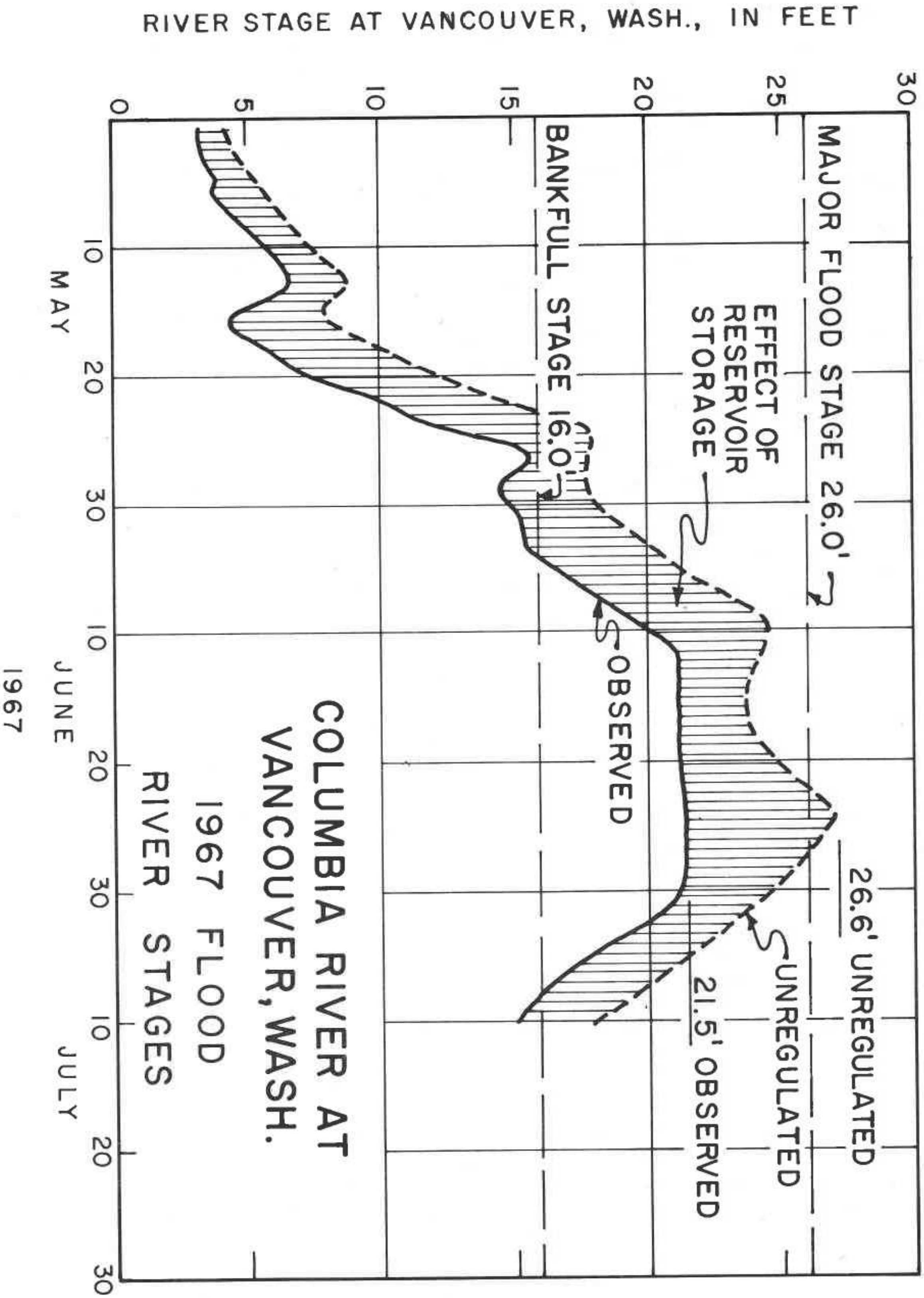
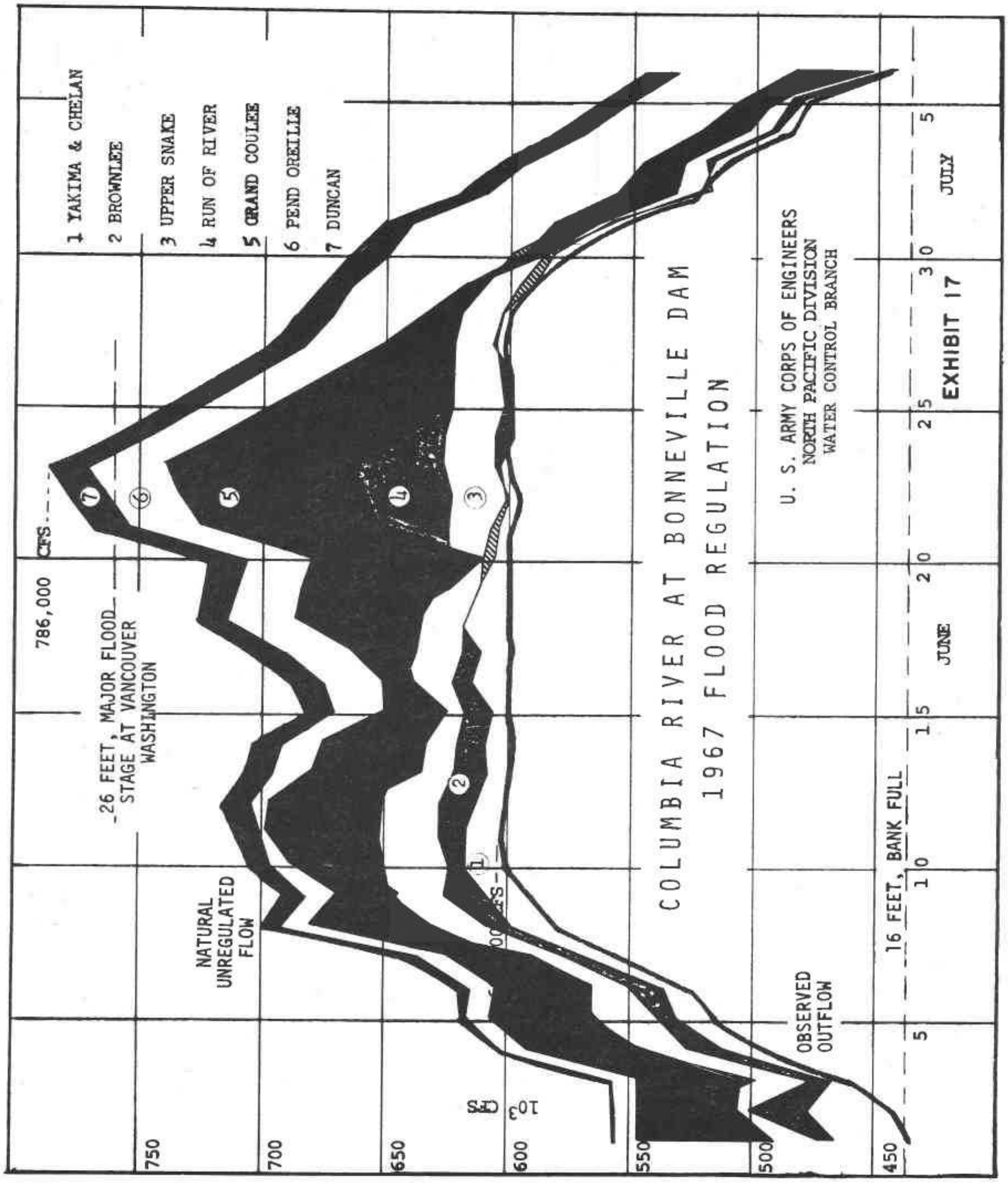

RIVER STAGE AT VANCOUVER, WASH., IN FEET
MAJOR FLOOD STAGE 26.0'
EFFECT OF RESERVOIR STORAGE
BANKFULL STAGE 16.0'
OBSERVED
26.6' UNREGULATED
UNREGULATED
21.5' OBSERVED
COLUMBIA RIVER AT VANCOUVER, WASH.
1967 FLOOD
RIVER STAGES
MAY
JUNE
JULY
1967

Figure
16



COLUMBIA RIVER AT BONNEVILLE DAM
1967 FLOOD REGULATION
1 YAKIMA & CHELAN
2 BROWNLEE
3 UPPER SNAKE
4 RUN OF RIVER
5 GRAND COULEE
6 PEND OREILLE
7 DUNCAN
786,000 CFS
26 FEET, MAJOR FLOOD STAGE AT VANCOUVER WASHINGTON
NATURAL UNREGULATED FLOW
OBSERVED OUTFLOW
16 FEET, BANK FULL
10^3 CFS
750
700
650
600
550
500
450
5
10
15
20
25
30
5
JUNE
JULY
U. S. ARMY CORPS OF ENGINEERS
NORTH PACIFIC DIVISION
WATER CONTROL BRANCH
EXHIBIT 17

Figure
17

SUMMARY CONCLUSIONS

I have attempted to show you today some of the practical applications of snow hydrology that have been applied to specific river regulation problems here in the Pacific Northwest. I have not attempted to deal with the multitude of details involved in this type of analysis, but rather have tried to show you some of the practical uses of this type of information. I would suggest that anyone who is interested in pursuing some of the theoretical evaluations of snow hydrology and computer programming techniques used in developing these regulations may write to the North Pacific Division Office, Corps of Engineers.

Prepared by MARK F. MEIER, U.S. Geological Survey, Tacoma, Washington, who was unable to appear. DR. NORBERT UNTERSTEINER, Department of Atmospheric Sciences, University of Washington, substituted for him and spoke on the same topic on May 22, 1969.

Why Study Glaciers?

Most hydrologic knowledge has been derived from studies of low-elevation areas at temperate latitudes. Cultural and population pressure on cold regions and high mountain areas is increasing markedly. Much of the water supply of the western states is deposited as snow in the high mountains. Thus a need exists to understand the hydrology of snow and ice, and the unique hydrologic problems encountered in cold regions and at high altitudes. An efficient way to do this is to study a glacier basin: all problems involved in snow and ice hydrology are encountered here in their greatest concentration and profusion, and the results obtained here are widely applicable to other areas, including those where snow is only a temporary feature of the landscape.

QUANTITATIVE IMPORTANCE OF SNOW AND ICE IN THE HYDROLOGICAL CYCLE

1. Worldwide. About three-fourths of all of the fresh water in the world is stored in the form of glacier ice. These glaciers cover about 11 percent of the land area of the world. Another 10 percent of the land area is covered with perennially frozen ground. At any one instant in time 30-50 percent of the land area is covered with snow and about 23 percent of the ocean area is covered by sea ice or icebergs.

2. Alaska. The State of Alaska is covered with an estimated 20,000 square miles of glaciers which store a huge amount of water, perhaps on the order of 12 billion acre-feet. About half of the state is underlain by permafrost, and snow covers most of the state most of the time. Over 50 percent of the surface water in interior Alaska, and almost all of the available surface water storage, is derived from the

mountain areas above 5,000 feet in altitude. Along the southeast coast, the hydrology is dominated by glaciers and mountain snow. In the north, the hydrologic regimen is completely dominated by frozen ground and snow.

3. Washington. The 135 square miles of glacier ice in this state store about 40 million acre-feet of water, an amount of storage roughly equivalent to the combined total of all of the surface water reservoirs, lakes, and streams. These glaciers release about 800,000 acre-feet of water to streamflow during the dry months of July and August; this volume of water is of the same order of magnitude as the total amount pumped from groundwater reservoirs for a whole year. Most of the precipitation in the state falls and is temporarily stored in the high mountains as snow; precipitation rates in the mountains range up to 5 times greater than in the lowlands where the population is concentrated. About 15 percent of the summer flow of the Columbia River at the Canadian border is derived from about 1,000 square miles of glacier ice in Canada.

4. All other states in the mountain West store water in the form of high altitude snowpacks and/or glaciers, which is released during the hot, dry season. Even the arid State of Wyoming possesses in its inaccessible and relatively unknown mountains about 18 square miles of glacier ice--the water from these ice masses (estimated at 100,000 acre-feet in summer) is an important source of streamflow during the hot, dry growing season. Montana, Oregon, and California also have appreciable amounts of glacier ice, and the streamflow in all other states in the West is controlled in no small degree by mountain snowpacks and persisting masses of ice and snow.

MAJOR PROBLEMS IN AN UNDERSTANDING OF THE HYDROLOGY OF SNOW AND ICE

1. Paucity of data. In the mountain West almost all of the precipitation gages, stream gaging stations, observation wells, and other hydrologic instruments are in the lowlands where people live. However, the high rates of precipitation and the storage of water as snow and ice occur predominantly in the mountains. Thus very little hydrologic data is at hand in those areas which are hydrologically of greatest importance. For instance, in the western half of the State of Washington about 20 percent of the land area is above an elevation of 4,000 feet.

Precipitation rates on this high altitude land probably average at least twice that of the rates on the lowlands, so that perhaps a third to a half of all the precipitation falls on this high country. Yet in this half of the state there are no streamflow gaging stations, no observation wells, and only 7 precipitation gages above 4,000 feet, except for our South Cascade Glacier installations. Similar conditions exist at high altitudes in other states.

2. Unusual hydrologic processes involved. The release of water from snow and ice masses is more a thermal than a hydraulic or mechanical problem. No single parameter (such as air temperature) determines the rate of snow and ice melt. Predicting runoff from a snow or ice field is difficult, and accurate prediction of runoff amount and timing will not be possible until we have a deeper understanding of the processes involved.

This requires more attention to direct cause-and-effect relations--enormous sums already spent on empirical studies (such as the snow hydrology studies) have, in general, not been productive. The movement of liquid water and water vapor through temperate snowpacks is controlled largely by thermo-dynamic considerations. Thus an entirely different type of physical understanding is involved when considering the hydraulics, climatology, and hydrology of either meltwater production or the release of this water from the base of the snowpacks.

3. Inverse effect of precipitation on glacier runoff. Glacier runoff is determined by energy balance considerations. Recent precipitation (snow) is highly reflective to solar radiation; old ice is less reflective. Thus a thick winter snowpack or fresh snowfall in summer impedes summer melt. Glacier runoff is high in hot or dry periods and is decreased during cool or wet periods. This statement applies on a daily, seasonal, year-to-year, and long-term basis.

In general, a reasonably good relation is seen between yearly values of precipitation and runoff deficit in drainage basins which are influenced by glaciers. This, of course, means that many conventional hydrologic forecast procedures cannot be used. Stochastic models of hydrograph synthesis using precipitation events as input must recognize this difficulty.

4. Difficult working conditions. Data collection in the mountains is unconventional, expensive, difficult, and not without a certain amount of hazard to personnel and equipment. The summer field season is short; in some areas good weather and snow-free ground occur for only about one month per year. Snow and ice avalanches, debris flows, rockfalls, and glacier outburst floods can overwhelm any hydrologic or other installation in their path, and none of these events are predictable at the present stage of knowledge.

EXAMPLES OF SPECIFIC ECONOMIC ADVANTAGES OF INCREASED UNDERSTANDING

1. Water resources payoffs

a. Snow surveys. Snow surveys already operate with an impressive cost/benefit ratio. For instance, data from a very few snow courses in the Skagit River drainage enabled Seattle City Light to save about one million dollars due to more efficient reservoir regulation during 1966. We do not yet have enough understanding to be able to predict or model the growth and decline of the mountain snowpack from synoptic meteorological data. One of our main objectives of our South Cascade Glacier study is to do just that.

The only major problems remaining have to do with freezing level and accumulation patterns in the mountains at intermediate (meso) scales. Once these problems are solved, engineers could synthesize the snowpack in the mountains quite precisely on a day-to-day "real time" basis using standard meteorological data. This technique would be far less expensive, would require less hazard to personnel, would produce no encroachment on Wilderness values, and would provide data which were far more complete both in space and time than the present technique of monthly snow course measurements.

b. Predicting seasonal glacier runoff. Some hydroelectric or irrigation developments are on streams which are fed by glaciers. The flow of these streams cannot be predicted by the power companies at the present time. Sufficient knowledge is now, or soon will be, at hand to permit the prediction of total summer runoff from glacier basins as the spring and summer progresses, if only the engineering techniques were worked out.

One example is Thunder Creek, which provides about 14 percent of the flow of Skagit River into Ross Lake Reservoir, an important source of power in Western Washington. The mean runoff of Thunder Creek is about 80 inches per year. By late spring most of the water year precipitation has already occurred. Our studies indicate that for a year of deficient precipitation (say 60 inches) the glaciers normally provide increased summer runoff, amounting to about 15 inches additional water averaged over the basin.

On the other hand, if the precipitation was high, say 110 inches, the increase in ice storage would decrease the runoff by an average of about 20 inches over the basin. These estimates could be refined as the summer progresses, and when combined with other forecast information would permit much more refined reservoir regulation procedures.

c. Artificial regulation of snow and ice reservoirs. Solar radiation provides most of the energy causing snow and ice melt, but snow is highly reflective so small changes in the reflectivity of the snow can produce very large changes in the amounts of heat absorbed and therefore the amount of meltwater produced. It can be shown that a very thin layer of dark powder can increase melt from a thick snow or ice body by 5 to 7 times. Thus glaciers and perennial snow fields could be dusted to produce additional meltwater on demand.

Conversely through cloud seeding or strategic placement of snow fences additional snow accumulation could be produced on these snow fields. Ice reservoirs might naturally regenerate after being artificially reduced in size. The artificial regulation of glacier runoff is performed routinely in central Asia both in the Soviet Union and in China. There is a possibility that in the U.S. techniques such as these might be required very soon, to cope with "emergency" situations. For instance, the program schedule for the filling of reservoirs on the Columbia River in Canada assumes that the flow of the Columbia will not be below normal at the time of filling.

If the natural flow of the Columbia is abnormally low at that time, the filling would have to be delayed or the filling requirements would produce a dearth of water available for power production in the Columbia River basin; either alternative would have rather severe economic consequences. If the flow of the Columbia is abnormally low it might be possible to dust mountain snow fields and glaciers to supply the extra water needed.

d. "Normal" streamflow records from glacier streams. Long-term streamflow records are used for predicting future "normal" streamflow in the design of hydroelectric developments and installations. Many developments are now planned on rivers which are fed in part by glaciers. During the last 50 years most of these glaciers have been retreating. The ice loss has gone into increased streamflow. Streamflow due to this irreplaceable ice loss amounts to a few percent of the flow of the Columbia River at the border and about 5 percent of the flow of the Tanana River in Alaska.

This increment in streamflow cannot be expected to continue for very long in the future. Either the climate will change (in fact it has in many regions) or the glaciers will become greatly reduced in size or disappear. It is absurd to assume that this "normal" streamflow can continue in the future but this has apparently been done in studies of the

Columbia River basin and in other important areas. By knowing the amount of water supplied due to long-term changes in the ice reservoirs one can make valid predictions of the base for future streamflow.

e. Glaciers as indicators of climate change. Glaciers are perhaps the most sensitive climatic indicators in nature. For instance, the climatic change in the Pacific Northwest which took place in the late 1940's was not detectable in meteorological records until mid-1950's and is still barely noticeable. Nisqually Glacier, however, began thickening in 1946 and in the following decade thickened by 100 feet, accelerated its speed of flow by nearly 20 times, ceased receding and advanced many hundreds of feet. It is obviously important for planning future hydrologic developments to know something about the structure of present day and past climatic changes. Glacier records extend far back in time.

It will soon be possible to obtain sensitive, quantitative meteorological information from glacier variation data. Two problems are involved: the dynamic problem (ice flow) has been essentially solved; our South Cascade Glacier data were instrumental in the solution. The remaining meteorological problem is our present focus of attention at South Cascade Glacier.

2. Interdisciplinary, longer-term payoffs

a. Rheology of glacier flow is one of the most useful illustrations of the plastic flow of a crystalline material. The stress which causes the flow, the complete geometry of flow, and the resulting changes in crystalline structure can be readily observed. Therefore the flow of ice is perhaps better known than the flow of any metal or rock material. Consequently the interest of metallurgists and structural geologists has been directed to glaciers in order to obtain basin information on flow mechanisms in crystalline materials.

A recent review article on viscoelastic processes in the earth used a flow law derived from studies of glaciers as the basic, general equation for the flow of materials in the earth. Metallurgists in England and in the United States have developed the most sophisticated theories of glacier flow in the course of their investigation of ice flow as an analogy to metal flow. It is hard to place a price tag on this information derived from studies of glacier flow but the value to society is tangible and is large.

b. Weather prediction. Of obvious importance to civilization is large-scale, long-term weather prediction. Supercapacity computers and improved models of atmospheric circulation are now being developed which will make it possible to solve and predict the atmospheric circulation on a global basis, which will result in satisfactory long-term predictions. A major difficulty in this program is the lack of knowledge about the energy transfer parameters in the region dominated by snow and ice.

Most of the world has a very low albedo (reflectivity) to solar radiation. However, snow cover has a very high albedo and thus the extent of the snow cover is of critical importance to the amount of energy absorbed by the earth and is a critical boundary condition for any large-scale models of atmospheric circulation. It may be possible with only a bit more understanding to be able to know and predict snow cover distribution, temperature, and thickness in the inaccessible polar and mountain areas on the basis of synoptic weather parameters.

c. Food supply from the oceans. The greatest future source for food for mankind is the sea. The most prolific protein producing areas in the ocean are the convergence zones at the margin of the subpolar ice covers. The circulation of the ocean waters, which determines the production of phytoplankton, is determined in part by the dynamics of the sea ice cover and in part by the rate of energy transfer through the ice. These problems are clearly glaciologic and awaiting a better understanding of thermodynamics and deformation processes in ice.

d. Glaciological catastrophies. Society needs protection from certain catastrophic events involving snow or ice either by prediction of their occurrence or actual modification or regulation. In this category are snow avalanches (which take several lives or tens of lives each year in the United States and hundreds of lives each year in the Alps), ice avalanches, and glacier outburst floods.

Civilization is now moving further into the mountains and into cold regions where such disasters must be considered ever possible. Even now mining personnel and recreational areas are subjected to considerable hazard to life and property. Glacier outburst floods are of little economic importance in the conterminous United States except in Mount Rainier National Park where bridges have been repeatedly demolished. In Alaska, however, there are more than 100 glacier outburst flood situations known and some of these cause major disruption of existing transportation arteries there.

The ability to predict these floods may be forthcoming in the next 10 years if the understanding of the flow of water through ice increases at its present rate of progress.

Presented May 29, 1969 by CARL BROWN, Assistant Professor, Department of Anthropology, Oregon State University.

Snow and Culture

The anthropologist's concern with climate as a significant variable in human development is twofold. On the one hand he is interested in the biological aspect, which would include concern for natural selection and adaptation, and on the other hand he investigates the cultural aspect---attempting to elucidate the technological, organizational and ideological patterns a people have developed to cope with their environment. If we are to believe some contemporary writers, such as Art Chipman who wrote an article titled Chances For Another Ice Age (Northwest Magazine, Sunday Oregonian, May 25, 1969) in which he claims that another Ice Age is fast upon us, then this seminar is very apropos, and should be a plea for more research into all dimensions of human adaptation to cold and snow.

Keeping in mind this bio-cultural perspective of the anthropologist, I will begin with some comments on areas of permanent snowpack. Research focused upon human physiology indicates that the climate imposes severe demands upon the human biological system. It has been found in Antarctica for example, that when the hand is exposed to -70°C temperatures great pain is felt within six to ten seconds, and within twenty-five to thirty seconds the hand becomes numb and the fingers turn white (Tikhomirov 1963). A comparable condition can exist in the American arctic or on Mt. Hood with a temperature of -30 or -40° C with a twenty or thirty mile per hour wind creating a wind chill factor equal to the severe Antarctic condition.

Without the mediating factor, culture, man cannot survive in an area of permanent snow. Interestingly, even the modern industrial societies with their ever amazing technologies are pushed to their technical limits under arctic conditions. One need only consider the problems of building a radar site on the Greenland ice cap to bring home the challenge of that environment.

In the areas of intermittent or seasonal snow cover, there have been people residing for a number of millennia. Despite a large portion of the United States being in this zone, the knowledge we have is limited and has been obtained in a somewhat sporadic fashion. A look at the history of biological and technological research indicates a surge of interest during World War II due to some of the war being fought in winter climes, then a lack of interest until the Korean War when a large number of cold injuries and technical problems demanded a re-focus upon cold weather research.

The Arctic Aeromedical Laboratory was one result of this reawakening in cold weather research. As well as solving pragmatic military problems, the staff at Arctic Aeromedical Laboratory was able to do basic research on possible physiological adaptations in different human populations residing in cold climates. Several kinds of physiological responses to cold stress were found.

Some of these are cultural (e.g. diet) and some may be true adaptations (e.g. Eskimo ability to maintain warmer digits). This facility has been closed down since the U.S.A. became involved in Vietnam, a tropical area. One wonders if the interest in snow and cold climate research is again shifting away.

ENERGY REQUIREMENTS

I think it would be interesting to do some research on energy expenditures in areas of annual snow coverage. What is the caloric intake necessary to just keep functioning from one day to the next under the demands of winter?

Even though there is some variation in degree of stress imposed by winter, depending on whether one is in Alaska, Oregon or New York City, intermittent snow coverage poses an energy and time demand upon humans. Anthropologists in the field have been surprised at the time and energy needed just to accomplish the daily chores during winter, let alone do a full day's research. (See Hughes 1960:26-27).

Technological and organizational challenges are clearly seen in the history of military operations in winter climate---in peacetime as well as wartime. I will say more on technical and organizational limitations later.

People who live outside of snow regions have interesting perceptions of those who do live in the harsher climatic regions. There is almost a mystique about northerners, such as the Mongols, the Vikings and various "barbarians from the north." Even songs such as the Frozen Logger attribute great prowess to people of northern origin. Curiously, biologists have found that people are afraid of winter conditions. That is to say, when people who have never lived in cold regions arrive in winter conditions, they exhibit fear, which can very much limit their operation in that environment.

Adaptation has become a key word in anthropology in recent years. Human biology and culture are both seen as adaptive mechanisms. Looking briefly, first, at the biology of man, it is clear that man is a tropical mammal. He does not exibit any of the major mammalian adaptations to winter climates, such as increased pelage and plumage or subcutaneous fat as insulation. Further, the fossil record indicates man emerged evolutionarily in the tropical zone. Man cannot survive in snow zones without culture.

There has been a lot of speculation in physical anthropology as to whether peoples who have inhabited snow zones for many generations do, in fact, have some specific biological adaptations to that environment. Hypotheses of varying value have been put forth. For example, the epicanthic fold of Mongolian peoples may act as a natural snow goggle along with the darkly pigmented iris. Both the fold and the pigment limit extraneous light from snow glare from penetrating the cornea and, thereby, distorting visual acuity.

DIFFERENCES IN GROUPS

The white American population is one of mixed European ancestry possessing no physical features or physiological responses leading to a survival advantage in snow zones (or in tropical humid zones, either). Physiological studies which have compared white office clerks with white mountain climbers (just off Mt. McKinley) and Alaskan Eskimos and Indians living in the Willamette Valley indicate superior ability on the part of natives to maintain warmer extremities under standardized cold tests, with no significant differences between the two white groups despite the fact that the mountaineers had had the most recent cold exposure and were by far the most physically fit group.

The anthropologist views culture through time and space. Glancing at the history of man we find that the archaeology record indicates that man became a tool-using animal in a tropical environment. This occurred nearly two million years ago during the Lower Pleistocene geological period, based upon potassium-argon and fission track dating of materials in East Africa uncovered by L.S.B. Leakey.

By Middle Pleistocene time, we know that man occupied more temperate zones and controlled fire. Evidence for this was discovered with the famous skulls at Choukoutien near Peking, China.

It was not until the Würm glaciation that it is clear man occupied snow zones. Classic Neanderthal man occupied the non-glaciated areas of Europe, but the challenge of the environment may have been too great since most evidence indicates that he died out during this period. Modern man arose about 40,000 years ago in a less severe environment but was able to accupy winter zones with his Upper Paleolithic artifact kit. The famous cave paintings in Europe tell us something about his cultural adaptations to an arctic or sub-arctic climate.

Around 12,000 years ago Siberia was occupied. Evidence for the occupation of far north areas beyond 15 to 20 thousand years ago is not yet available (Hopkins: 391). So, in the long view of human cultural evolution during the past two million years, it is not until quite recently that man has occupied snow zones. This may be due to the need for a modestly sophisticated technology (Upper Paleolithic) as well as the time needed to understand the environment and adjust social and ideology patterns for efficient exploitation. That is, it may have necessitated specific adaptations in the cultural system rather than generalized patterns widespread in earlier times.

AFTER INVENTION OF AGRICULTURE

It was not long after the colder zones were occupied that man invented agriculture. Evidence from Iraq, Anatolia, Palestine and Mexico indicate dates of 7-8,000 B.C. for the domestication of plants. Shortly thereafter, at 4,000 B.C., are finds giving evidence of the origins of cities and civilization. There have been many theories proposed to explain the origins of agriculture and civilization. Anthropologists do not see climate, per se, as the critical variable of explanation, but tend to look towards ecological explication---especially with regard to the domestication of plants and animals.

Turning to a view of cultures through space, one finds that until quite recent times, the snow zones were inhabited by hunters and gatherers and a few people practicing a limited form of pastoralism. Interestingly, these people are in the same environment. The Yukaghir, for example, live by hunting reindeer, and their neighbors, the Tungus, herd reindeer. Others use reindeer as draft animals.

This variation in exploitative patterns, along with variations in the other aspects of culture, between peoples in the same environment, lead the anthropologist away from theories of environmental determinism as explainers of cultural patterns. (See, for example, Forde 1949). One must look at the historical development of a culture to understand its pattern. When we look at cultures through space, at those occupying snow zones, we see a variety of cultural adaptations. There are different social organizations, different world views, as well as different technologies, all of which allow societies to survive in this area.

Everyone is aware of the successful material adaptations the Eskimos have made to their environment, but one should remember that their social organization and world view are quite well adapted, also, to the rigorous conditions of life.

Modern industrial cultures appear to have had a predominantly extractive interest in zones of heavy snow pack thus far, especially with respect to high country and the far north regions. Only recently have there been thoughts of replenishment. In a few decades man has jumped from primitive exploitative techniques of hunting and gathering and some pastoral nomadism directly into industrial exploitation of arctic and sub-arctic environments. It does not appear that American culture is very well adapted to snow zones. American technology is limited, the social organization does not stand up to rigors of winter in many areas, and the world view or value system is often irrelevant to conditions of severe winter and heavy snowpack.

A new topic of research by anthropologists with linguistic training is ethno-ecology, studying the cognitive world of a people and seeing what the ecology looks like through their eyes. The Eskimos are a classic illustration with their dozens of words for snow --- words for snow of varying degrees of hardness and softness, snow suitable for sledding, snow for housebuilding, etc.

The Eskimo perception of this environmental phenomenon, snow, is more discrete than ours is. We have only one word, used with a few adjectives that the skiers think appropriate. It is clear that for peoples intimately involved with snow, snow isn't just snow. If one's cognition changes towards more discrete categories there is greater chance for expanded exploitation of snowpack. Perceiving of snow as water storage is a start in seeing snow as a resource.

Certainly there are some beginnings in the realm of recreation. However, one has the feeling that most Americans, such as the New York commuter trying to get to work on time, think of snow as a nuisance.

It might be very interesting to do a study on how Americans perceive snow. This type of study might anticipate problems that will arise from the public if, and when, cloud seeding for snowpack is instituted, for example. We can anticipate some of the legal ramifications of cloud seeding, but there may be strong social sentiments, also. Would people east of the Rockies appreciate the absence of "White Christmases" to the benefit of other states?

The problem that I see, which is a cultural problem, is the exportation of a culture not adapted for heavy snow and severe winter conditions in all three dimensions of culture --- the technology, the social organization, and the ideology. We keep exporting a cultural package which is, for the most part, non-relevant to snow zones, and we tend not to anticipate the consequences.

NUMEROUS DANGERS

The realm of technology provides good examples. For instance, there is the proposed pipe line from the new Arctic Slope oil fields in Alaska to an ice-free port eight hundred miles to the south. Writers (in Alaska) have said that the technical problems involved, because of the warm temperature of the oil, will be one of the greatest technical challenges we have had. This 48 inch pipe line will probably be built above ground creating an eight hundred mile barrier to migrating caribou. Conservationists point out that the pipe line will block the traditional migration routes, leading quickly to the demise of the caribous since they have to migrate in order to survive.

Our technology may be seriously threatening the snowpack. A recent report indicates that all particles from jet exhausts at 40,000 feet do not precipitate out of the atmosphere. It has been claimed that these particles are trapping energy on the surface of the earth to the degree that the ice caps will have melted in two hundred years, flooding eighty per cent of the world's urban area! If this is so, we can only speak of technological focus in our society which has run amok.

Contemporary American culture is not organizationally adapted to snow conditions except on an intermittent basis. Heavy snowpack leads to relative isolation of communities, limiting broad social interactions to intense local interaction; not infrequently resulting in aggression. Customary law is often invoked and self-help in righting a wrong occurs more frequently.

An examination of the operation of the Distant Early Warning system illustrates the problems of exportation to the arctic of individuals selected by non-relevant cultural values. The D. E. W. Line from Greenland to Alaska is manned by civilians organized on a para-military basis. The contracting corporation began by hiring people from the continental United States with standard corporate techniques. A number of suicides and mental breakdowns occurred at the radar sites.

It was realized that one does not want an individual who is happily adjusted to urban and suburban life, but rather the best adapted individuals for the job are men who are used to hardship, being without women for long periods of time, and who do not crave all the luxuries of American life. The corporation adapted by hiring as many people as possible in Edmonton and Fairbanks, cities on the edge of the frontier which attract that sort of individual.

In the ideological or cognitive dimension of culture, one finds paradoxical responses to severe winter conditions. Psychological stress is often high, leading to what has been variously called "arctic hysteria" or "cabin fever". At the same time, the difficult environmental conditions lead to crisis tolerance. A pragmatic orientation to life is seen in both native and white populations in the north. It has been suggested (Service, 1966) that the native cultures in rigorous environments develop an existential world view.

CONCLUSIONS

I see many aspects of American technology, social organization, and world view which are non-synchronous for greater development of the snow zones. A minority of Americans enjoy the winter environment. Research on the social and psychological selection of people who do, and do not, move into and out of snow zones is needed if we are to further develop snow as a resource in both the public and private sectors of society. In cultural terms, snow itself is unimportant. Snow is a physical phenomenon; therefore; its cultural significance is important only insofar as people perceive of it.

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