

Measurements of terminal recession of these three glaciers were started in 1931 by the National Park Service. The first determinations were based on several linear measurements from previously marked points to the ice front. Starting in 1945 the Park Service and the Geological Survey, working together, initiated a system for mapping the entire fronts, working from a series of permanently marked points. Periodic successive mapping of the ice fronts has afforded a convenient way of determining terminal changes.

Profile lines were established on the Sperry and Grinnell Glaciers in 1949 and 1950, respectively, for the purpose of obtaining a definite measure of changes in surface altitudes. The measurements to date indicate very little change in the surface elevation of these two glaciers.

Limited observations have been made on the rate of movement for the Grinnell and Sperry Glaciers. For the Grinnell Glacier the recession rate has been from 30 to 40 feet per year. The rate observed for the Sperry Glacier has been considerably less.

The Grinnell, Sperry and Jackson Glaciers were mapped by ground methods in 1937, 1938 and 1939, respectively, by the National Park Service. The Grinnell and a portion of the Sperry Glaciers were remapped in 1946. Aerial photographs were obtained of most of the known glaciers in the park in 1950 through the cooperative efforts of the National Park Service, the U. S. Forest Service, the Glacier National Park Historical Association, and the American Geographical Society. Maps of the Grinnell and Sperry Glaciers were compiled from these photographs and have been published by the Geological Survey. A map of the Jackson Glacier has been compiled from the photographs by the U. S. Forest Service but has not been prepared for publication.

The investigations in connection with the Grinnell Glacier have included the measurements of annual precipitation and runoff. In 1949 a storage precipitation gage was installed near the end of the horse trail which is only about 1/3 mile from the glacier. This installation was made through the cooperative efforts of the National Park Service and the Weather Bureau. In the same year a stream flow measuring station was established by the Geological Survey on Grinnell Creek just below the outlet of Grinnell Lake and about 1 1/2 miles from the glacier. This station measures the runoff from the glacier and its enclosing cirque. The records that have been obtained to date at the two stations above mentioned show a remarkable consistency and give very valuable information on precipitation and runoff in the higher altitudes of this section of the Rocky Mountains. The stream flow measuring station on Grinnell Creek (about 1-1/2 miles from the glacier) is believed to be nearer to a glacier than any other such station in the United States, suggesting that this record is the most representative of the runoff from a glacier and from its immediate surrounding area that is now available. This record is a most significant contribution to the study of meteorology in a glacier area.

The aerial and terrestrial photographs that have been obtained in recent years, the maps that have been compiled, and the field measurements of terminal recession, surface changes, and movement of the ice, in addition to the information that has been obtained from other sources, provide a store of basic data for studies of various kinds. The data recently obtained will become even more valuable as observations are continued from year to year.

## ESTABLISHING SNOW SURVEY NETWORKS AND SNOW COURSES FOR WATER SUPPLY FORECASTING

by  
A. R. Codd and R. A. Work<sup>1/</sup>

### INTRODUCTION

The several purposes to be served by a snow course network or by the individual snow courses must be kept in mind continuously during the planning and installation of the system. These are foremost considerations in the annual operations which follow.

The chief value of snow surveys to members of an organization such as Western Snow Conference lies with the resultant forecasts of runoff. These give the information needed for the manipulation of water storage structures and diversions for best results, the planning of annual farm crop seedings in line with the estimated supply of irrigation water, or the planning of farming operations on a fixed acreage commensurate with the forecast water supply. While it is true that forecasting the irrigation water supply for agriculture is probably the most important single use of snow surveys, numerous other essential uses should be mentioned. These include aiding regulation of multiple use reservoirs for power generation, flood control and irrigation; planning best use of water supplies for domestic, municipal and industrial use, and so on.

<sup>1/</sup> The authors are respectively Snow Survey Leader for Montana and Missouri River Basin, and Head, Water Supply Forecasting Section, Soil Conservation Service, U. S. Department of Agriculture.

The dollars-and-cents value of a streamflow forecast largely determines the number of courses in a snow survey network as well as their location. Value of the forecast in turn is directly related to water value. Where water for all purposes is plentiful every season, forecasting the seasonal supply is not valued so highly as in the regions where water supplies are more scarce or improperly distributed for adequate seasonal flows. In these areas, particularly, advance forecasts of the seasonal runoff are most needed.

For those reasons snow surveys were initiated in the western United States 45 years ago. Although snow surveys have provided the most generally accurate index to the runoff during the seasonal period on a majority of western watersheds, it is fully recognized that measurement of water equivalent of snow alone is not sufficient in many cases to form the basis of the most accurate possible forecast. The principal forecast of April 1 should be qualified on May 1, and probably again on June 1 by U.S. Weather Bureau data of precipitation collected during April and May.

The writers believe that direct readings of soil moisture will eventually show closer relationship to the so-called "soil priming" factor than the indirectly related readings of precipitation during the fall season. However, such watershed soil moisture readings are available only on a very few watersheds. The practice of adjusting values of snow water equivalent by fall departures of precipitation from normal is therefore commonly accepted by runoff forecasters.

The use of stream discharge records developed by the U.S. Geological Survey for derivation of a base flow index to watersheds is providing improved forecast results in some cases.

#### PLANNING SNOW COURSE NETWORKS

The fundamental theory involved in snow survey sampling should be kept firmly in mind during all of the planning for a snow survey network.

Successful use of snow surveys in forecasting runoff is due to the fact that most of the snow falling at high elevations occurs in a few major storms which usually are uniform in intensity over large areas. Good snow courses accumulate snow in direct proportion to later runoff from the basin. Relatively few snow courses in a large drainage basin thus provide a dependable INDEX to the winter snow accumulation on the watershed. Snow surveys do not measure the total volume of water stored in a basin as snow, but measure instead the water accumulated at only a few locations in the basin. Snow courses provide for enough observations to smooth out variations due to topography or snow drifting.

Snow courses at high elevations better reflect the accumulated winter's snow pack than courses at low elevations, since little winter melt occurs at high elevations. Snow courses at intermediate to low elevations are used to confirm the usual presence or absence of snow cover at those levels, thus providing correction factors to the data from high elevations. Snow courses at low elevations sometimes prove particularly useful as indicators in years of unusually plentiful snow accumulation and consequent hazard of unusually high or damaging flows.

If the singular purpose of the water supply forecast be the prediction of seasonal volume for irrigation, and should there be ample reservoir storage space above the irrigated lands to store most of every season's runoff, then a snow survey on or about the date of peak accumulation of the snow pack will suffice for reasonably accurate predictions. April first in most years is recognized as such a date for high level watersheds, but on low level drainages March first is often more important, and for the highest watersheds, May first is often best.

This means then that if the economic value of the forecast be sufficient, the surveys in various parts of the watershed, or even in all parts, must be made at least on March 1, April 1, and May 1.

Now, in cases of multiple use of water -- that is, where falling water generates electrical energy and the water is reused for irrigation or for industrial or urban purposes -- and where flood control also is involved, the annual main snow survey or a single forecast, as of April first or May first, is not sufficient.

The planners and operators must be informed continuously, almost from day to day, as to the progression or diminution of the snow pack. Frequent forecasts of the volume of the runoff yet to come should be provided and it may even be desirable to forecast the shape of the hydrograph to the greatest extent practical.

This situation calls for snow surveys to begin earlier in the winter, sometimes as early as December first, and also to extend beyond May 1, even to June 1 or June 15. The surveys also may be required more often than once monthly.

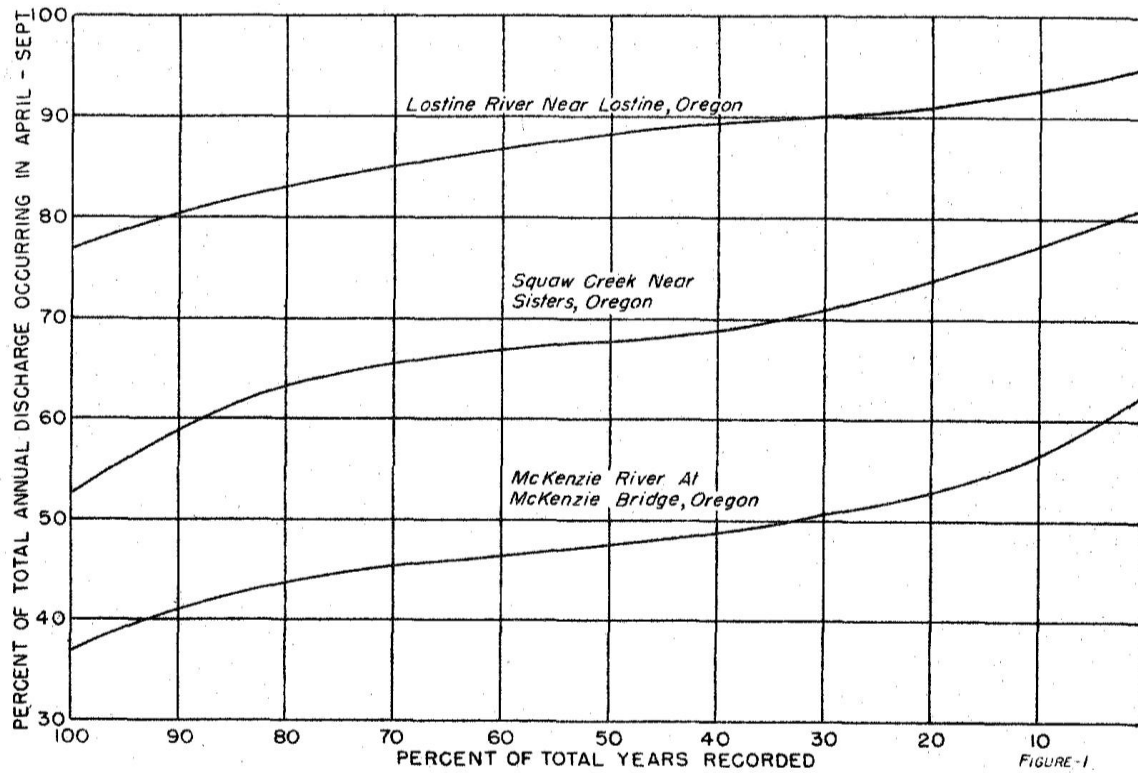


FIGURE-1.



Figure 2. A snow course sampling point in a densely forested area; no overhead canopy to intercept snowfall. Snow accumulation in a spot such as this represents a maximum in the forest. [USDA-SCS]

## NUMBER OF SNOW COURSES

The number of snow courses needed to forecast runoff for a large river system is difficult to estimate. The individualities of the tributary basins enter into the problem. Far fewer snow courses per hundred square miles or per thousand acre-feet discharge are required for the same degree of forecast accuracy in larger basins than in smaller basins. After about 20 courses are located in a large basin the point of diminishing returns in improved forecast accuracy for the main stream itself is reached rather quickly. However, in order to forecast the sub-basin contributions to the main stream with reasonable accuracy, two, or better three, courses with a spread in elevation are usually needed in each sub-basin. Thus the aggregate number of courses in a large basin may greatly exceed the number strictly required to forecast the runoff of the total basin outflow.

All things being equal, snow courses located directly in the basin usually produce more accurate forecasts than courses in adjacent basins. At times the off-basin courses produce good results if not too far removed. This usually is due to the fact that the off-basin snow course represents a large area within the basin which is not sampled by a snow course.

## BASIN CHARACTERISTICS

The climatic zone of a river basin influences in some degree the characteristics of the snow survey network, such as density of courses, elevation of courses, etc.

There are wide differences in the dates of snowmelt and especially in the ratios of seasonal to annual runoff between western river basins. The runoff for the seasonal period expressed as a percentage of the annual runoff is shown in figure 1 by means of smoothed curves for three examples of far western rivers.

The curves illustrate the fact that there is no exact or predictable ratio between the seasonal and annual runoff for any given stream. For instance, on the McKenzie river, which lies on the west-facing flank of the Oregon Cascade mountain range, and which consequently is exposed to fierce winter rainstorms, as little as 38 percent of the annual runoff may occur during the April-September period, but 10 percent of the time the April-September runoff can be expected to exceed 57 percent of the annual.

Sharing a joint ridge line with part of McKenzie basin is Squaw Creek, a small river basin on the east-facing flank of the Cascades. Here, the water-producing areas are higher, winter temperatures are colder, and precipitation is much less than on the west-facing slope of McKenzie river. Although the total annual or total seasonal precipitation is much less on Squaw Creek than on McKenzie river (annual average runoff of Squaw Creek is 21.7 inches as compared to 66.1 inches for McKenzie river) a greater percentage of the annual precipitation comes as snow over a greater percent of the Squaw Creek basin due to colder temperatures. Consequently, the seasonal runoff during the period of least rainfall and greatest need for water (April-September) on Squaw Creek has never been less than 52 percent of the annual, but 10 percent of the time the seasonal runoff exceeds 75 percent of the annual.

Even farther east, in the Lostine river basin which heads in 10,000-foot peaks of Oregon's Wallowa mountains, the seasonal runoff is never expected to be less than 75 percent of the annual. Ten percent of the time it is expected to exceed 90 percent of the annual. In the case of this particular stream, which is typical of the western rivers which originate in the highest mountains, the seasonal runoff is derived almost entirely from snow-melt.

Such factors as the time of year of maximum accumulation of snow pack, the duration and timing and variations thereof of snowmelt and subsequent runoff of large proportions, should be studied in connection with both location of courses and measuring schedules.

The direction the basin faces and the direction the streams flow have considerable bearing on snow accumulation, snowmelt and resulting time and volume of runoff. As a result, these factors affect the location and schedule of measurements of snow courses.

The months of heaviest precipitation are important in affecting estimates of probable runoff. A preliminary study of precipitation patterns should be made to determine the probable effect upon the seasonal runoff.

The direction of storm paths across the basin from west to east has a decided effect on snow accumulation. Local ranges of obstructing mountains may alter the lower strata of moisture-producing air masses, changing the volume of snow deposited in particular sub-basins of the main river basin. The occurrence of heavy and light snow belts within a large basin is important to keep in mind during the initial studies when planning a snow survey network.



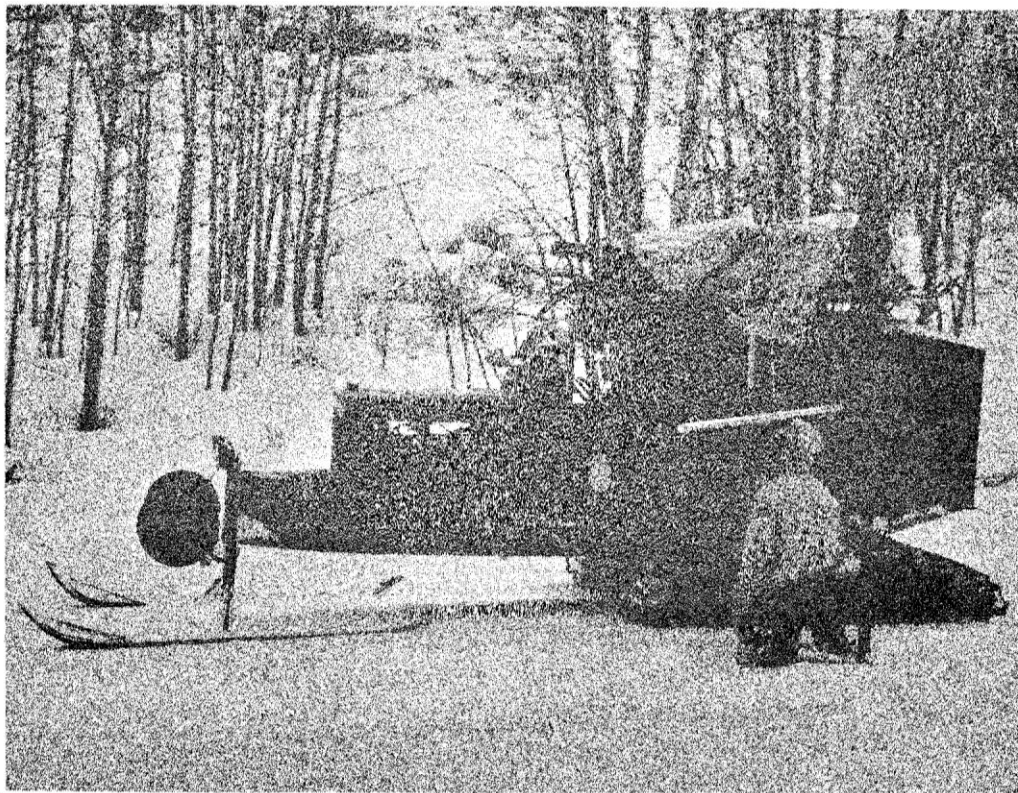


Figure 3. A snow course sampling point in a quaking aspen grove. Aspen groves generally provide ideal conditions for snow courses, as there is little or no drifting, practically no interception and snow pack usually represents the maximum accumulation. [USDA-SCS]

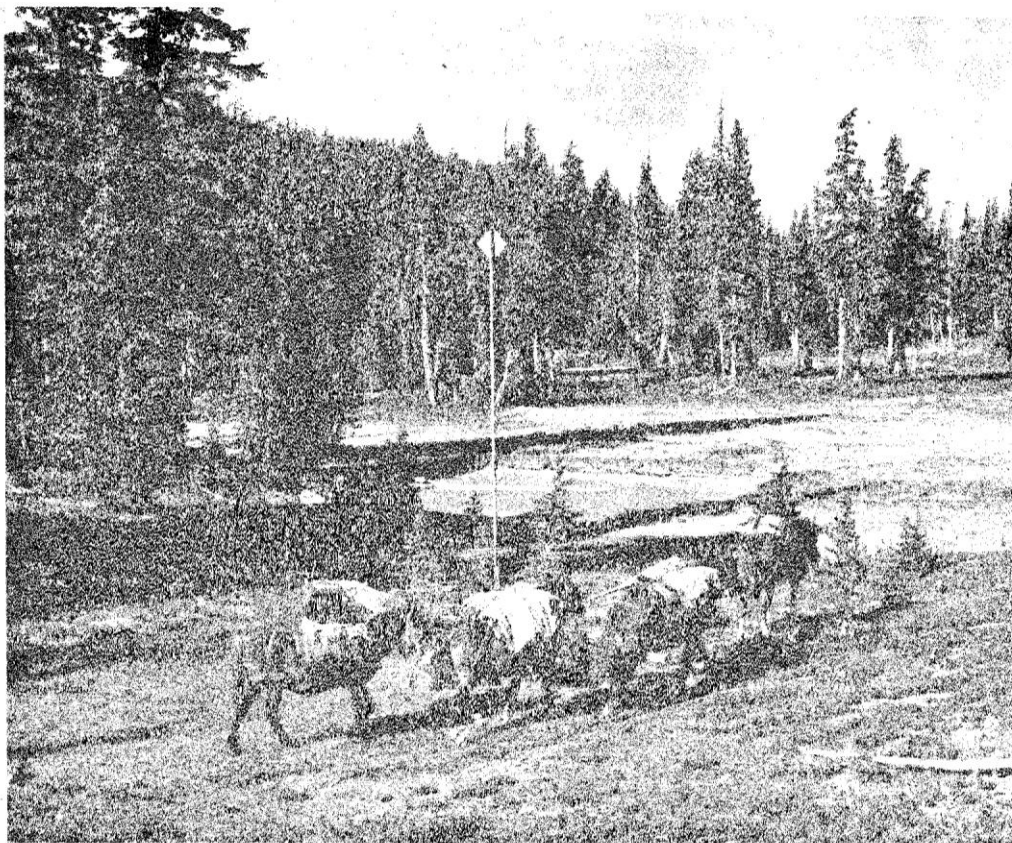


Figure 4. A typical ideal high mountain meadow snow course. The course angles north from the marker pole directly along the shadows' direction. Accumulated water equivalent

## CRITERIA FOR SNOW COURSE LOCATION

Elevation. Probably the most important factor in the location of the snow course is the elevation zone within the basin where the snow course is to be placed. An elevation must be selected where a minimum of pre-season melting occurs. In most portions of the West, the elevation is selected where snow will remain past April first, and a good portion be left by May first. However, south of 37 or 38 degrees latitude, February or March readings may be most advantageous. At the same time, the course should not be so high that the area sampled is too small to be representative of a major water-producing elevation zone. An area-elevation curve of the basin aids materially in preliminary studies. Snow survey courses must be established at different elevations on a given watershed to define the rate of change in snow cover with elevation. This rate of change varies from year to year. Water supply forecasts based solely on high snow courses may prove in error due to excess or deficiency of low level snow cover. In some stream basins, such as those of the Malheur and Owyhee rivers of southeastern Oregon, low elevation (4 to 5 thousand feet) snow courses are essential to best forecasts, even should such courses be bare of snow by April first in as many as 8 or 9 years out of ten.

Water-Producing Area. Varying amounts of water are produced from certain small tributaries of a basin. The major water-producing subportions of a watershed can usually be detected by studies of runoff characteristics. Most, if not all, the measurements of snow pack should be made in the zone from which the bulk of the water is produced. Where adequate streamflow data are available from the Surface Waters Branch of the U. S. Geological Survey, most accurate answers are provided to this elusive problem. Lacking measurements of runoff, consultation with local residents will often result in information as to streamflow conditions during the snowmelt season; also, detailed information as to accessibility and desirable routes of travel can be obtained.

Adjacent Snow Courses. The availability of records from an existing snow course or snow courses in an adjacent basin should be considered. A study at these other courses of the correlation of snow pack to streamflow will often assist in the selection of more satisfactory locations of new snow sampling stations in the basin.

Accessibility. Before too much scientific reasoning is put into the selection of exact locations, the practical problem of winter accessibility and safety must be considered. There is little point in locating a snow course at such a remote spot that surveyors in future years will not be able to reach the station. The day of finding the mountaineer who will buckle on a pair of skis or snowshoes and take off for two or three weeks of traveling in snow-covered mountains is about gone. Modern machines and airplanes have almost taken the place of the legendary "Snowshoe Thompson." The use of airplanes as a means of over-snow travel has proven very economical and satisfactory. This method of travel should never be overlooked by the planners. The selection of a snow course location in close proximity to a possible landing strip should definitely be considered. Actual clearing of landing strips has sometimes proven economical. Oversnow vehicles that are dependable on the snow fields have been, and are being, developed. Terrain to be traveled is a factor in selecting an accessible route for snow machine travel. Secondary mountain roads, old woods roads, or even well located forest trails can be used with certain machines.

There always will be certain locations where foot travel on skis or snowshoes will be imperative. Where foot travel is required for considerable distance, shelter cabins must be provided at the proper locations for the safety of the field parties. Avalanche areas must be located and routes of travel planned to avoid them. If avalanche areas simply cannot be avoided, then special traveling rules need to be adopted for greatest possible safety.

Physical Characteristics of Sites. The detailed location of the course in the desirable elevation zone in a water-producing area must meet several requirements. The course should have good ground drainage, and if possible, the course should be partially shaded from the south. The danger of beaver dam flooding in creek bottomland should always be avoided, even though no beaver sign be detected when the course is located.

The course should be placed on high ground with some definite slope for drainage. North-facing courses are always preferred. This is very important. South or west-facing slopes, even of slight gradient, should be avoided.

Heavy brush areas should be avoided as well as dense stands of second-growth timber. It is permissible for selected snow survey courses to represent the forest cover of the major portion of the basin, keeping some sampling points in the open and a portion of them in the timber. Generally, however, snow courses in clearings are preferred.

The selected location should have fairly even depth of snow and there should be no evidence of drifting. If the selection of the site is made during the off-snow season, the exact location should be tentative and subject to revision when the surveyor can see how the snow lies on the proposed site. All other things being equal, snow courses are best located when the seasonal snow pack is at its approximate maximum. Figures 2, 3, and 4 illustrate the appearance of some good snow courses in both summer and winter.

Variability. For best forecasts there must be some variability on any given date in water equivalent of snow. The number of courses installed in a basin is dependent upon the variability which is expected to be observed. The actual variability can be determined only following accumulation of a few years records. If correlation proves lacking and forecasts are poor, more courses or substitute courses are needed.

Number of Samples. The number of samples should be at least ten and not more than fifteen. It is far more desirable to have two courses of 10 samples each, at 1000-foot differences in elevation, than to have 20 samples at one elevation. The accuracy of the average of 20 samples over the average of 10 is not significant if the course is well located. The sample interval, or distance between sampling points, is not particularly important so long as the distance is convenient to measure; 25, 50, or 100 feet are usually selected. The course should be long enough to assure a good average of the snow pack. The snow sample should be taken as close as possible to the same spot each time it is measured, at least within a diameter of four feet. The ground should be cleared of all brush and down timber and large loose rocks. If obstacles are too large to move, the sample interval should be changed to a more suitable location. The spacing should be marked plainly on the sketch map of the course.

Snow Course Security. By this term we mean the lasting and stable relationship between the snow course and its environment needed to assure a dependable forecast relationship. This relationship can be impaired by forest fires, construction activities such as highways, dams or reservoirs, or by landslides or logging practices. Full effort must be made to foresee such occurrences so far as possible and to locate the snow course so as to avoid probable changes in the future. There are a growing number of cases of forested areas where forests were heavily logged, but timber adjacent to the entire length of the snow course left undisturbed in order to protect the environment of the snow course. Studies are needed to better define the permissible limitations of environmental changes.

Marking the Snow Course. When the location has been found satisfactory, the snow survey course and the trail to it, should be well marked. The markers should extend above the deepest snow. End points and angle points should be marked with two-inch or larger diameter steel pipe poles set in concrete. Snow course marker signs should be bolted securely to the top of the poles and the pipes painted orange or red and yellow. Individual sampling points in thin timber are often marked with numbered metal tags nailed on trees or wood poles set at the points as indicated. This method assures accurate selection of sampling points and is a great convenience to the surveyor, but is not much favored where the course can be chosen in open clearings as is preferable.

Airplane observation markers are often used at isolated snow courses. These markers consist of one-by-six-by-three-foot boards fastened to a steel pipe pole. One board is placed at the ground level with the bottom of each board two feet above the other. A diagonal one-by-three-inch board is bolted to the lower left corner of a cross board and to the upper right corner of the board above. This forms a series of two-foot by three-foot "Z's" up the pole. The height of boards covers the range of deepest snow. Under conditions when it is unsafe or impossible to land a plane at the snow course, the snow depth can be read from an airplane.

The water content is then estimated through application of a known snow density from snow courses in the general vicinity and altitude. Although water content data so estimated are not as reliable as actual measurements, this process is proving useful and economical, especially for early season snow surveys.

A detailed sketch map should be prepared for the snow course. All essential information should be shown, together with a small location map showing route of travel, etc. The details should include the course lines, sampling points, obstacles if any, the proximity of trees and clearings, distances to shelter cabins and points of orientation, creeks and other landmarks that would assist the surveyor to locate the course or sampling points.

## CONCLUSION

Among the many snow survey courses maintained over an extended time period, certain ones will prove key courses by virtue of their high correlation with subsequent streamflow.

Data relating to physical characteristics of each snow course of most far western states are filed in Soil Conservation Service snow survey offices, on a form entitled "Snow Course Biography." If an elaboration of these biographies were transferred to punch card form, and each snow course were rated for its forecasting usefulness and dependability, it seems possible that IBM analysis might define the more critical characteristics of successful snow courses and provide clues to the criteria for the location of the most successful snow course networks.