AERIAL SNOWPACK MAPPING

by

William L. Warskow

INTRODUCTION

Melting snow is the primary source of water for the 1.1 million residents of the eight cities and 104,000 hectares (257,000 acres) of urban and agricultural lands located in Maricopa County, Arizona served by the Salt River Project. Seventy-five percent of the 135,700 hectare-metre (1.1 million acre feet) mean annual runoff flowing into Project reservoirs from the 33,670 square kilometre (13,000 square mile) Salt-Verde watershed is generated by winter cyclonic and frontal storm systems which occur during the December to May runoff season. Much of the precipitation which falls during these storms occurs in the form of snow.

Snow deposited above 1,980 to 2,135 metres (6,500 to 7,000 feet) on the Verde River watershed and 2,135 to 2,285 metres (7,000 to 7,500 feet) on the Salt River watershed normally remains in place until spring snowmelt which usually occurs in March and April, respectively, for the two watersheds.

Snow deposited at lower elevations down to 1,370 metres (4,500 feet) on both watersheds is ephemeral in nature and subject to rapid melt induced by either subsequent rainfall or sharp increases in temperature. Sixty-five to seventy percent of both watersheds falls within the ephemeral snow zone. The areal extent and instability of the ephemeral snowpack combined create a major flood potential when Project reservoirs are at or near capacity. Though not frequent, snowfalls down to 760 metres (2,500 feet) have occurred and only add to the flooding potential.

Modern man's continued existence in Arizona hinges on sound management of Arizona's precious water resources. Recognizing early that successful coordination of its surface and groundwater resources to minimize groundwater withdrawals while optimizing hydroelectric generation required an ability to forecast spring runoff from the high altitude snowpack, the Project established Arizona's first snowcourse at Beaverhead Lodge in 1938. While additional snowcourses and several aerial snow-markers were established over the years in cooperation with the Soil Conservation Service, it was not until 1965 that a method for providing additional snowpack information became available.

The author is Lead Watershed Specialist, Salt River Project, Phoenix, Arizona.

HISTORY OF AERIAL SNOWPACK MAPPING

Runoff from heavy precipitation during the fall of 1965 filled Project reservoirs almost to capacity by mid-December. Watershed soils were saturated. Above 1,370 metres (4,500 feet) the watershed was blanketed with snow.

Rain up to 2,135 to 2,285 metres (7,000 to 7,500 feet) during a storm on December 29, 1965 stripped the heavy ephemeral snowpack off the watershed within a matter of hours, triggering a major runoff event that made it necessary to spill both the Salt and Verde river reservoir systems. Developments which had encroached on the normally dry Salt River channel throughout the metropolitan Phoenix area since the last spill in 1941 suffered major damage.

Because Project reservoirs were at capacity and had no room to contain the spring runoff, which was anticipated to be above average due to the heavy high altitude snowpack, controlled reservoir release became necessary. The threat of similar catastrophic runoff events from additional storms also remained.

While the Project had no legal responsibility for flood control, it felt morally obligated as a good neighbor to try and minimize the potential for additional flooding while at the same time meeting its legal responsibility to its shareholders to maximize reservoir storage. To maintain the delicate balance required, more data than that provided by the established snowcourses which were mostly located above 1,980 to 2,285 metres (6,500 to 7,500 feet) was needed. Because of the flood potential presented, the areal extent and depth of the ephemeral snowpack were of prime interest. To obtain this information, low level aerial reconnaissance flights over the snowpack were initiated by the author. Crude maps drawn at a scale of approximately 1:3,000,000 generalizing the outline of the snowpack were used to keep Project Management appraised of watershed conditions. Snow depths were estimated using range and highway right-of-way fences.

In December, 1967, a record breaking snowstorm which deposited from 1.22 metres (4.0 feet) of snow at elevations of 1,065 metres (3,500 feet) up to 2.13 metres (7.0 feet) at 2,135 metres (7,000 feet) created a far greater flood potential than existed during the fall and winter of 1965-66. Because existing snowcourses, aerial snow markers, soil moisture stations and snowpillows were all point samples and did not give any indication as to the areal extent and depth of the ephemeral snowpack, the following technique for estimating snow depths and mapping snowpack areal extent and percent coverage was developed.

TECHNIQUE

AIRCRAFT

A Cessna 182 equipped with long range fuel tanks was selected for making the Project's snow reconnaissance flights. This aircraft has the power required for high altitude mountain flying, the range and speed for extended cross-country flight, excellent slow flight stability and a high wing which permits easy observation of the ground. Faster aircraft, such as the Cessna 210, have not proven sufficiently superior to justify their increased cost. Also, the higher stall speeds of higher performance aircraft becomes a disadvantage in the event of a forced landing. Low wing aircraft interfer with the observer's view of the ground and make both observation and photography difficult or impossible.

SAFETY

Mountain flying is not for the uninitiated and requires a skilled pilot if operational safety is to be maintained. Also, because it is humanly impossible to divide one's concentration between that required for safe flying and that required for accurate snowpack mapping, the two should never be attempted at the same time by one person. Vertigo and disorientation may occur - with fatal results.

The reliability of the modern light aircraft engine makes a forced landing an unlikely event. However, if one should occur, rapid recovery of the observation team is essential. The nature of the terrain overflown by most aerial snow surveys makes locating a downed team at best very difficult. To facilitate recovery, the aircraft should be equipped with an emergency locating transmitter (ELT). A flight plan should be on file with both the local Federal Aviation Agency Flight Service Station and the team's home office. An emergency recovery procedure triggered by the flight being overdue or the team failing to make enroute reports as prescribed should be in effect. Teams should fly a standard route and where possible maintain constant radio contact, reporting each time they enter or leave a specified area. Full winter survival kits should be carried for each person aboard the aircraft.

Oxygen should also be carried if possible. Its use, even where not legally required, has been found to add materially to the team's comfort and observation ability.

No flights should ever be permitted or demanded by supervision if weather conditions exist which would compromise the safety of the flight. Snowpack data is never worth the cost of someones life.

MAPPING

For the first two years, maps of the Salt-Verde snowpack were drawn at a scale of approximately 1:3,000,000 from notes taken during each flight. The snowline depicted on these early maps was generalized - primarily on the basis of elevation.

Direct enroute mapping was first attempted in 1969 using the 1:1,000,000 Arizona aeronautical chart. This proved so successful that a copy of the Salt-Verde portion of the chart was mounted permanently on a 28 by 43 centimetre (11 by 17 inch) lapboard. Superimposed over this base map was a removable mylar overlay showing the watershed boundary, elevation by 305 metre (1,000 feet) increments, towns, and the major drainage systems.

The shaded relief on the Arizona aeronautical chart very accurately depicts watershed topography, enabling the aerial observer to map the snowpack with considerable precision. The edge of the pack is traced on the mylar overlay with a colored pencil as the flight progresses over the watershed. Ocular estimates of the percent of the ground covered with snow are made and recorded marginally. Snow depths are recorded in a similar manner.

ESTIMATING SNOW DEPTHS

Highway right-of-way and range fences were originally used to obtain aerial estimates of snowpack depth. The aerial observer's knowledge of fence heights and strand placement coupled with a simple observation of how many strands remained above the snow and an estimate of the distance between the top of the snow and the lowest exposed strand permitted fairly accurate estimates (± 5.0-7.5 centimetres; ± 2-3 inches) of snow depth. By using fence shadows, estimates with similar accuracy could be obtained from a height of 305 to 460 metres (1,000 to 1,500 feet) above the ground.

The infrequency of fences over much of the watershed, however, limited the amount of snowdepth information which could be obtained. Another method for estimating depths over vast unfenced areas was needed.

Early observations indicated that surface rock, vegetation and cull logs might be useful yardsticks. Capitalizing on the author's extensive knowledge of the variations in these features over the Salt-Verde watershed, a technique utilizing them to estimate snow depths was developed.

The volcanically-derived soils underlying most of the juniper vegetation zone on the Salt-Verde watershed are covered with dark rocks of varying size. These contrast sharply with the white of snow. With a familiarity of their size (height above soil line), it becomes relatively easy to estimate depths from the air. A "powdered sugar" appearance with numerous dark "freckles" indicates depths of less than 2.5 centimetres (1.0 inches). As snow depth increases, fewer rocks are visible and the snow takes on a "wet, lumpy cotton" look. By the time snow depth reaches 15 centimetres (6 inches), the sides of individual rocks are no longer visible and their presence is indicated only by mounds "softly" outlining them.

At this stage, it becomes necessary to transfer the reference point to remnant grasses or suffrutescent shrubs. Because of its growth form and height, sideoats grama (Bouteloua curtipendula) is a good indicator for depths of 15 to 20 centimetres (6 to 8 inches). The dried culms sticking out of the snow are readily visible giving it a yellow cast. The half-shrubs, particularly snakeweed (Gutierrezia sarothrae), are useful for depths of 15 to 30 centimetres (6 to 12 inches). Depths greater than 30 centimetres (12 inches) require the use of logs or some other indicator.

The widespread occurrence of logs makes them one of the most useful references available for estimating snow depths. A knowledge of the relative sizes of logs in each area is, however, required for accuracy. The ability to classify logs by 7 to 8 centimetre (3 inch) size classes from the air can be achieved by most observers with practice.

The visibility of the underedge and sides of the log, presence or absence of snow bridging between its top and sides and the form of the snow mound over the log are all used to determine the depth of the snow relative to the log's diameter. If the snow is less than half the log's diameter, its curved underedge will be visible. If one-quarter or less, significant shadow can usually be seen depending on the log's orientation to the sun.

Bridging between the snowcap on top of the log and the snow on the ground occurs at depths between fifty and sixty-five percent of log diameter depending on the wetness of the snow. At depths greater than two-thirds log diameter, the sharp outline of the log under the snow begins to soften to the point it almost disappears at depths equal to or slightly greater than the log's diameter. A very flat mound revealing the log's presence may sometimes occur up to depths of fifteen to twenty-five percent greater than the log's diameter depending on other factors such as wind and snow wetness. The upper limits for using this method in Arizona is about 107 centimetres (42 inches). Depths greater than this require the use of man-made aerial snowmarkers.

ESTIMATING SNOWPACK CONDITION

Relative condition of the snowpack can also be observed and mapped aerially. The presence of ice can usually be detected by a dull sheen at or just below the surface of the snow. Pack discoloration, striation and deformation can all be used to detect the imminence of snowmelt. The presence of on-going melt can be determined from the brilliant, mirror-like reflectance of the sun through small holes in the pack.

PROCESSING-DISSEMINATION OF SNOWFLIGHT INFORMATION

If the information obtained during the low level (150 to 460 metres; 500 to 1,500 feet) aerial snowpack reconnaissance flights is needed for emergency reasons, the mylar overlay is either simply xeroxed or blue-line printed and copies promptly distributed. If time is not of the essence, a new map with corrections is drawn prior to reproduction and dissemination.

LIMITATIONS

The primary limitation is the observer's relative immunity to vertigo and his ability to withstand the airsickness which may be induced by the head movements involved in enroute aerial mapping. In rough air, induction of vertigo can be reduced by the use of a tape recorder to reduce the observer's need to look down at the lapboard.

The lack of contrast and shadows on cloudy days reduces most observers' ability to accurately estimate depths or to see the shape of the snow over the reference features being used.

The low oblique at which the snowpack is observed will induce errors where mapping is done at a distance instead of by direct overflight. This is particularly true where the snow has melted off of south-facing slopes but not the north-facing ones. Observation to the north may show a total absence of snow while looking towards the south may give the observer the impression of an unbroken snowpack. Observation towards the east or west helps prevent this type of error.

Percent snow cover becomes difficult to estimate at percentages less than sixty-five - particularly in the juniper vegetation zone where the bulkiness of the plants screens much of the snow or the snow is hidden in deep shadow. No solution to overcome the optical tricks played on the observers' vision has yet been developed.

RESULTS

The quality of snowpack information obtained by the method described is directly affected by the experience of the observer, his physical condition during the flight, the time spent at altitude without supplementary oxygen, the quality of existing light conditions, and the depth of snow relative to the depth indicators being used. Under good to fair conditions, experienced aerial observers have been able to consistently estimate snow depths within ± 5.0 centimetres (± 2.0 inches) of the depths reported independently by various ground observers. For operational purposes, this variation is more than acceptable.

Barnes (1974), independently comparing the author's snow maps for seven dates in 1972-73 with snow maps compiled from imagery obtained in the 0.6-0.7 μm spectral band by the ERTS-1 satellite, reports a mean areal difference of only seven percent between the two mapping methods. Snow melt or deposition occurring between the date of a low level reconnaissance flight and the date of the comparable satellite image plus approximation of the snowline by the aircraft observer for areas not directly overflown account for most of the differences between the satellite and aircraft maps. Other differences arise due to the aerial observer's ability to map shallow, partial snow cover which may not at times be visible on the satellite imagery. The difference between the two mapping methods dropped to two percent when the low level maps were produced from direct overflights conducted on or near the same day the satellite passed overhead.

USE OF INFORMATION COLLECTED

The existence of distinct snow zones on the Salt and Verde river watersheds became evident early in the Project's aerial snow survey flights. Subsequent observations made on snow accumulations, depths, and melt characteristics were used to identify and map areas having similar snowpack characteristics. Snow zone characteristics and size coupled with ground and flight information on existing soil moisture and snowpack conditions have been used for empirical calculations of maximum potential streamflow, timing of runoff from individual watersheds, and the total amount of reservoir inflow anticipated for the season.

Snowmelt information provided by the flights has also been successfully used as a guide for making adjustments in reservoir outflows during critical runoff periods.

Project snow maps are presently being utilized in several studies by the University of Arizona and the U.S. Geological Survey investigating the use of remote sensing techniques for mapping snow and the correlations between snowpack areal ablation and runoff.

COSTS

Aircraft rental and manpower costs vary from one part of the country to another and from agency to agency. For this reason and to allow the reader to estimate expenses for aerial snow mapping related to his own operations, costs have been expressed in units of time rather than in dollars.

Normal flight time for the Project's average aerial snow survey covering 1,130 kilometres (700 miles) has been slightly under 5.0 hours. Flight-related activities (assembling survival gear, loading and unloading the aircraft, filing of flight plans, etc.) usually require an additional 2 to 3 hours. Map correction and redrafting prior to reproduction take 2 to 4 hours.

BENEFITS

The Project's low level aerial reconnaissance flights of the Salt-Verde watershed snowpack provide information not presently obtainable by any other method. Snow reports from local watershed observers often over or under-estimate snowpack conditions - particularly for the lower elevations. Aerial reconnaissance permits rapid confirmation of the extent, depth and condition of the ephemeral pack and the potential for flooding.

The single greatest benefit derived from the snow flight information is the opportunity to make early adjustments in reservoir releases required to handle high runoff. Snowmelt runoff may take from a few hours to one or two days to reach the nearest Project early-warning gaging station. Water is money to the Project and any early detection of major runoff events when Project reservoirs are at or near capacity permits additional time for orderly releases through Project hydroelectric generators and into the canal system for use by Project shareholders. Release of the same volume of water over a shorter period of time may require the use of spillway gates with attendant tailrace damage and loss of the water down river.

When down-river spills are already in progress, early detection of flow recession becomes important. The early knowledge provided by the aerial flights that the snowmelt supporting a runoff event is almost ended permits earlier termination or reduction in reservoir releases than is possible when stream gages are the only source of data. By utilizing the flight information, the amount of water that would otherwise be wasted down river is materially reduced.

CONCLUSIONS

The aerial snow survey and mapping techniques described provide a method for rapidly determining and recording the areal extent and depth of snow over large areas. The method is relatively inexpensive and easy to learn. Most persons with a good knowledge of the surface features used to reference depth can become qualified observers by the end of a single season.

Primary limitations of the method are the presence of suitable depth indicators, available light conditions and the observer's resistance to motion sickness.

REFERENCES CITED

Barnes, James C., Clinton J. Bowley, and David A. Simmes. 1974. The Application of ERTS Imagery to Mapping Snow Cover in the Western United States. Environmental Research and Technology, Inc., Lexington, Massachusetts.