

THE APPLICATION OF HYDROMETEOROLOGICAL DATA OBTAINED BY REMOTE SENSING TECHNIQUES FOR MULTIPURPOSE RESERVOIR OPERATIONS

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ABSTRACT

Watershed snowpack and streamflow data obtained and transmitted by (ERTS) satellite has been used in the operational and water management decisions in the Salt River Project. Located in central Arizona, the Project provides water and electric power for the more than 1.1 million residents of the Salt River Valley. The water supply source is a 33,670 square kilometre (13,000 square mile) watershed and 250 deep well pumps. Six storage reservoirs, four of which have hydroelectric capability, located on two river systems have a storage capacity of over 246,600 hectare-metres (2,000,000 AF.). Information from the watershed during the normal runoff period of December to May and more especially during critical periods of high runoff and minimum reservoir storage capacity is necessary for the reservoir operation regimen. Extent of the snowpack, depth of snow, and the condition of the pack has been observed and reported by an observer in aerial flights over the watershed. Snow density, air temperature, accumulated precipitation and streamflow quantities have been relayed by satellite data collection stations. These data, along with bi-weekly snow surveys have been the bases for runoff volume forecasts and for the development of the reservoir operations plan. The application of snow mapping techniques from satellite imagery which can provide frequent definition of the areal extent of watershed snow cover holds good potential for improved accuracy of the volume forecasts as well as providing needed information for the day to day critical operational decisions.

INTRODUCTION

Water for municipal, industrial, and agricultural use in the Salt River Valley of Central Arizona is provided, in large part, by the Salt River Project. The 1.1 million people and 101,175 hectare (250,000 acre) urban and agricultural area requires annually about 148,000 hectare-metres (1,200,000 acre feet) of water from the Project, water that is diverted from the surface supply or pumped from the groundwater basin.

Surface Water

The surface water originates from precipitation falling on a 33,670 square kilometre (13,000 square mile) watershed which ranges in elevation from about 400 metres (1300 feet) to almost 3870 metres (12,700 feet). Three separate major drainage basins, the Salt, Tonto, and Verde, comprise the watershed, and runoff from these basins flows into six reservoirs on the Salt and Verde rivers. About 75% of the mean annual runoff, 1913-1974, from the three streams results from winter cyclonic and frontal storm systems which occur during the December - May runoff season. Much of the precipitation from these storms falls as snow. The snow that is deposited above the 2135 metre (7000 foot) elevation normally remains until the spring snowmelt period of March, April and May. About 90% of the total watershed lies below 2135 metres (7000 feet) and the snow that falls on this area, down to as low as 760 metres (2500 feet) is ephemeral in nature and subject to very rapid melt induced by either subsequent rainfall or sharp increases in temperature. Because of the large areal extent of this portion of the watershed and the instability of the snowpack, very high runoff volumes can be experienced in relatively short periods of time creating major flooding potentials if reservoir storage is high.

Groundwater

The groundwater supply for the Project is pumped from the alluvial aquifers of the Salt River Valley within the Project's water service area. Two hundred fifty-five deep well pumps, which are located throughout the water transmission and distribution system, can develop 35 to 40% of the annual water requirement. Operation of these pumps is normally minimized in order to conserve both groundwater and energy; their use is supplemental to the surface water supply.

Reservoir System

The Salt River Project has six dams which create a reservoir storage capacity of 255,485 hectare-metres (2,072,050 acre feet). Four of the six dams are located on the Salt River and two on the Verde River. Theodore Roosevelt dam and lake is the largest of the six providing just over 65% of the total water storage capacity. Each of the four dams in the Salt system are equipped for hydroelectric power generation with a total capacity of 248,000 KW; two of the dams have reversible pump turbines providing a water pump-back capability. The two dams on the Verde River have reservoirs with a combined capacity of 39,175 hectare-metres (317,715 acre feet). This is used for short term or temporary storage of water and the system does not have hydrogeneration capability.

Water Management

The water management objectives of the Salt River Project are (1) have sufficient quantities of water available from either surface or groundwater sources or both to meet the demands for municipal, industrial and agricultural use in the Salt River Valley; (2) provide reservoir carryover 123,300 to 160,290 hectare-metres (1.0 to 1.3 million acre feet) at the end of each year to insure sufficient surface supply for two years hence; (3) maximize hydroelectric generation during the high power demand summer months; (4) to the extent possible, minimize pumping (5) use Verde system storage to supplement outflow from the Salt system so that release of water on the Salt other than for power generation is not necessary; (6) reduce Verde system storage to 10-15% of capacity by the first of December each year; (7) during periods of high runoff and maximum storage, limit necessary controlled spillway releases to flows that would result in minimal flood damage to property along the Salt River channel through the Valley area and maximize power generation and agricultural water use; (8) end the December-May runoff period with reservoir system full.

A Project Reservoir Operating Plan is formulated during the latter part of each year to meet these objectives. This plan is under constant review during the ensuing year and modification or adjustment is made periodically to meet the prevailing conditions of demand, runoff, and storage. Operational criteria that must be considered includes: (a) the total monthly demand for water, (b) the amount of groundwater pumping that is required; this is a function of the amount of storage and the prospects for runoff as well as the availability and cost of energy for pumping; (c) the amount of surface water demand; (d) the reservoir system or systems from which the surface water should be withdrawn, whether the Salt, the Verde or both in order to accomplish objectives 3, 5, and 6; (e) runoff quantities forecasted or expected in each of the reservoir systems for the month.

Runoff Forecasting

The present method for forecasting seasonal runoff at the Salt River Project is based on the multiple regression analysis theory. It is also known as the Index Forecast Method. Briefly, this method involves correlations of historical runoff records with indices of important determinants of runoff for the area. The use of this method provides seasonal volumetric runoff forecasts utilizing bi-weekly snow survey information from mid-January to April 1st. The method was developed in Arizona in 1961 as the result of a research effort between the Soil Conservation Service and the University of Arizona (Cluff, 1961). The present updated and improved runoff forecast equations were obtained during 1967 by Project personnel (Wilson, 1970). Present runoff forecasting is done cooperatively by Soil Conservation Service and the Salt River Project personnel. The two main drawbacks of the present

method are: (1) the method relies strongly on averages, therefore it fails to accommodate abnormal snow or weather conditions. (2) the seasonal volumetric runoff information may not always be adequate for the critical reservoir operation decisions.

The present goal is to develop short range runoff forecast techniques and monitor the effects of the major storms on the reservoir system. While the Project has no legal responsibility for flood control, it feels obligated as a good neighbor to try to minimize the potential for flooding through the Salt River Valley while at the same time meeting its legal responsibility to its shareholders to maximize reservoir storage. To maintain the delicate balance required, more information than that provided by established data collection sites is needed. Few snow survey sites exist in the ephemeral snow zone. Information on areal extent, depth, and condition of the snowpack over large areas in this snow zone is required if the flood hazard was to be adequately monitored. Snowcourses, aerial snow markers, soil moisture stations and snowpillows are all point samples and do not provide all the information needed for the lower-elevation snowpack. A technique for estimating snow depths and mapping snowpack areal extent and percent coverage has been developed by the Project (Warskow, 1975).

AERIAL SNOWMAPPING TECHNIQUE

Mapping

During the years 1965-68, maps of the Salt-Verde snowpack were drawn at a scale of approximately 1:3,000,000 from notes taken during each watershed 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) lap-board. 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 ground.

Early observations indicated that surface rock, vegetation and cull logs might be useful yardsticks. Utilizing a knowledge of the variations in these features over the Salt-Verde watershed, a technique 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. For example, 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 other features. Grass stems are a good indicator for depths of 15 to 20 centimetres (6 to 8 inches). Half-shrubs 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 in Arizona forests 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 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 and Runoff Stage

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 ongoing melt can be determined from the brilliant, mirror-like reflectance of the sun through small holes in the pack. Relative river stage can also be determined by an aerial observer. A rising stage is indicated by heavy sediment loads and lack of fresh high water marks. Wet sandbars, presence of bank seepage, fresh high water marks and clearer water generally indicate flow recession.

Accuracy

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 Project's snowmaps 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 overflowed 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 SATELLITE INFORMATION

Data Collection

Streamflow data is telemetered to Project offices from six upstream gaging stations. In the past, problems with ice detuning the antennas on the mountain top repeaters has made data unavailable when it was most needed during critical runoff events. System performance has been improved with the installation of better equipment but is still not perfectly reliable.

In 1973, data from an ERTS-1 DCP located on the Verde River at Camp Verde was relayed to Project offices by NASA several times a day when the Project's communication link with the site failed. Installation of another ERTS-1 DCP on the Black River the same year and at several other sites, including two snowpillows and meteorological data sites, since has permitted acquisition of data from remote watershed areas without the necessity of installing additional, high-priced, mountain-top repeaters. This information plus streamflow data received via the Project's telemetry system and via ERTS-1 has been successfully used as a guide for making adjustments in reservoir outflows during critical runoff periods. Snowmelt runoff may take from a few hours to one or two days to reach the nearest Project early-warning gaging station. Early detection of major runoff events when Project reservoirs were at or near capacity has permitted 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 would have required the use of spillway gates with attendant tailrace damage, loss of power revenues and wasting of the water down river. When reservoir releases are already in progress, early detection of flow recession becomes important. The early knowledge provided by the aerial flights and satellite telemetry that the snowmelt supporting a runoff event was almost ended has permitted earlier termination or reduction in reservoir releases than would have been possible when stream gages were the only source of data. By utilizing the flight and satellite information, the amount of water that would otherwise have been wasted down river was materially reduced.

Snow Maps

Because the hydrologic diversity and the transient characteristics of the snow pack in the Salt-Verde watershed, snow maps could become an important integral part of the general evaluation for the reservoirs operational decisions. The results of investigation (Barnes, 1974) indicate that ERTS imagery has substantial practical application for snow mapping.

The current application of snow mapping techniques from satellite imagery is in the initial stage at the Salt River Project. But based on the experiences in the application of the hydrometeorological data obtained by remote sensing techniques it can confidently be stated that the use of satellite snow maps is highly promising at the Project. Timely, accurate, and dependable information of areal extent of watershed snow cover could be invaluable for critical reservoir operational decisions.

A limited study was undertaken by the Project personnel on a set of snow maps prepared from NOAA imagery by the Environmental Products Group for the 1974-75 snow season of Salt and Verde basins. These maps have been prepared on an operational basis and the snow cover was expressed in percent of the total watershed area by S. R. Schneider of NOAA.

An attempt was made to analyze the Salt River Basin snow cover percentage. Using the basin's hypsometric curve, a snow line was determined from the percent of snow cover. The snow melt area was computed for each specific melt time and the average elevation was calculated for the area. Due to the lack of the average snow density (water content) at the computed average melt elevation, potential snow melt volume could not be computed. If the water content were available then the potential melt volume could be computed. Then a basin yield factor could also be determined from the gaged versus computed potential runoff.

The basin yield factor could be very valuable for monitoring and also for predicting the inflow from major storms. Availability of this information can be used to develop short range forecasting and storm monitoring techniques which are needed for timely reservoir operational decisions.

It is the authors' opinion that satellite snow maps can be used at the Salt River Project as a direct input to streamflow synthesis models and also in the regression analysis method for computing seasonal runoff. Frequent snowmaps obtained in real time would contribute positively to stream flow forecasting accuracy, which has direct impact on the Water Resource Operations Department's ability to meet the Project's water management objectives.

CONCLUSION

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. It is anticipated that the availability of repetitive imagery and telemetered snowpack data from the LANDSAT, NOAA AND GOES satellites will make it possible to develop this same information quantitatively within the next few years. Operational applications will require that both the imagery and telemetered data be available to the user in real time.

Accurate and timely long and short range runoff forecasts are essential tools for reservoir operations and for estimating the quantity of water available for an adequate and assured water supply for the Salt River Project and Central Arizona.

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