THE APPLICATION OF AERIAL AND SATELLITE SNOW-MAPPING TECHNIQUES FOR MULTI-PURPOSE RESERVOIR SYSTEM OPERATIONS IN ARIZONA 1/ 634-77

By

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Introduction

The Salt River Project encompasses about 101,000 hectares (250,000 acres) in Central Arizona and provides municipal, industrial and agricultural water for a large majority of the Salt River Valley's 1.2 million residents. About 76 percent (1966-1975 average) of the Project's total annual water demand of 157,500 hectare-meters (1,277,000 acre feet) comes from its multi-purpose reservoir system. The remaining 24 percent of its total demand is produced by 255 deepwell pumps.

Description of the Reservoir System

The reservoir system is comprised of six dams having a total water storage capacity of 256,000 hectare-meters (2,072,000 acre feet). Four of the six dams are located on the Salt River and two on the Verde River (figure 1). The largest is Theodore Roosevelt Dam which provides over 65 percent of the total water storage capacity. All four dams on the Salt system produce hydroelectric power. Two of the dams have reversible pump turbines providing a water pumpback capability. The two reservoirs on the Verde River have a combined capacity of 39,190 hectare-meters (317,715 acre feet). The Verde system does not have any hydroelectric generating facilities.

Salt and Verde Watershed

About 75 percent of the mean annual runoff (1913-74) from the Salt and Verde Rivers originates from winter cyclonic and frontal storms during the December-May runoff season. Much of the precipitation from these storms falls as snow.

Snow deposited above 2135 meters (7000 feet) elevation normally remains until the spring snow melt period of March, April and May. However, about 90 percent of the total 33,670 square kilometer (13,000 square miles) watershed lies below 2135 meters (7000 feet) elevation. Snow that falls on this area is ephemeral in nature and subject to very rapid melt. Because of the large areal extent of this portion of the watershed and the instability of its snowpack, very high runoff volumes have been experienced in relatively short periods of time, creating major flooding.

The System Operation

The complexity of the Project's reservoir system operations combined with the watershed's peculiarities necessitates systematic and continuous evaluation of watershed conditions, particularly when storage in the system is near capacity. The reservoir system has to be operated with the following constraints:

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1. Release water only to meet users' demands.

2. Maintain adequate carryover storage from one year to the next.

3. Perform flood control operations efficiently to preclude unnecessary spills (any release from the system to the normally dry Salt River below the Granite Reef diversion dam is considered to be a flood by local residents and may cause damage).

4. Optimize hydroelectric generation.

5. Regulate groundwater pumpage relative to reservoir storage and seasonal energy demand.

6. Minimize reservoir fluctuations with regard to recreational values.

7. Meet all contractual obligations.

8. Optimize the operational efficiency between the Salt and Verde reservoir systems.

Use of timely and dependable hydrometeorologic information has become an integral part of the Salt River Project's evaluation of watershed conditions. When runoff is forecast to exceed available reservoir storage, these data are critical to reservoir system operations. Since 1975, daily snowcover maps of the watershed have proved to be a valuable decision-making tool in the Project's multi-purpose reservoir system operations.

History of Aerial Snow-Mapping in Arizona

Unusually high runoff during the fall of 1965 filled Project reservoirs almost to capacity by mid-December. Watershed soils were saturated. Snow blanketed the watershed above 1,370 meters (4,500 feet).

During a storm on December 29, 1965, rain stripped the heavy ephemeral snowpack lying below 2,285 meters (7,500 feet) off the watershed within a matter of hours. This triggered a major runoff event that made it necessary to spill both the Salt and Verde river reservoir systems. Developments which had encroached upon the normally dry Salt River channel throughout the metropolitan Phoenix area since the last spill in 1941 suffered major damage. The threat of similar catastrophic runoff events from additional storms remained.

Data regarding the aerial extent and depth of the ephemeral snowpack were of primary importance. However, most of the established snow courses were located aboue 2,285 meters (7,500 feet) in the seasonal snowpack zone. To obtain the required information, low-level aerial reconnaissance flights over the snowpack were initiated.

Snow maps were drawn at a scale of approximately 1:3,000,000 from notes taken during each flight. The snow line depicted was generalized, primarily on the basis of elevation. Snow depths were estimated using barbed wire fences. This method for estimating snow depth was later refined to make use of natural surface features such as rock, vegetation and cull logs (Warskow, Wilson and Kirdar, 1975).

Direct in-flight mapping of the snowpack was first attempted in 1969 using the 1:1,000,000 Arizona aeronautical chart. The shaded relief on the Arizona aeronautical chart very accurately reflects watershed topography and enabled the aerial observer to map the edge of snowpack with acceptable precision. Ocular estimates of snow depth and the percent of the ground covered with snow were made, and the relative condition of the snowpack mapped using the techniques previously described by Warskow (1975).

The quality of snowpack information thus obtained was 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 used. Under good conditions, experienced aerial observers were able to consistently estimate snow depths within ±5 cm (2.0 inches) of the depths reported independently by various ground observers. Barnes (1974), comparing Project aerial snow maps compiled from satellite imagery, reported a mean areal difference of only seven percent between the two mapping methods. These variations were acceptable for operational purposes.

The current availability of operationally accurate snow maps derived from satellite imagery has freed the aerial snow survey team from the need for detailed mapping of the snowpack. This permits them to concentrate on obtaining snow depth information and low altitude photography of selected watersheds for use in developing snowpack area-runoff relationships.

Satellite Snow Cover Observations

Three satellite systems are being used to provide timely information for evaluating Salt-Verde watershed conditions. These systems, the Landsat, ITOS and SMS/GOES satellites are being evaluated under the NASA funded Applications Systems Verification Test (ASVT) on Snowcover Mapping. A brief description of each satellite system will be presented together with a discussion of satellite image interpretation techniques.

Landsat Systems

The experimental Landsat series consists of two satellites that operate in circular, sun-synchronous, polar orbits at altitudes of approximately 925 kilometers (570 miles). Multispectral scanners (MSS) aboard these satellites provide high-resolution imagery (80 meter ground resolution) covering 185 x 185 kilometer areas (Landsat Data Users Handbook, 1976). The Landsat imaging system that can provide coverage of any ground point every nine days is shown diagrammatically in figure 2.

The use of 1:1,000,000 scale Landsat MSS imagery allows rapid and direct mapping of snowcover distributions. The snowline is first traced onto a transparent overlay that contains the watershed outline and major drainage patterns. The areal extent of the snow-covered areas can then be determined by the use of grids or manual planimeter methods. These methods provide inexpensive measurements of snowcover distributions. However, they are relatively slow and the degree of precision obtained is dependent on the experience and skill of the interpreter.

Color-additive viewing of the multispectral Landsat (MSS Band 5 and 7 color composits) enhances the contrast between snowcovered and bare areas and greatly facilitates snowcover mapping in densely forested areas (Schumann, 1975). Snowcovered area measurements can be made from color composits using transparent overlays as previously described. The major disadvantages of using the color-additive viewing technique is the high cost of projection-type viewing equipment and the time required to make the area measurements.

Improved TIROS Operational Satellites (ITOS) System

The ITOS system of improved TIROS operational satellites (NOAA series) is being used to produce satellite-derived snowcover maps of selected river basins including the Salt-Verde watershed of Central Arizona (Schneider, 1976). These satellites operate in sun-synchronous polar orbits about 1,500 kilometers (790 nautical miles) above the earth. They provide daily coverage over the Western United States in the visible spectrum and twice daily in the thermal infrared part of the spectrum by means of Very High Resolution Radiometers (VHRRs). This imaging system is shown diagrammatically in figure 2.

The VHRR imagery provides horizon-to-horizon coverage, has a spatial resolution of 0.9 kilometers at the subpoint, and has a scale of about 1:10,000,000. This imagery provides a distorted panoramic view of the earth's surface that requires geometric correction before it can be related to planimetric basin maps. A zoom transfer scope has been used to optically enlarge and stretch the VHRR imagery and to project the corrected image onto 1:2,500,000 scale Arizona basin maps (Schneider, 1976). The snowline, as interpreted on the corrected image, is then traced onto an overlay of the watershed map. The percentage of snowcovered area over the watershed is then determined by either manual or electronic planimeter methods. These maps are then transmitted to the Salt River Project in Phoenix, Arizona by telecopier from Suitland, Maryland.

The principal advantages of using the VHRR imagery for snow mapping in Arizona are its availability on a daily basis and also its total coverage of the entire Salt-Verde watershed. The principal disadvantage of using this imagery is its relatively low resolution and its geometric distortion.

SMS/GOES Satellite Systems

The Synchronous Meteorological Satellites (SMS) will be designated Geostationary Operational Environmental Satellites (GOES) at some future date. The SMS/GOES satellites are in geostationary orbits at about 35,200 kilometers (19,000 nautical miles) above the earth. Their position with respect to the earth remains fixed. The subpoint of SMS-1 is at longitude 75°W over the equator and SMS-2 is at 135°W (Breaker, 1975).

The SMS/GOES satellites acquire earth imagery in both the visible and thermal infrared Spin Scan Radiometers (VISSRs). Although these sensors can image almost the entire earth (full disc) per scanning cycle, "sectors" of limited and specified geographical areas are extracted for detailed study. The sectorized VISSR imagery, having a maximum spatial resolution of 1 kilometer at nadir, is routinely available every 30 minutes (Breaker, 1975). The SMS/GOES imaging system is shown diagrammatically in figure 2.

The SMS/GOES imagery produces a distorted view of the earth's surface that changes in both scale and resolution north and south of the equator. As previously described, the zoom transfer scope can be used to correct the VISSR imagery and to project it onto basin maps.

The principal advantage of using the VISSR imagery for snowcover mapping is its availability each one-half hour. This capability allows the hydrologist to monitor rapidly changing snowcover distributions and weather systems.

Hydrometeorological Data Relay Systems

Several different data relay systems are being used by the Salt River Project to relay hydrometeorologic data for use in reservoir system operations on the Salt-Verde watershed. These systems include microwave telemetry and two satellite data collection systems. The SNOTEL system soon to be implemented in Arizona will utilize a meteor burst communication system

Microwave System

The Salt River Project operates a microwave system to monitor stream flow rates at key gaging stations. These sites can be interrogated and the required information obtained in real time. The principal disadvantage of using this type of system is the high capital and maintenance costs involved.

Landsat Data Collection System

The Landsat Data Collection System (DCS) provides the capability to collect hydrometeorologic data by means of Data Collection Platforms (DCP's) and to relay these data via the satellite to ground-receiving sites located at Goldstone, California; Greenbelt, Maryland; and Fairbanks, Alaska (figure 3).

The Landsat DCP's transmit each 90 or 180 seconds. When the satellite is in mutual view of a transmitting DCP and one of the ground-receiving sites, the satellite relays the DCP transmission in real time to the ground-receiving site. This system is designed to relay information from anywhere in North America during at least two orbits per day, one at about 9:30 in the morning and one at about 9:30 in the evening. The Landsat DCS has been successfully used to relay hydrometeorologic data from Central Arizona (Schumann, 1975).

SMS/GOES Data Collection System

The SMS/GOES geostationary satellites provide an operational data collection system (DCS) capable of telemetering large volumes of hydrometeorologic data collected at remote unattended sites. Data from earth-based environmental sensors are transmitted to the SMS/GOES satellites by data collection platforms that can be operated in either a self-timed mode (unit will transmit only at preassigned times) or in an interrogate mode (transmits upon commands relayed from the satellite). The SMS/GOES data collection system is being used to relays streamflow data from selected gaging stations in Central Arizona and is shown diagrammatically in figure 3.

SNOTEL System

The Soil Conservation Service is in the process of establishing about 20 hydrometeorologic data collection sites in Arizona that will utilize a meteor burst communication system (figure 3). Data from these sites will be routinely provided once each day (more frequently if needed) for use in monitoring snowpack conditions on the Salt-Verde watershed.

Comparison of the Systems

Satellite and aerial snowcover observations made during the spring of 1976 over the Black River drainage on the upper Salt River watershed are shown on figure 4. Runoff measured at the mouth of the Black River, by a gaging station now equipped with a SMS/GOES DCP, is also shown. The ITOS satellite observations indicate rapid and frequent changes in snowcover distributions. Only four Landsat snowcover observations were obtained during the spring of 1976, and these did not adequately describe the changes that occurred. Aerial flights provided supplemental observations during periods when cloud cover prevented effective satellite snowcover observations. These comparisons indicate the value of frequent satellite observations as well as aerial flights for monitoring rapidly changing Salt-Verde watershed conditions.

Conclusions

1. Reservoir system operations in Arizona require timely and dependable information on watershed conditions. This information is invaluable when the total runoff is forecast to exceed available reservoir storage. The information required can be provided by frequent snowcover observation together with hydrometeorologic data relayed in near-real time.

2. Aerial reconnaissance flights furnish estimates of snow depths and melt conditions together with visual mapping of snowcover distributions. When cloud cover precludes effective satellite observations, snowcover distributions over the Salt-Verde watershed can often be obtained through aerial observations.

3. Frequent satellite snowcover maps have proved to be a valuable decision-making tool. Timely snow maps and telemetered hydrometeorologic data have become an integral part of the Salt River Project's multi-purpose reservoir system operations in Arizona.

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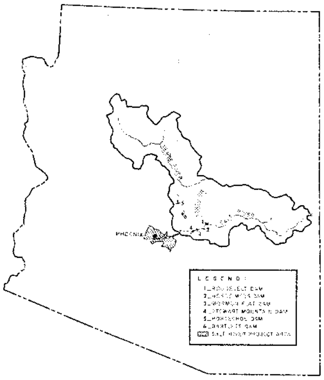

FIGURE 1. -- Map showing the Salt-Verde Watershed, Arizona

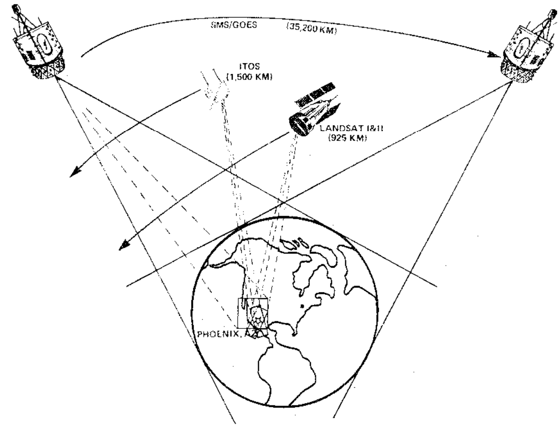

FIGURE 2. -- Satellite Imaging Systems

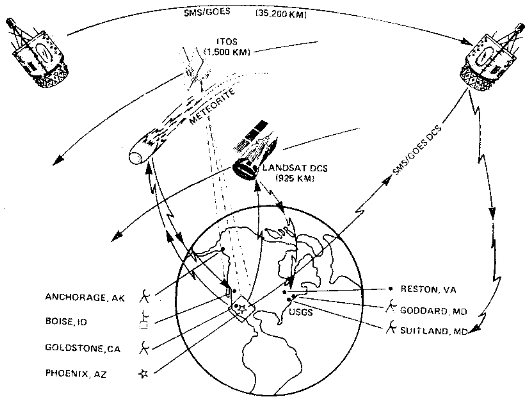

FIGURE 3. -- Data Relay Systems

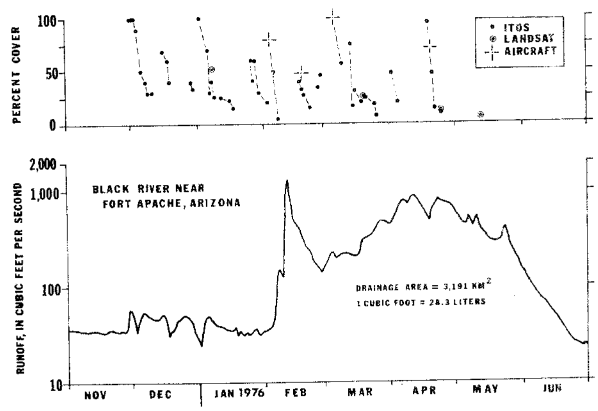

FIGURE 4. -- Snowcover Observations and Runoff

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