AIRBORNE SNOW OBSERVATORY: NEXT GENERATION OF BASIN SNOW MEASUREMENT, MODELING, AND FORECASTING

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ABSTRACT

The Airborne Snow Observatory (ASO) demonstration mission will collect detailed basin-wide snow information for portions of the Tuolumne Basin in California and the Uncompahgre Basin in Colorado in spring of 2013. The ASO uses an imaging spectrometer and LiDAR system mounted in an aircraft for collecting data allowing determination of snow water equivalent, snow depth, and snow albedo. Weekly flights over the Tuolumne will produce both basin-wide and detailed sub-basin SWE estimates that will be used in a hydrologic simulation model to improve the accuracy and timing of runoff forecasting tools used to manage Hetch Hetchy Reservoir, the source of 85% of the water supply for 2.5 million people on the San Francisco Peninsula. The USGS PRMS simulation model will be calibrated to the 459 square mile basin and will be updated at weekly time steps with both weather forecast data and distributed snow information from ASO flights to inform the reservoir operators of predicted inflow volumes and timing. Information produced by the ASO data collection and PRMS modeling is expected to improve the ability of reservoir operators to more efficiently allocate the last half of the recession limb of snowmelt inflow and be more assured of meeting operational mandates. This presentation will provide preliminary results from the project as it begins its first year. (Keywords: snow water equivalent, runoff forecasting, LiDAR, Tuolumne, PRMS, Hetch Hetchy)

INTRODUCTION

Snowmelt is an important resource for western agriculture, hydropower, and municipal water supply. In the maritime regime of California's Sierra Nevada, more than 75% of the seasonal precipitation is in the form of snow during the winter months. Most of the rivers on the west slope of the Sierra Nevada have both mid-elevation small- and medium-sized reservoirs as well as large reservoirs at the rim of the Central Valley. These reservoirs store a significant portion of the annual runoff and hold if for use during the dry summer months. The reservoirs tend to be lowest in January, have their peak storage in early June, and then decline during the summer months. The quantity and timing of the runoff vary from year to year and reservoir operators vary their management strategies to optimize their use of the annual runoff volume. Significant annual variability in runoff is common, and inflow from the Tuolumne River, in the south-central portion of the Sierra Nevada, varies from 28% to 230% of its normal annual runoff at LaGrange of 1,860 thousand acre feet (TAF). The larger reservoirs, such as Don Pedro (near La Grange and below Hetch Hetchy), have a capacity (2,010 TAF) in excess of average annual runoff and only fills after above-normal winters. It can, however, supply adequate irrigation water to the downstream users even after several below-normal winters. The mid-elevation reservoirs, such as Hetch Hetchy (360.4 TAF) would cycle from full to mostly empty each year if operated as a power reservoirs. Hetch Hetchy cycles from full to about half full each year because it is instead operated with water supply and drought protection as its prime goal. Over 2.5 million people in the San Francisco Bay Area depend entirely or partially on water from Hetch Hetchy, so system goals do not allow extra generation to be produced until there is a very high level of certainty that water supply can be assured during each year's spring runoff season. Accurate and timely runoff forecasts are important because generation at Kirkwood Power House with Hetch Hetchy water is worth approximately $66,000 per day.

Hetch Hetchy Reservoir is also operated to maintain and improve the aquatic ecosystem in the reach between O'Shaughnessy Dam and Kirkwood Powerhouse. Operational goals call for ecological pulse flows to be made early in the runoff season to maintain spawning areas, with pulse sizes and durations dependent on forecasted water-year magnitude. An additional goal is to avoid large, late-season spills after the reservoir fills, and that goal is also dependent on accurate and timely runoff forecasts. Avoiding spills means drafting water during the runoff period so that adequate space exists in the reservoir to absorb the late season runoff pulses. Tension exists between the goal to ensure a full reservoir at runoff's end and the goal to not have a late-season spill of significant magnitude.

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RUNOFF FORECASTING AND WATER MANAGEMENT

Forecasting for the Tuolumne extends back to 1946 and M.J. Bartell, general manager of HHWP. Bartell acknowledged the start of snow course information in 1930 by the California Department of Water Resources (DWR) snow survey program, but believed that 15 years of data was too short a record for development of a predictive equation. Bartell had or developed precipitation records back to water year (WY) 1890, or 55 years. He had stream flow measurements for the Tuolumne River at La Grange or Modesto from WY 1897 and he used that period or record to extend estimates of runoff back to 1890. He had stream flow measurements at Hetch Hetchy, Lake Eleanor, and Cherry Lake from WY 1911, and he also extended those back to WY 1890 by comparison to the total flow at La Grange or Modesto. He constructed a plot with water year precipitation on one axis and runoff in hundreds of thousands of acre feet (Figure 1). Lines for La Grange, Hetch Hetchy, and Eleanor Cherry Creeks relate annual runoff to annual precipitation. Bartell derived a system for making March 1, April 1, and May 1 forecasts by estimating seasonal normal-to-date precipitation ratios and relating them to streamflow percent of normal, so mid-winter forecasts could be made using accumulated precipitation. Bartell also calculated preliminary precipitation-runoff curves for the American, Yuba, Stanislaus, and Merced rivers using the same technique. He suggested that his preliminary work could be expanded into a system that could be used for any west-flowing Sierra Nevada river (Bartell, 1946).

Figure 1. Plot showing runoff (abscissa) and annual runoff (ordinate) and the hand fitted lines for Eleanor+Cherry, Hetch Hetchy, and other combinations on the right side.
**Snow Survey-Based Forecasting**

In the 1960's, DWR developed monthly runoff forecasting equations based on the more than 30 years of snow survey data and runoff measurements that had been collected concurrently. DWR's equations combined the basin's snow courses into an index value, calculated the ratio of the current year to the long-term normal, added factors for prior year's precipitation, and predicted runoff for each month from February through May. It was assumed that peak snowpack occurred about April 1, and the forecast was made for the April-through-July period. Forecasts made prior to April 1 use the snow course and precipitation information for the date of the forecast plus the historical median expected snow and precipitation, and each basin in the Sierra had their own equation. The AJRO volume of predicted runoff was then allocated between the four months based on historical analysis so operators knew what to expect as inflow during each month. Hetch Hetchy Water and Power (HHWP), a division of the San Francisco Public Utilities Commission, used the DWR forecasting equations starting in the late 1960's. The regression-based equations were calibrated using long periods of monthly SWE indices in the Tuolumne basin with records of annual flow at LaGrange and the HHWP reservoirs. Runoff forecasts may commence as early as January, but are definitely produced from February through May.

In 1997, HHWP contracted to have its own forecasting tool developed. The Water Supply Forecasting Model (WSFM) was programmed in both FORTRAN and Visual Basic languages and estimated runoff based on the relationships between runoff, snow, precipitation, temperature, and antecedent conditions (Hannaford, 1997). WSFM runs on a personal computer, although results are also written to an external network hard drive for archival purposes. WSFM, like the DWR procedure, also predicts AJRO and distributes the volume through the four runoff months, plus provided statistical estimates of what inflow would be during the remaining months of the year. WSFM also allows forecasts to be updated by HHWP staff in between the monthly snow surveys using precipitation, temperature, and daily SWE information from eight snow sensors that are telemetered via GOES satellites.

**Daily Forecast Models**

In 2006, HHWP added a daily forecast model to assist with storm response, peak runoff, and recession of the snowmelt runoff period. The VISTA DSS model is a commercial hydrologic simulation model that runs on an hourly time step and includes a 5-10 day weather forecast to allow prediction of snow melt and stream response. VISTA is supplied by the Synexus Global Inc., and the model splits the basins into high, middle, and low elevation zones and does calculations of snow accumulation, ablation, and runoff routing in each of the zones.

HHWP staff also refer to satellite snow coverage and melt models that have recently become more available. Snow cover from NASA's Moderate Resolution Imaging Spectrometer (MODIS) has been available since approximately 2000, but the pixel size is 1 km and the delay between imaging and delivery of processed scenes for the Tuolumne have been a week or more until very recently. The National Weather Service's SNOW Data Assimilation System (SNODAS) uses snow data cover and associated variables to do large-scale hydrologic modeling. SNODAS is also based on a 1 km grid, and while simulations have been made since 2003, only in the last several years has the data been available in a timely manner. SNODAS uses the best available satellite and ground data, but there is no validation on the estimates of SWE across a landscape.

**Water Management Challenges**

Water management is critical to the state of California, and power generation, water supply, flood control, and storage of water for irrigation are just some of the uses for water in California. For example, Pacific Gas and Electric, California's biggest independently owned utility, has hydropower facilities on 16 river basins, operates 100 reservoirs in mid- to high-elevation zones, operates 68 powerhouses with ~4,000 megawatt (MW) peak capacity, and supplies up to 20% of the annual electrical demand in California from its facilities. Accurate and timely information on the mountain snowpack extent, depth, and water content is very important to their water managers.

Water from the major reservoirs allows irrigation in the Central Valley and the production a wide range of crops, animals, fiber, and other agricultural products. Agricultural output was valued at $43.5 in 2011, making California the largest agricultural producer in the U.S (U.S.D.A., 2012). These larger reservoirs may be operated by federal agencies, or they may be operated by irrigation districts. Both groups depend on accurate measurement of the mountain snowpack.
Water managers are facing an array of challenges that make water management more complex. Climate change is expected to make extremes more extreme, so larger or more frequent floods may occur more frequently. Droughts may also be more severe or more frequent, and while better snowpack information will not solve these problems, more accurate information will reduce the risk that managers have to deal with. Further, as wintertime temperatures rise, the snowline for storms is expected to rise, and less of the basin is likely to be covered with snow on April 1 than prior to 2000. Since forecasters still use statistical tools and basin indices calibrated with the prior snow deposition patterns, there is concern that the forecasting equations will become less accurate. With reduced accuracy, water managers must hedge to be assured of filling. Increased hedging leads to more water being lost as spill instead of being used for generation, and that generally leads to more fossil fuel being used to generate the lost hydropower.

Releases from reservoirs typically increase as facilities are relicensed, and these releases are often sized to match the water year magnitude. For the smaller reservoirs at the middle elevations, pre-spill releases are also frequently made to avoid overly large spills after the reservoir has filled. Accurate information on basin snow water volume at intervals from April 1 until the end of snowmelt can be very helpful in avoiding not filling or in having large post-fill releases.

On the positive side, water managers have more frequent data due to the installation of snow sensors and other remote climate stations. As opposed to the monthly snow course data, over 110 snow sensors are now operating in California, reporting hourly temperature, snow depth, and SWE. New sensors are being installed at the snow sensor sites, including insolation, wind, and soil moisture. While it is helpful to have these sites and the new information, the spatial representation from even a growing network is still very poor. In the Tuolumne basin above the three HHWP reservoirs, 17 snow courses provide monthly information, and 8 snow sensors provide hourly data. These sites leave large areas of the wilderness basin with no measurement stations, and if the area measured by all the stations is combined, less than a millionth of a percent of the basin is directly measured.

Satellite snow data are helpful in addressing the spatial issue of the sparse direct measurements. MODIS is commonly used to measure snow extent, but is unable to detect information about depth or density. Also, after years of there being up to a month lag between measurement and distribution of the data, lags have recently been reduced to as little as a week. As noted above, modeled products such as SNODAS make use of the MODIS data and other available data to provide gridded estimates of SWE in Sierran basins. The grids are typically 1 km or larger, and there is no verification of the simulation results.

**AIRBORNE SNOW OBSERVATORY DEMONSTRATION MISSION**

As computational power has increased, forecasting models that can use the current hourly or daily data plus forecasted climate data have become available. Further, these models are now highly distributed, dividing river basins into hundreds or thousands of polygons or grids. Geographic information system analysis can provide small-scale information on vegetation, soils, slope, aspect, elevation, and drainage systems, and all of these factors can be incorporated into hydrologic simulation model running on an hourly or daily time step. In essence, the models implement the hydrologic cycle on each polygon in the basin, typically on a daily basis, and build and then melt a snowpack during the winter and spring season. Because the relationships follow physical laws of thermodynamics, soil science, and hydraulics, the simulation models are not sensitive to climate change or extreme storms. The models do need, however, the very best distributed data possible. They also benefit from verification data sets that allow correction of simulated state variable values such as SWE and albedo, two of the key time series that determine future runoff volume and timing in a model.

The Airborne Snow Observatory makes use of an shortwave infrared imaging spectrometer built by Jet Propulsion Laboratory staff and a imaging LiDAR (light detection and ranging) built by Optech, Inc. The spectrometer has a ~5 m spatial resolution when it is used at 5 km (16,402 ft) above ground level, and it measures solar radiance in each of the pixels across ~220 spectral bands from 350 to 2500 nm. The LiDAR system uses a 1064 nm wavelength with a waveform imaging system optimized for snow retrievals, and it has a spatial resolution of ~5 m at 5 km. The instruments were mounted in a Twin Otter aircraft with cutouts in the floor to allow the close synchronization of the fields of view of each device. Geographic positioning system (GPS) devices were also mounted in the plane as well as on the ground in several locations and post-processing of the aircraft GPS data was done to provide the greatest locational accuracy possible.
A snow-free data collection event was done in August, 2012, over the Tuolumne watershed above Hetch Hetchy Reservoir. A collection event consists of flying parallel transects on a north-south grid while holding the aircraft at approximately 6,096 m (20,000 ft) above sea level. The 36 transects are shown draped over a Google Earth scene in Figure 1.

Figure 1. The north-south transects of the aircraft mounted with the imaging spectrometer and the LiDAR to measure snow extent and the ground or snow surface

The snow-free flight was processed to produce an extremely high-resolution topographic map of the Tuolumne headwaters, also known as a digital elevation model (DEM), with a grid size of approximately 4 m. The image processing included removal of the vegetation using the spectrometer data and terrain extrapolation algorithms (Figure 2). Winter flights were initiated on April 2, 2013, and are scheduled to continue at about weekly intervals until the snowpack is almost gone. By subtracting the elevation of each geo-located pixel from the snow-free DEM from the elevation of each pixel in the snow DEM for the flights, snow depth for each pixel throughout the basin can be calculated.

In addition to the use of the spectrometer to detect vegetation and bare ground from snow cover, the spectrometer was also used to detect the albedo of the snow. Albedo is a measure of the reflectivity of the snow, and albedo measures how much of the incident shortwave radiation (insolation) is absorbed by the snow. While it is commonly assumed that warm air temperature is what melts snow, studies have shown that more than 75% of the snow melt is caused by shortwave radiation (U.S. Army Corps, 1956). Albedo is highest for new snow and during the accumulation season and can range from 75 to 90%, meaning that only 25 to 10% of the insolation is absorbed and converted to heat that melts snow. During the ablation (melt) season, albedo decreases after new snow due to the change in the crystal structure of the snow on the surface. Melting snow albedo ranges from 60 to 75%.

Deposition of tree debris, dust, wind-blow soil, and black carbon can further decrease the albedo. Anthropogenic sources such as dust, soot, and black carbon are becoming more common and can have a significant effect on the heat balance of snowpacks in affected regions (Painter et al., 2012; Skiles et al., 2012).

The ASO flights will provide albedo and a snow depth and extent map for the basin. Ground field campaigns are planned in concert with the snow surveys, so density at numerous elevations and locations within the basin will be measured. Those data, along with density derived at snow sensors, will be used to validate a
distributed density field calculated by the ISNOBAL model (Marks et al., 1999). By combining the snow depth and extent with a density field, SWE volume can be calculated for each of the 4-m pixels in the basin. Basin SWE can then be calculated directly, and it can be aggregated into smaller regions for insertion into hydrologic simulation models.

SIMULATION MODELING FOR FORECASTING

The Precipitation Runoff Modeling System (PRMS) was developed by the U.S. Geological Survey research division in the early 1980's (Leavesley et al., 1987). PRMS is a modular, distributed-parameter watershed model. The basin is divided into Hydrologic Response Units (HRUs) and each is characterized in terms of physical parameters such as location, slope, aspect, elevation, vegetation cover and density, soil type and water holding capacity, percent impervious area, and other factors. Slope and aspect maps are shown in Figure 3. The model requires, at the minimum, daily minimum and maximum temperature and precipitation from one or more stations in or near the basin. Calibration is achieved by comparing simulated streamflow with one or more streamflow hydrographs from gaging stations in the basin. For the ASO project, unimpaired inflow (1970-2013) to Hetch Hetchy Reservoir as well as flow at two other USGS gages on subbasins in the headwaters of the Tuolumne watershed above O'Shaughnessy Dam. Climate data from five precipitation stations and eight temperature stations were used to drive the simulation. For the full 44-year calibration record, the mass balance difference between the observed and simulated runoff was less than 1 cm, and the $R^2$ was 0.79.

The basin was subdivided into 280 HRUs to take advantage of the small pixel size available from the ASO data collection and processing effort (Figure 4). While even smaller HRUs could be defined, the underlying soils
Figure 3. Slope (left figure, light shades are steeper) and aspect (right figure) for the Tuolumne above Hetch Hetchy

Figure 4. HRUs and subbasins in the 456 mi² area above Hetch Hetchy Reservoir
and vegetation data are not at that fine a scale. The underlying digital elevation model (DEM) is a 30-m product obtained from the National Hydrology Dataset (http://nationalmap.gov/viewer.html). PRMS executes the hydrologic cycle calculations for each day on each HRU, and accumulates and routes runoff from the HRUs based on subbasins that are established based on the stream network. Because the basin is rather large, the Muskingum routing option was chosen to account for the 2-3 day travel time from the top of the basin to Hetch Hetchy Reservoir. PRMS has a plotting routine that can plot most of the state variables and water or heat fluxes, including all the input data. Daily SWE at five snow sensors was included in the input data file so that the traces could be plotted and compared to the HRU in which they were located. The basin snowdepth, SWE traces in two subbasins, the five snow sensors, and simulated and observed Hetch Hetchy inflow are shown in Figure 5.

RESERVOIR OPERATIONS

Reservoir operators strive to meet multiple goals as the snowmelt season begins on approximately April 1, the nominal date of peak snowpack. Most reservoirs have hydropower generation capability below them, so maximizing revenue by drafting water is an important goal. Draft rates for power generation are limited by the capacity of the tunnels, canals, and powerhouses, so maximizing generation means starting drafts as early as possible in the season. Forecasting of total April-through-July runoff (AJRO) provides the information needed to make the decision as to when drafts for generation can start. The operator must balance the amount of water needed to fill the reservoir, make required streamflow releases for the downstream aquatic ecosystem, and also drafts that are required for water supply or other beneficial uses. As snowmelt declines in May, June, or July (depending on the water-year magnitude), the reservoir should be nearing full, power generation should be at a maximum, and releases or spills should be declining in a pattern that mimics the natural inflow. Ideally, the reservoir reaches the top of the gates on the spillway as inflow matches the sum of drafts for power, water supply, and streamflow releases. Power drafts then decline as inflow continues to decrease, and reservoir level finally begins to drop when snowmelt is at a minimal level and as late in the season as possible. During the final month of snowmelt, daily forecasting models are used to predict inflow rates during the next 5-10 days, depending on the length of weather forecasts an operator believes to be useful. For short-term forecasting, HHWP operators use both a commercial daily forecast model (VISTA) as well as a prediction tool produced by the National Weather Service's California-Nevada River Forecast Center (NWS). Predicted inflow is plotted along with drafts for power, valve releases, based
on the starting value of storage in Hetch Hetchy, as shown in Figure 6. Power draft is at the maximum, so planned releases were increased on 26 May for 2 days to slow down the fill rate and delay reaching the 360,000 acre foot (AF) capacity of the reservoir.

Uncertainty arises from several sources, but predominantly the disparity between the two predicted inflow rates, and the weather forecast accuracy in excess of 5 days. In Figure 6, the NWS inflow rate is about 1000 cubic feet per second (cfs) greater than the VISTA inflow rate, leading to a much more rapid fill rate. If the NWS rate turns out to be correct and releases are made as shown, a significant spill will result. If the total volume of snow in the basin was known as early as April 1, power drafts might have been started earlier, and the high release of 21 May might have been continued longer or stepped down more gradually. If weekly or biweekly information on the remaining snowpack had been available during this year, beyond the few point measurements as snow sensors, a higher level of certainty on the inflow forecasts would have been possible.

Accurate measurements of basin-wide volumetric SWE are most helpful in normal and below-normal water years. In years with over 110% of normal AJRO, the smaller mid-elevation reservoirs will normally fill and spill. Depending on the timing of the storms, operators may not be able to predict the AJRO amount until late in the season and therefore not be able to start the early power draft that would draw down the reservoirs to make room for the inflow and maximize revenue. Conversely, if several large storms occur early in the year, such as in 2006, operators know they will fill and spill and can start drafting by February. However, even in large years, weekly or bi-weekly basin SWE would be of great use during the last half of the snowmelt recession.

Figure 6. Daily forecasted inflow from VISTA and NWS models, planned powerdraft and valve releases, and the calculated fill rates based on the inflow forecasts (from A. Mazurkiewicz and M. Tsang, HHWP)

PRELIMINARY ASO RESULTS AND DISCUSSION

The first two flights by the ASO team have been completed, and preliminary basin SWE have been computed. The results from the April 3 flight estimated that the amount of SWE above Hetch Hetchy was 218,087 AF. The results from the April 10 flight estimated that the amount of SWE was 205,434 AF, showing a loss of 12,653 AF. Inflow into Hetch Hetchy during that week was 17,242 AF, indicating that melt from the prior few weeks of very warm weather was in transit in the basin.
When more flights and information on the SWE decline versus the reservoir inflow are available, it will be of great interest to examine patterns of inflow against the volumetric loss in SWE. PRMS runs will be performed that are based on the current calibration, and then ASO data will be inserted into the model to replace the simulated SWE in the HRUs, and comparisons of runoff rates and volumes will be made. Also, the model's overall formation of a snowpack and then its melting pattern will be able to be compared to the volumes of SWE that are measured by ASO. While the model is well calibrated and matches the snowmelt hydrographs quite well, it is possible that PRMS is storing water as snow and releasing it when it should be stored as soil and groundwater. Recalibration of the PRMS model may be warranted once new ground validation data on distributed SWE are available.

**CONCLUSIONS**

The Airborne Snow Observatory will collect data at a level of accuracy that has never before been available to runoff modelers, runoff forecasters, and reservoir operators. Snow extent, snow depth, and albedo will be available at approximately weekly intervals and in a timely manner so that they can be used in forecasting models to improve reservoir operations. Reservoir operators need these data to allow them to meet the increasing demands for water due to climate change and population growth. Operators also need better data to allow them to maximize power generation and minimize the effects of reservoir releases on downstream aquatic ecosystems. ASO can deliver timely SWE and albedo information that will be especially valuable in below-normal water years, but the SWE and albedo information will be very valuable during the recession limb of the snowmelt hydrograph in all years.

**LITERATURE CITED**


