CAN SATELLITE SNOW MAPS, GROUND MEASUREMENTS AND MODELING IMPROVE WATER MANAGEMENT AND CONTROL IN THE KINGS RIVER BASIN, CALIFORNIA?

EFFORTS TOWARD FINDING THE ANSWER

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ABSTRACT

The U.S. Army Corps of Engineers has begun implementation of a new operational system for monitoring snow conditions, modeling changes to the snow, and routing snowmelt runoff through the stream and reservoir system of a watershed. This system has as its basis four functional elements, including a graphical user interface for displaying, manipulating, and analyzing data; a system for mapping snow extent and water equivalent; a spatially distributed snow model, and a grid-based runoff routing model. The user interface links snow maps and model results, as well as Corps of Engineers and other agency databases. We use measurements from the Advanced Very High Resolution Radiometer (AVHRR) to make maps of snow extent represented as fractional extent per pixel. When merged with interpolations of ground-based measurements, these maps estimate the spatial distribution of water equivalent. A grid-based distributed snow model makes independent estimates of water equivalent and melting, which feeds the runoff routing model. The satellite-derived product will provide the basis for updating model results. Our demonstration area, the Kings River watershed, lies in the Sierra Nevada, California. This paper describes the functional elements and integration of these elements, the current status of the project, and future directions.

INTRODUCTION

In the western United States, snowmelt contributes approximately 80% of total runoff. Temporal variability in snowfall at interannual scales can have dramatic impacts on land cover, agriculture, and human and nonhuman populations. The California drought of 1987–1992 resulted in severely depressed water tables, increased fire frequency, and broad societal changes such as statewide trends to more use of water efficient appliances and construction of expensive plants for seawater desalinization. The spring and summer of 1998, an El Niño year, saw large snowfall in the Sierra Nevada, with a snowpack growing into early June, past the mean date of peak accumulation near April 1. By July 14, most California Cooperative Snow Survey sensors had melted free of snow, while more than 25% of the total runoff for water year (WY) 1998 had yet to come in many basins. This proportion of such a large water year total holds enormous value to reservoir managers and the growers in the nationally important San Joaquin Valley. As population increases in the United States, particularly in the water-sensitive West, our predictive capacity for timing and magnitude of melting becomes more critical.

Current forecasts of snow runoff volume and peak flows from montane watersheds in California and other areas throughout the western United States use spatially lumped statistical models that link indices of snow volume and melting rate to stream flow (e.g., *Peck,* 1976). Experience shows that river flow forecasts have reasonable accuracy for any WY close to the mean of the historical record. While this family of statistical models for runoff forecasting makes use of data sets with several decades of observations, problems can arise when climatic conditions vary greatly from the historical mean. It appears that systematic trends in runoff timing over the last few decades may represent changes in the climate of California (*Dettinger and Cayan*, 1995; *Pupako*, 1993; *Roos*, 1991, 1990). Trends appear in the records of snow water equivalent (SWE) as well, represented by less snow accumulation at low elevation, compared to rainfall, and more snow at high elevations (*Johnson et al.*, 1997). These trends may have two consequences: (1) greater probability of rainfall in the winter during periods of large snow extent in areas below timberline, and (2) less snow cover in forests at the onset of spring melting. Both could lead to increases in the frequency and magnitude of peak flows (*Kattelmann*, 1991).

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Public pressure to improve runoff forecasts, water management, and apportionment continue to increase, which has motivated development of improved techniques to monitor the Sierra Nevada snow cover and track its changes. The U.S. Army Cold Regions Research and Engineering Laboratory's Remote Sensing / GIS Center (RS/GISC) in collaboration with the U.S. Army Corps Hydraulic Engineering Center (HEC) continues to develop improved methods to monitor and model snow cover and runoff displayed in a common spatial context. Spatial data and spatially distributed models have not yet seen wide use or acceptance in operational forecasts of snowmelt runoff, but as competition for water resources and requirements for precision water control increase, the potential of spatial data for forecast guidance and assessment of basin condition has shown increasing promise. This paper describes current development of tools for providing links to Corps of Engineers databases and models, analyzing and displaying hydrographic data in a spatial context, monitoring the snow cover, and estimating runoff. We have formed a team of practitioners, scientists, and engineers in a cooperative research and development effort to improve estimates of snowmelt runoff in the Kings River basin, California, for future use in water management and control.

OVERVIEW OF OPERATIONAL SNOW MONITORING SYSTEM

We have the goal to develop and implement a snow monitoring system that includes the ability to display, manipulate, and analyze map-based snow products provided to the system in near real-time, suitable for water management and control. The initial system includes a basic modeling capability to predict snow cover conditions, which provides daily updates to products derived from remote sensing. The system also includes a calibrated model for predicting streamflow runoff, which forms a basis for decision making. Four functional elements compose the system: (1) CorpsView, a graphical user interface (GUI), customized for U.S. Army Corps District use, that serves as a front end to a commercial geographic information system (GIS); (2) snow map products, including snow extent and snow water equivalence; (3) the Distributed Snow Process Model (DSPM), a computational system for estimating the snow conditions in a large number of distributed cells that describe a watershed or watershed subbasin; and (4) the Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS), a runoff storage and routing model. In the following section we briefly describe each of these elements, the status of the project, and directions of future development.

DATA ANALYSIS, MANIPULATION, AND DISPLAY—CORPSVIEW

We have found that development of a GUI customized interactively with the users to respond to a specific operational situation facilitates the transition of recently developed technologies. CorpsView provides our product delivery mechanism, with which users access and visualize data, manipulate spatial coverages or time series, and exploit historical design studies we have prepared for selected water years. CorpsView does this from within a geographic map interface (*Ochs*, 1997), an extension to the UNIX ArcView[3] GIS package (Environmental Systems Research Institute [ESRI]).

CorpsView contains tools developed by RS/GISC to display data from various sources including time series from the Hydrologic Engineering Center – Data Storage System (HEC-DSS), inundation data from the Hydrologic Engineering Center – River Analysis System (HEC-RAS), Water Control Data System (WCDS) model results, and results from our snow mapping modeling and runoff routing functional elements. Users can select from multiple map views of project areas, select stream flow or precipitation gages within these views to obtain real-time DSS data in plot or tabular form, and load inundation maps generated through the WCDS to spatially overlay with base map data. For example, Figure 1 shows a version of the map base with a graphics window, which shows plots of station air temperature and snow water equivalent from the DSS. CorpsView can use all spatial data supported by ArcView, including ArcView Shapefiles, ARC/INFO coverages (ESRI), digital line graph (DLG) images from the U.S. Geological Survey, computer aided design (CAD) data, remote sensing imagery, and scanned photography.

SNOW EXTENT AND WATER EQUIVALENT—SNOW MAPPING

Cloud cover permitting, we currently map subpixel "snow-covered area" (SCA) on a daily basis using imagery from the Advanced Very High Resolution Radiometer (AVHRR) (*Rosenthal*, 1996). Five steps make up this pro-

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[3] Use of product names, trademarks or manufacturers' names does not constitute endorsement by the U.S. Army Corps of Engineers.

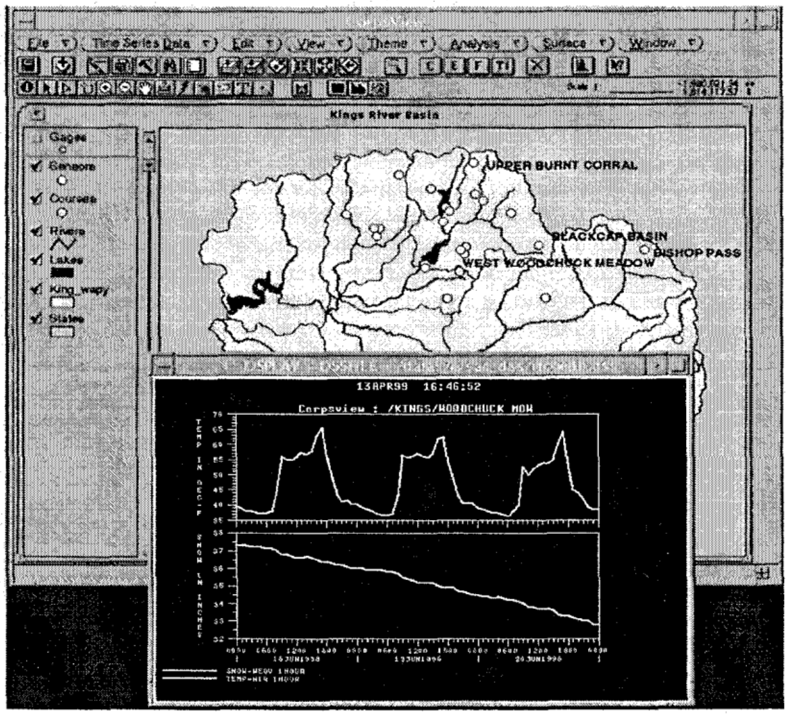


Figure 1. Example of main CorpsView window and graphics box showing tools for data access, display, manipulation, and analysis. Graphics box shows air temperature and snow water equivalent retrieved from DSS.

cessing. First, we interactively georegister the imagery using a variety of reference images including vector-based hydrography, digital elevation models, and previously registered images. The registration step also bins the output into 1.0-km pixels. After calibrations of the raw data and atmospheric correction using 6S (*Vermote et al.,* 1997), the second step separates the reflectance component of channel 3 (3.5–3.9 μm) from the emittance component using the temperature from channel 4 and assumptions about the surface emissivity to make a new, synthesized channel 3. As a third step, we interactively form a cloud mask using a variety of threshold tests on individual bands and band combinations, then merge this mask with a water mask formed from the GIS hydrographic coverage. Occasionally, this step requires manual image editing. In the fourth step, the algorithm first masks areas with clouds and areas too warm to contain snow using a temperature set by the user. The algorithm then projects reflectance from channels 1 and 2 along with the synthesized channel 3 to form a 2-D data cloud in the plane of the first two principal components, to which it fits a convex hull. Vertices on the convex hull represent candidate spectral endmembers, which the algorithm uses to unmix pixels using a linear mixture model. The algorithm applies a threshold of 2% RMS error to decide whether to keep the candidate endmembers and mask fitted pixels from further analysis, or to reject them and select new vertices on the hull. Typically, the unmixing process maps more than 99% of the pixels in a scene with fewer than 12 successive iterations of endmember selection. At the end of iteration, the fifth step compares accepted endmember sets with a spectral library to adjust for fractional purity. Figure 2 shows two SCA maps from water year 1998 (WY98), superposed on a gray-level image of south-central California.

The SCA data require further processing to yield products that have value to snow monitoring for Corps of Engineers water management and control applications. Since cloud cover can mask snow and incomplete snow maps add an unnecessary level of complexity at the user end, we use two techniques to estimate SCA in masked areas. First, we form composite SCA maps over periods of 2–3 days depending on the persistence of clouds, taking the average SCA observed in each pixel. Second, if clouds prove persistent over some areas of the watershed, we relate observed SCA in the composite maps to the independent variables describing elevation, slope, aspect, location, etc., using a regression-tree model, then run the vectors of independent variables down the tree to estimate SCA in masked areas (*Elder et al.*, 1998a). Finally, we bin the SCA values to the 1-km grid of the snow model.

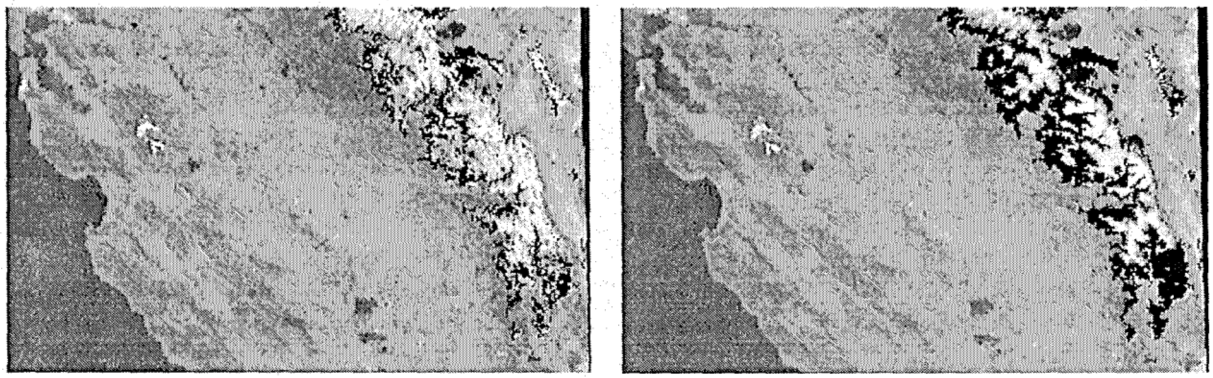


Figure 2. Images showing snow cover in the southern Sierra Nevada, California, on 19 May (left) and 28 June (right) 1998, composited with an image showing San Francisco Bay in the upper left and the California coast. Snow lies within the black outline, which shows the maximum extent for the season. The gray values represent snow extent per pixel: black to white shows cover from 0–100%.

For operational application we have developed methods to map SWE (snow water equivalent) by merging interpolated snow sensor measurements of SWE (*Winstral et al.,* 1998) with satellite-derived SCA. The interpolation method uses weighted inverse elevation differences. Reanalysis of interpolation surfaces from a previous experiment (*Elder et al.,* 1998b) provided the weights used in this method. Sensors scattered through the western U.S. measure SWE using snow pillows, which measure the mass of the overlying snow. These sites have characteristics that make the measurements suitable for index modeling (i.e., more snow than nearby areas), so that spatial fields interpolated from these data tend to overestimate the total SWE on the area. While the general trends of the interpolated SWE follow ground-based surveys (*Elder et al.,* 1995, 1998b), multiplication with subpixel SCA greatly improves overall estimation of the total SWE by introducing the spatial patterns of bare area. In our project, we multiply interpolated ground-based SWE with SCA from AVHRR to produce an operational product representing corrected SWE in each 1-km cell.

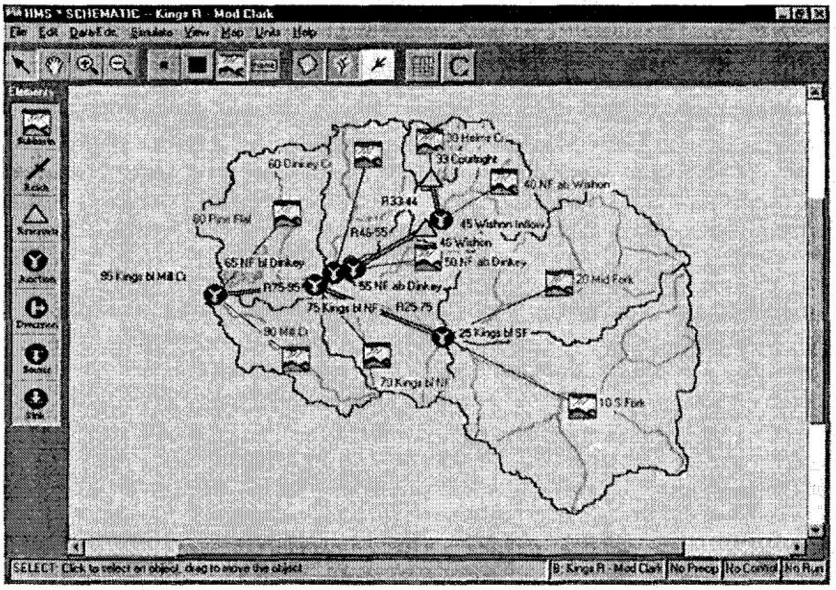
MODELING THE SNOW MELT PROCESS —DSPM

The Distributed Snow Process Model (DSPM) consists of a computational framework for estimating the snow conditions in a large number of distributed cells that describe a watershed or watershed subbasin (*Daly et al.,* 1999). The DSPM uses the standard geographic grid proposed by HEC, which defines cells for carrying out one-dimensional calculations of snow condition and melt production. These cells have equal area throughout the coverage using the Albers equal-area map projection. Depending on the modeling requirements, the grid resolution can range from regular squares 10 m on a side to 10 km, with a 2-km resolution as default. The standard hydrologic grid has the advantages of equal area property of the projection, the universal support of the Albers equal-area projection by nearly all GIS software packages, the wide use of Albers projection for a number of national mapping products, and the ease of graphical display. The DSPM cycles through all cells composing a subbasin during each time step, managing the data flow into and out of the snow routine, as well the attributes of each cell. Currently, the DSPM uses SSARR_grid, described below, to simulate the snow processes in each grid cell. The computational framework of the DSPM allows other snow process models to be used in place of, or in conjunction with, SSARR_grid. DSPM requires of any snow model the ability to exchange information on all state variables for each time step for each cell.

We developed SSARR_grid from the "Snow-Band" snowmelt computation, part of the Streamflow Synthesis and Reservoir Regulation (SSARR) model (e.g., *Speers et al.,* 1979; *Cassell and Pangburn,* 1991; *Rockwood and Kuehl,* 1993). The routine estimates the liquid water available at the soil surface for a cell for one time step. The time step may range in time interval up to 24 hours. Interpolated precipitation and air temperature drive surface processes of accumulation and melting. Vegetation on a model cell may intercept precipitation before it reaches the snowpack or soil surface. SSARR_grid simulates the accumulation of precipitation on the foliage, and evaporation from the foliage. Therefore, interception represents a loss from precipitation. Currently, the temperature index method predicts snow melting with either of two options to describe the melting rate: a function of an antecedent temperature index or a predetermined function of month of the year. Heavy rain events trigger a separate melt rate coefficient. As an option the model includes a table giving ground melt rate as a function of month of the year. This melt occurs at the bottom of the snowpack independently from precipitation and other snow surface or volume factors. At any point in time an antecedent temperature index describes the cold content of the snowpack, which accumulates during cold events. The model must "satisfy" the cold content before melt runoff can occur. A simple "bucket" concept provides the mechanism to retain liquid water in the snow against drainage processes until the water content reaches a user-set threshold.

SNOW RUNOFF MODELING AND ROUTING—HEC-HMS

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), the Corps "next-generation" software for precipitation-runoff simulation, provides a variety of options for simulating precipitation-runoff processes and includes its own GUI (Figure 3), integrated hydrologic analysis components, data storage and management capabilities, and graphics and reporting facilities. HEC-HMS provides calculations relating to the unit hydrograph and hydrologic routing, capabilities similar to HEC-1 (*Hydraulic Engineering Center,* 1990). HEC-HMS also includes the modified Clark method, a linear distributed-runoff transformation that accepts gridded snowmelt or rainfall data (*Peters and Easton,* 1996). This represents a significant improvement over earlier precipitation-runoff calculations in the HEC model family. The modified Clark method requires dividing the basin into grid cells to track snowmelt and losses uniquely for each cell. DSPM estimates the snowmelt arriving at the soil surface in each cell, as described above. The modified Clark method lags and routes snowmelt runoff from each cell to the basin outlet through a linear reservoir. The method sums outflows from the linear reservoir and adds baseflow to obtain the total snowmelt hydrograph.



SELECT: Click to select an object, drag to move the object

Figure 3. Main window of graphical user interface for HEC-HMS showing schematic diagram of Kings River basin.

FUNCTIONAL INTEGRATION AND FUTURE DIRECTIONS

The snow mapping and modeling products use a common database to which CorpsView provides access. We have installed an interim version of CorpsView at the Corps Sacramento District office, trained their personnel in its use, and worked with them to develop custom tools. We feel this represents a critical step in bringing research results toward operational use, in particular since transition from current methods to new ones takes some time. That is, by providing the end users with visual and spatially indexed means to import, display, manipulate, and analyze measurements and model results, we encourage use of the various products and feedback that helps users gain confidence in the new methods and helps us establish future research priorities.

We have designed methods to process satellite imagery for mapping snow extent at sub-pixel scale and implemented these techniques in both an operational time frame and in production and processing of archived data. During winter months we follow a biweekly map publication schedule, increasing in frequency during the ablation periods to between three and seven days. We have developed methods to interpolate snow course and sensor measurements to spatial fields for merging with satellite-derived extent to produce maps of SWE. CorpsView, DSPM, and HEC-HMS use these products for visual display and analysis, update of the snow model, and comparison of runoff volume estimations. All spatial products used in monitoring the snow cover, including estimated SCA and SWE, predicted SWE, air temperature, and precipitation transfer to the same 1-km grid cell size. Both the SCA and SWE maps provide the means to compare through CorpsView current and forecasted conditions with previous design years (see below), allowing the user to compare spatial-temporal snow distribution as well as streamflow.

We have two methods for estimating the spatial distribution of SWE, the maps derived from AVHRR and interpolated ground observations, and the predictions from the distributed snow model. Both have different uncertainties: the errors associated with degree-day approaches and bucket models have seen wide examination in the literature, and the SWE obtained from merging ground observations and AVHRR-derived snow extent may likely overestimate total volume, as described above. But on a cell-by-cell basis, the AVHRR-derived SWE maps will show less ambiguity as snow depletes completely. We assume that if the snow mapping algorithms do not detect any snow, no snow in fact exists on an area, so if the model shows snow remaining, either the cell had too much snow or less-than-actual melting. On the other hand, if the model reduces snow to zero but the AVHRR algorithm detects snow, either the cell should receive more snow or the model may have melted the correct amount of snow too rapidly.

We have under development design studies for WY93, WY95, WY97, WY98, and WY99 for which ongoing analyses attempt to reconcile the two estimates of the spatial distribution of SWE, primarily through calibrating the melt factor in a cell-by-cell basis. The result will consist of time-series of melt factor maps that will serve in the operational forecast mode until we have tested more physically based approaches. This leads to our expectation of smaller adjustments to forecasts brought about by SWE map differences. Thus the satellite-derived products can provide a credible means to update the snow model, and hence update runoff forecast, to the extent that these products allow adjustment of runoff volume to date.

The users will see an operational capability for WY00, and in the near term we have the following research goals:

- In WY95 and WY98, significant SWE remained on the Kings River basin after most of the snow sensors lost snow. Using measured flows we will develop interim methods to relate SWE to SCA using depletion curves (e.g., *Martinec and Rango,* 1981) and enhanced methods to describe SWE distribution (e.g., *Winstral, et al.,* 1999).
- Forests mask snow from view, and the peak flows draining rivers on the west side of the Sierra Nevada tend to occur while snow remains below the timberline. We can show that a geometric-optical model of the effects of forest on a viewable gap fraction can lead to adjustments to SCA maps accounting for canopy cover. We will implement these techniques as our estimation of forest properties improves.
- The estimates of total SWE on subbasins in the Kings River catchment have sensitivity to the accuracy of image georegistration. During construction of design studies, we will carry out sensitivity analysis on required georegistration accuracy at scale of Kings River subbasins and model domains and document the climatology of ground control points.
- We use SCA derived from Landsat TM (*Rosenthal and Dozier,* 1996) to provide benchmark testing of the accuracy of the AVHRR-derived SCA. We will investigate use of Landsat TM, ETM+, and other data with high spatial resolution to improve/update AVHRR-SCA time series in both the design studies and the operational mode.

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