**Summary of Research and Final Report**

NASA Grant # NNG 05GB1

Project Title: Improving Water Supply Forecasts in the Western U.S. Using NASA Earth Science Products

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## 1. Introduction

In arid/semi-arid areas of western U.S., water managers rely on seasonal forecasts of water supply to make important decisions about the management of water resources for urban, industrial, agricultural, and environmental uses. The Watershed and River System Management Program (WaRSMP) is a joint United States Geological Survey (USGS) and United States Bureau of Reclamation (USBR) effort to develop decision support systems (DSS) to aid water resource managers in major river basins throughout the western U.S. The DSS tools consist of a database, hydrologic models, and river routing and accounting models. The primary objective of the DSS development and implementation is to provide the water managers with the ability to estimate short term and seasonal forecasts of streamflow into reservoirs and the associated impacts of different operational scenarios on streamflow deliveries to downstream water users.

In most WaRSMP basins, the primary source of water is from spring runoff of snowpack in mountainous areas. In these basins, streamflow forecasts are generally made using empirical relationships between historical observations of precipitation, snow water equivalent, and streamflow or with more

physically based hydrologic models to simulate (at some conceptual level) the water and/or energy balance in a watershed. The empirical approach is limited to watersheds with sufficient historical hydrologic observations and to conditions observed in the historic record (floods, droughts, land use change, climate change, etc.). The physically based hydrologic modeling approach requires spatial and temporal estimates of model inputs (e.g., precipitation, temperature, solar radiation, etc.) and parameter values to simulate current and future hydrologic conditions using the USGS Precipitation Runoff Modeling System (PRMS) (Leavesley et al., 1983) within the USGS Modular Modeling System (MMS) (Leavesley et al., 1996a and 1996b). In most areas of the western U.S., observations of model input variables are sparse and only available at point locations. Regional relationships are often used to transfer the point observations to and throughout the area of study. Model parameter estimation and evaluation also can be difficult due to limited availability of observations of spatial variability of important hydrologic information (e.g., soils, vegetation, streamflow, precipitation, snow water equivalent, temperature, etc.).

The main goal of this study was to investigate the use of NASA Earth Science products to improve the accuracy of hydrologic models used to produce streamflow forecasts in WaRSMP basins located in western U.S. In collaboration with scientists from the NASA Hydrologic Sciences Branch, researchers from the Desert Research Institute (DRI) identified several different NASA Earth Science products that may contain information that could lead to improvements in hydrologic models used to produce water supply forecasts in the western U.S. Because the simulation of the snowpack (both accumulation and melt processes) is so important to obtaining accurate streamflow response in WaRSMP basins, NASA estimates of snow variables became the main focus of this project. Initially, this project was proposed as a three-year effort to look at a variety of different NASA estimates of snow variables in WaRSMP basins in the Truckee River and Rio Grande systems. In the first year of the project, the primary focus was investigating the use of NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) for estimating fractional snow covered area (SCA) with the WaRSMP operational hydrologic model of the Sagehen Creek basin within the Truckee River system. In years two and three, the plan was to extend the MODIS SCA effort to other basins in the Truckee and Rio Grande Systems as well as investigate other NASA estimates of snowpack variables. Unfortunately, funding for years two and three was not available and the study was limited

to the MODIS SCA study in the Sagehen basin. The following describes the methods used and the findings from the first year of the study.

## 2. Methods

a. Study Area

The Truckee River is the primary water supply for urban areas of Reno, Nevada, and Nevada's largest agricultural area, the Newlands Project. The majority of water in the Truckee system originates as snow in the headwaters of the system above the USGS surface gaging station at Farad, CA (Figure 1). Accurate streamflow forecasts at the Farad station are critical to the successful operation of the reservoirs within the Truckee River system, by the USBR, to satisfy the downstream municipal and agricultural demands. The Sagehen Creek experimental watershed located in the Truckee River basins was selected as the initial study area for this project due to the absence of flow controls, an extensive streamflow record, and the existence of SNOTEL and National Weather Service (NWS) Co-operative weather stations within the watershed.

The Sagehen Creek watershed is a Pacific Southwest Research Station Experimental Forest located within the Truckee River basin, which straddles the western Nevada, eastern California state line just north of Lake Tahoe (Figure 1). The Sagehen Creek watershed area is 27.7 $km^2$ with an elevation range of 1,960 – 2,536 m. Streamflow is largely unobstructed and exits the watershed to the east at the USGS surface water station. Fur and pine forests dominate vegetation within the basin with grassy meadows in the low-lying areas adjacent to Sagehen Creek. The basin is about 90 percent forested and 10 percent meadow (Rundel et al., 1977; Andrews and Erman, 1986). Soils in the watershed are classified as Alfisols and consist of deep, well drained soils developed in material weathered from volcanic rocks and contain up to 90 percent rock fragments. A typical soil profile contains a dark brown, gravely/sandy loam that is up to 60 cm thick over a light brown sandy loam that extends to 115 cm depth (Johnson and Needham, 1966).

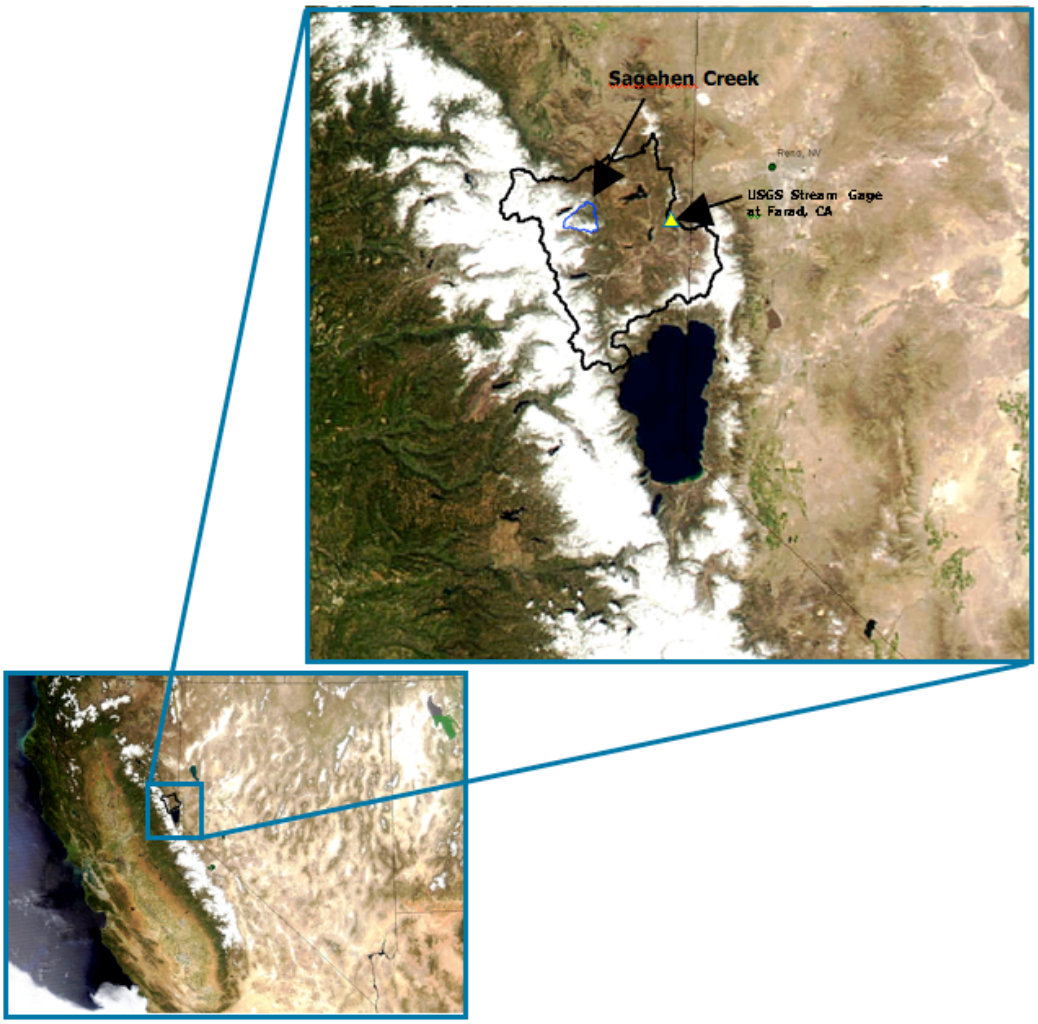


**Figure 1: Location of Sagehen Creek within the Truckee River system.**

b. Hydrologic Modeling of Sagehen Creek with PRMS

The USGS Precipitation Runoff Modeling System (PRMS) (Leavesley et al., 1983), is a distributed-parameter, physical process, hydrologic model that allows the user to partition the watershed into Hydrologic Response Units (HRUs) based on important hydrologic features within a watershed (e.g. soil type, vegetation type, slope, aspect, etc.), to generate daily estimates of streamflow. Each HRU requires daily estimates of input variables (e.g., precipitation, temperature, solar radiation, etc.) and simulates a variety of important hydrologic processes (e.g., runoff, ET, groundwater, snow accumulation and melt, etc.). PRMS simulates snow covered area (SCA) using a functional relation between the depletion of snow water equivalent (SWE) and the depletion of SCA (Anderson, 1973).

PRMS has been previously applied in the headwaters of the Truckee River Basin, including the Sagehen Creek watershed, as part of the USBR/USGS Watershed and River Systems Management Program (WARSMP) as an alternative approach to real-time simulations and forecasts of streamflow. The streamflow simulations and forecasts are used as input to a river operations model of the Truckee River system. Figure 2 illustrates the current WARSMP PRMS simulated streamflow vs observed streamflow of Sagehen Creek for water years 2001-2004.

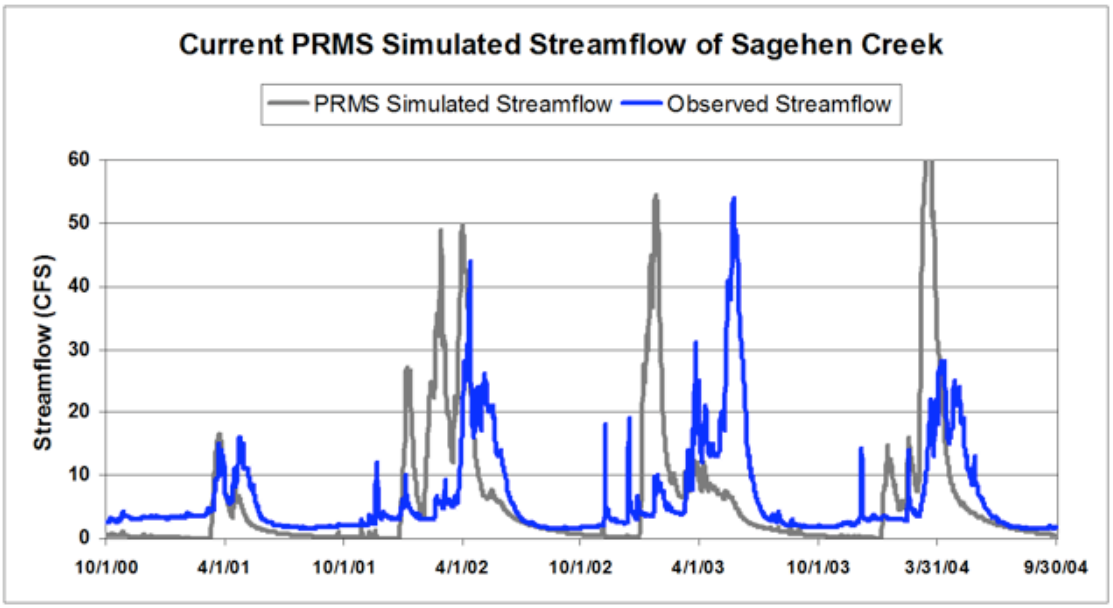


**Figure 2: Observed streamflow (blue line) at outlet of Sagehen Creek versus streamflow simulated with PRMS (gray line).**

Visual inspection of the observed and simulated streamflow in this figure reveals serious timing errors in the simulated streamflow during the spring melt season – the simulated streamflow is systematically leaving the watershed too early. The most likely source of these early streamflow timing errors is directly related to either the PRMS parameters values associated with the simulation of snowmelt within the watershed or the methods used to distribute observed point measurements of precipitation and temperature to the PRMS model HRUs throughout the watershed. Unfortunately, as is the case in most mountainous watersheds in the west, the paucity of ground-based observations of snow water equivalent (SWE) precludes a detailed investigation of spatial and temporal errors in the PRMS

simulation of the snowpack processes and precipitation and temperature distribution methods. In this study, we utilize MODIS fractional SCA estimates as a surrogate for "observed" SCA to compare with PRMS simulated SCA values to evaluate a different precipitation and temperature distribution method. The goal of the experiment is to get improved fits to observed streamflow and MODIS fractional SCA estimates, thus resulting in an improved simulation of the Sagehen watershed behavior.

c. MODIS Fractional Snow Covered Area Calculation

Spaceborne operational remotely sensed snow cover products have been produced daily from a variety of satellite platforms including the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) at a spatial resolution of 1 km, the Special Sensor Microwave/Imager (SSM/I) EASE-grid at a resolution a resolution of 25 km, and the Geostationary Operational Environmental Satellite (GOES) and SSM/I snow cover products at a resolution of 5 km. These snow cover products are all binary gridded products (snow/no snow). For regional scale hydrologic modeling these product provide sufficient resolution for data assimilation and comparative analysis, however for mesoscale watershed modeling, higher resolution products that represent SCA in a fractional form are preferred. A popular algorithm named SNOWMAP (Hall et. al., 1995), can deliver binary (snow/no snow) SCA estimates at a high resolution of 30 m using Landsat imagery. However, Landsat images do not provide sufficient temporal information because of a 16-day return period making it difficult to obtain cloud free periods. As an alternative to Landsat derived SCA, the Moderate Resolution Imaging Spectroradimeter (MODIS) on board Terra and Aqua can provide daily binary SCA estimates at 500 m resolution. For mesoscale hydrologic modeling and evaluation in complex terrain, however, 500 m resolution SCA images that are binary do not provide the resolution required for an accurate evaluation. Recognizing this limitation, a regression model was developed to estimate fractional SCA (Salomonson and Appel, 2004). The regression model is based on the correlation between the average of Landsat 30 m resolution binary SCA pixels that are within 500 m resolution MODIS Normalized Difference Snow Index (NDSI) pixels.

To estimate fractional SCA in the Sagehen Creek watershed daily MODIS images for water year 2003 were downloaded from NASA's Earth Observing Data Gateway in which cloud free images were manually

selected. An algorithm was developed in ARC/INFO to select images with view angles less than 30 degrees, apply a land/water mask, and calculate the NDSI and fractional SCA using regression model, described by Salomonson and Appel (2004);

$$NDSI = \frac{\rho_{MODIS\,Band\,4} - \rho_{MODIS\,Band\,6}}{\rho_{MODIS\,Band\,4} + \rho_{MODIS\,Band\,6}}$$

and,

$$Fractional\ SCA = 0.06 + 1.21(NDSI).$$

Where, $\rho$ is satellite reflectance corrected for solar zenith angle, $\rho_{MODIS\,Band\,4}$ is 1.6 $\mu$m, visible, and $\rho_{MODIS\,Band\,6}$ is 0.55 $\mu$m, short wave infrared. This algorithm was used to estimate SCA for each of the HRUs in the PRMS model of Sagehen Creek for 25 different cloud free days within the 2003 water year. Figures 3 and 4 show a graphical representation of the calculation of NDSI and fractional SCA with the algorithm for a single day and Figure 5 shows the scale of the resulting MODIS derived SCA estimates compared to the HRUs (shown in yellow) in the PRMS model of Sagehen Creek.

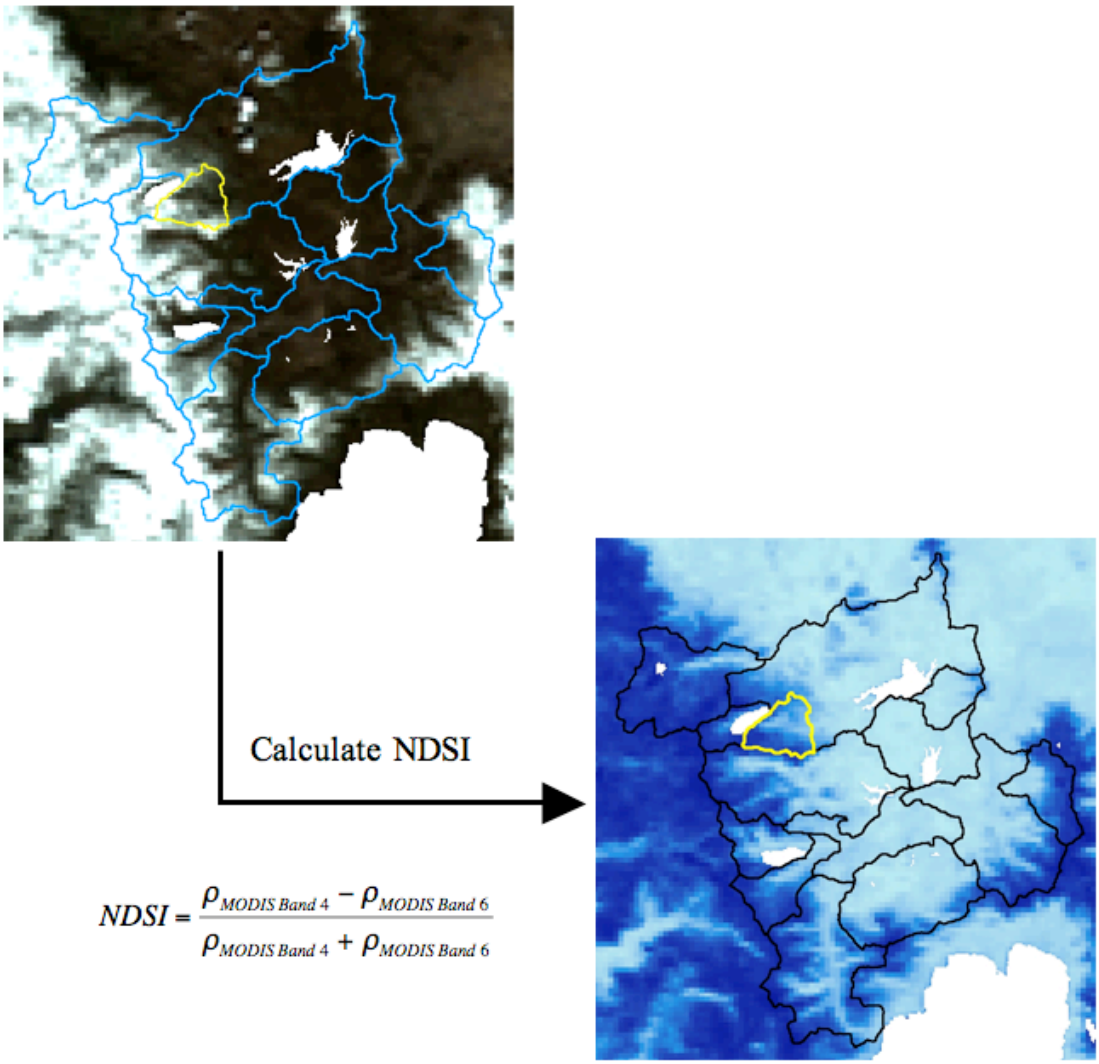


**Figure 3: Graphical example of calculation of NDSI from MODIS imagery.**

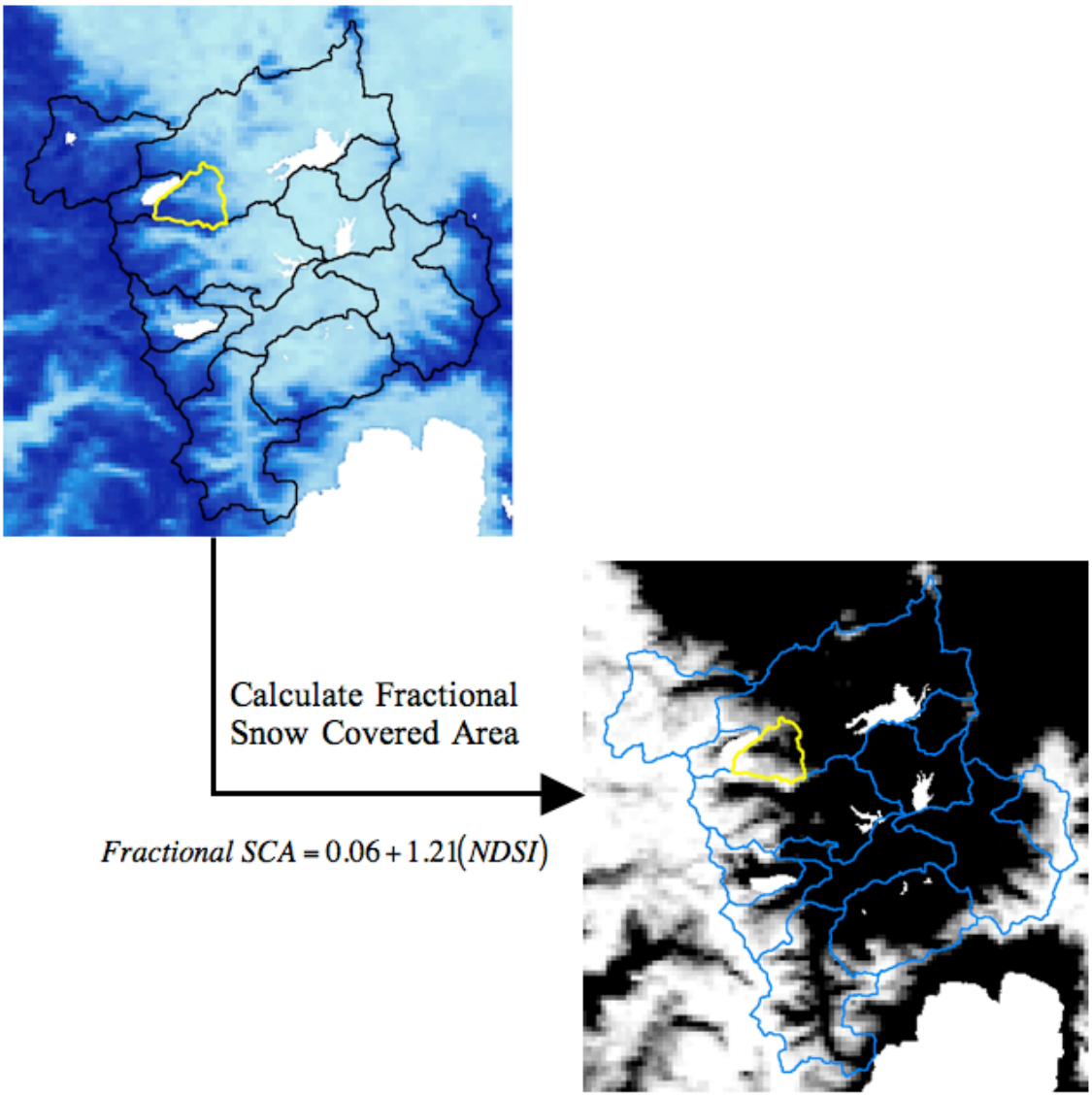


**Figure 4: Graphical example of calculation of Fractional SCA from NDSI values.**

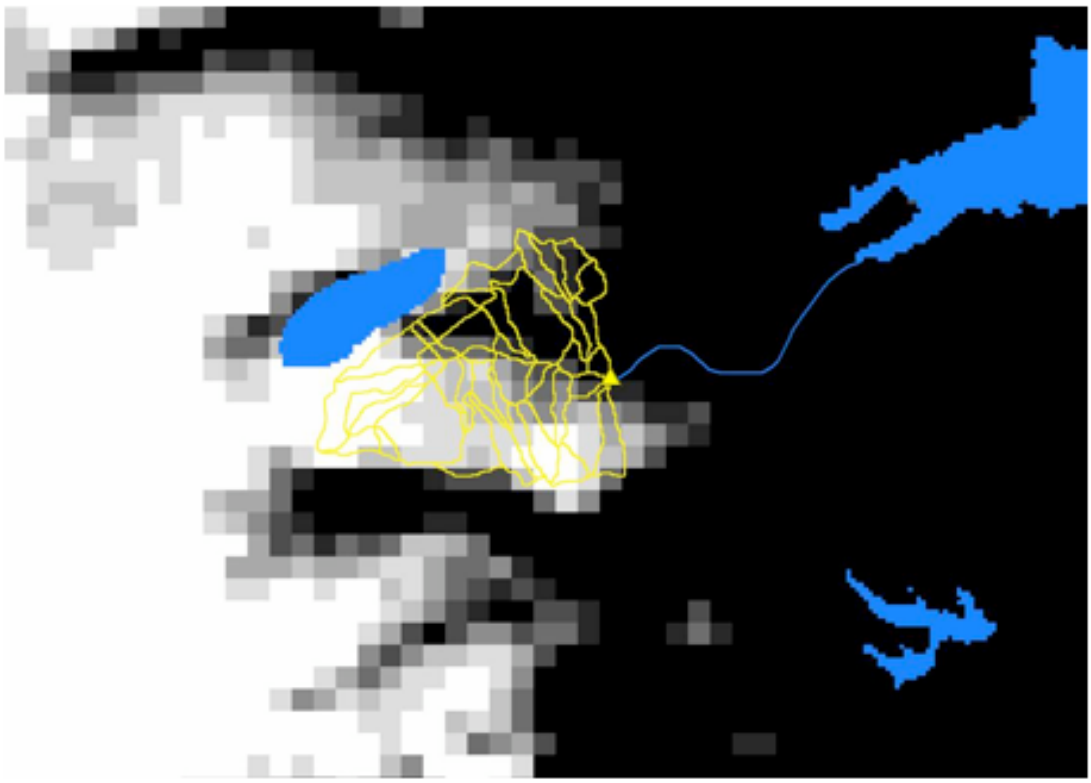

**Figure 5: Fractional SCA estimated from NDSI with PRMS HRUs for Sagehen Creek (yellow).**

## 3. Results

a. Evaluation of Existing PRMS Model with MODIS SCA Estimates

The SCA estimates from the algorithm using MODIS images and the PRMS model simulation of Sagehen Creek over the 2003 water year are shown in Figure 6. Notice that in the plot the SCA is plotted for both the MODIS and PRMS approaches at the watershed scale and below the plot differences between PRMS and the MODIS estimates are shown at the HRU scale. The basin scale plot indicates that the PRMS model simulations are generally highly variable throughout the time period and underestimate the MODIS values during the spring snowmelt period. At the HRU scale, notice the differences are highly variable on both the north and south facing slopes (e.g., 3/05) and after the snow melts on the south facing slopes (e.g., 5/22) large errors occur on the north facing slopes. Based on these results, and the fact that the difference in the observed and simulated streamflow volume is

small (see figure 2), it is hypothesized that streamflow errors are primarily associated with the rate of snowmelt controlled by the spatial distribution of daily precipitation and temperature.

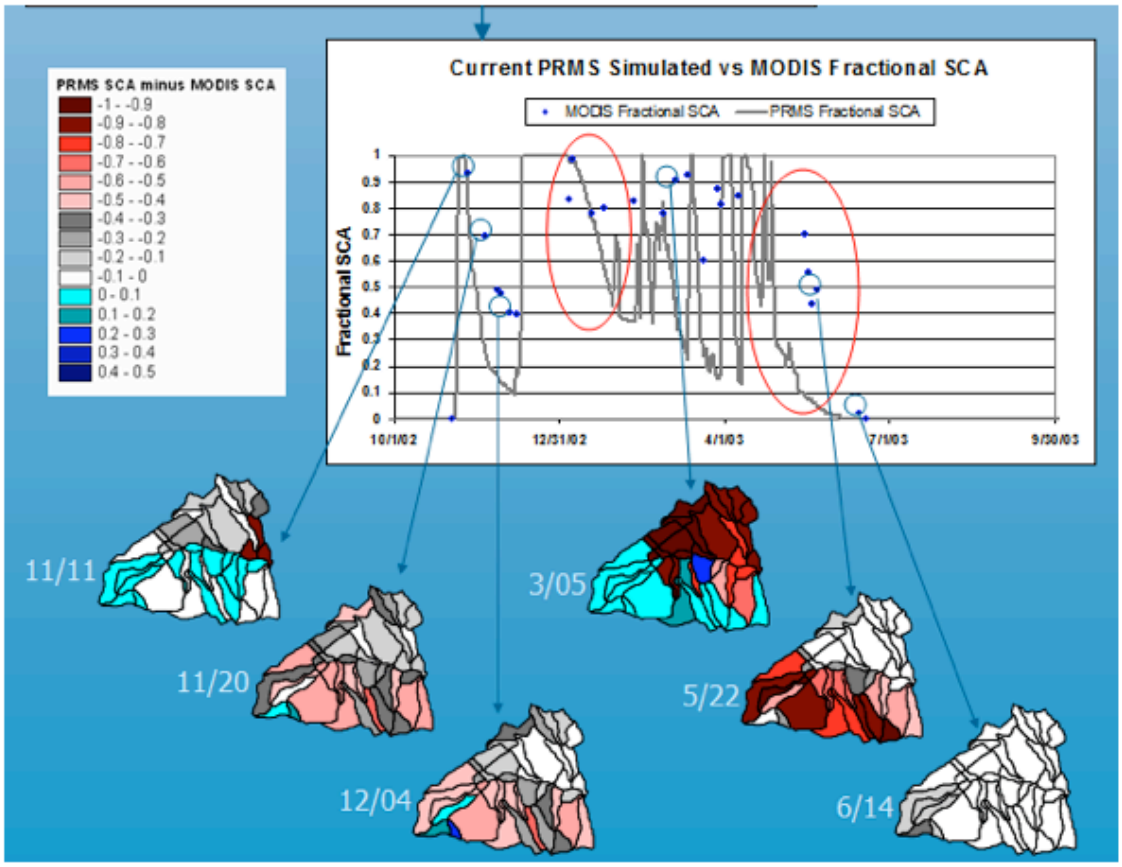


**Figure 6: Fractional SCA for basin (shown in plot) from MODIS imagery and existing PRMS simulation. Differences in estimated SCA at HRU scale (PRMS SCA - MODIS SCA) for six days in 2003 water year.**

b. Evaluation of Modified PRMS Model using MODIS SCA Estimates

The existing WaRSMP PRMS model of Sagehen Creek employs a method developed by Hay et al., 2000 for distributing point observations of precipitation and temperature to each HRU based on a regression model of latitude, longitude, and elevation of 15 weather stations and the centroid of each HRU. Boyle et al., 2006, implemented a different methodology for distributing precipitation and temperature from point observations to HRUs within the PRMS modeling software using monthly Parameter Regression on Independent Slopes Model (PRISM) (Daly, 1994) relationships. The new method utilizes mean monthly PRISM precipitation and temperature,

averaged to each HRU, and divided by the mean monthly precipitation and temperature from nearby observations (e.g., Independence Lake SNOTEL and Sagehen co-op weather stations). The HRU ratios are then multiplied by daily values of precipitation and temperature to estimate precipitation and temperature at each HRU. This alternative method provides an advantage over the method utilized in the WaRSMP approach by considering precipitation and temperature variability within the basin (i.e., variability of PRISM data within the basin) and local weather stations. In addition to implementing the new precipitation and temperature distribution approach, many of the PRMS surface, subsurface, and groundwater flow parameters were set to the recommended default values to avoid any errors associated with the calibration efforts previously undertaken within the WaRSMP model implementation.

The results for the new PRMS model implementation of Sagehen Creek in terms of SCA and streamflow are shown in Figures 7 and 8, respectively. Notice that, in Figure 7, the high degree of variability in basin-wide SCA has been reduced and the PRMS model is simulating values that are much closer to those estimated from the MODIS images. The timing of the streamflow (figure 8) is also much closer to the observed rising and falling limbs during the spring melt period. While there is clearly more work that could be done to improve the PRMS fit to observed SCA and streamflow, the results from this study have demonstrated the value of utilizing the MODIS derived SCA estimates to better understand and improve some of the erroneous behaviors in the existing WaRSMP PRMS model. This approach is currently being expanded from Sagehen Creek to other watersheds within the Truckee River system. We will report our results and any additional findings in the near future.

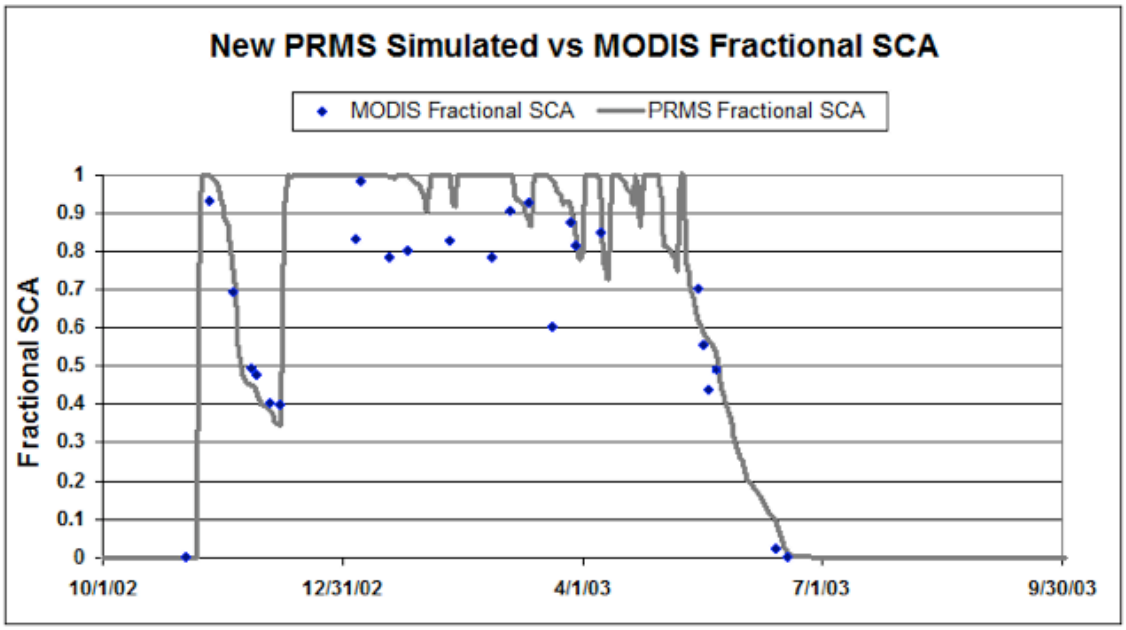


**Figure 7: Fractional SCA for basin from MODIS imagery and PRMS simulation using the new PRISM precipitation and temperature lapse rate method.**

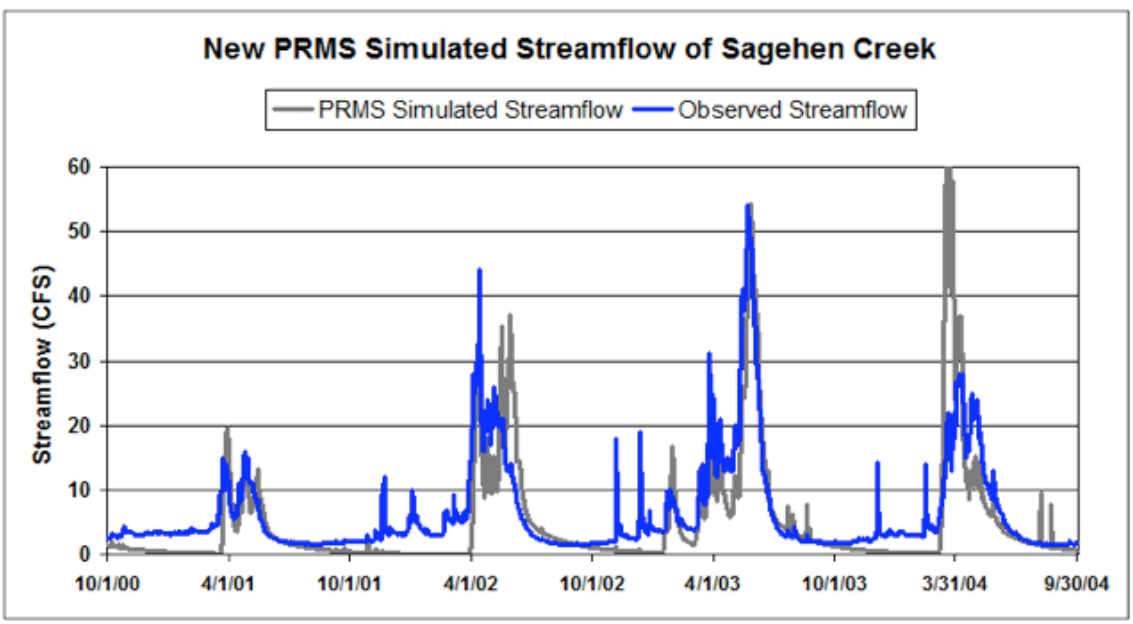


**Figure 8: Observed streamflow (blue line) at outlet of Sagehen Creek versus streamflow simulated with PRMS (gray line) using the PRISM precipitation and temperature lapse rate method**

## 4. References Cited


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