USE OF REMOTELY SENSED SNOW COVERED AREA IN WATERSHED MODEL CALIBRATION FOR THE SPRAGUE RIVER, OREGON

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Abstract: This study presents a multiple-objective, step-wise, automated procedure for hydrologic model calibration in the Sprague River basin, a mountainous watershed in the Upper Klamath Basin. The procedure includes the sequential calibration of simulated: (1) solar radiation, (2) potential evapotranspiration, (3) annual water balance; (4) snow-covered area; and (5) components of daily runoff. Remotely sensed snow-covered area data for model calibration was processed for the Sprague River. These data extend from February 24, 2000 to present. The surface hydrology of the Sprague River basin is dominated by snowmelt runoff, making snow-covered area prediction crucial for accurate streamflow forecasts. The multi-step calibration procedure ensures that intermediate model states and fluxes, as well as the annual water balance, components of the daily hydrograph, and snow-covered area are being simulated consistent with measured values. In comparison to models calibrated using streamflow data alone, this sequential calibration procedure produces model parameter sets that are more reliable for hydrologic data assimilation.

INTRODUCTION

The Sprague River basin is located in the upper Klamath Basin (UKB) in south-central Oregon (Figure 1). The climate of the UKB is characterized by semiarid to arid conditions with the highest precipitation totals occurring in the mountainous regions. Melt of the snowpack in the spring provides most of the surface water for the UKB. Water-resources management conflicts, simplified here as a competition for water between agriculture and endangered-fish species, have been escalating in the UKB. The competition for water in the UKB, coupled with the effects of climatic variability and potential climatic change, has stimulated research efforts to develop better water-resources management tools.

This study presents a multiple-objective, step-wise, automated calibration procedure for a distributed hydrologic model calibration in the Sprague River basin. The procedure uses the Shuffled Complex Evolution global search algorithm (SCE, Duan et. al, 1992; 1993; and 1994) to calibrate the U.S. Geological Survey's Precipitation Runoff Modeling System (PRMS, Leavesley et al., 1983; Leavesley and Stannard, 1995). PRMS model output is examined using two procedures for model calibration: (1) the sequential calibration of PRMS-simulated: solar radiation (SR); potential evapotranspiration (PET); annual water balance; and components of daily runoff (as shown in Hay et al., in press) followed by (2) an additional step in the sequential calibration procedure which optimizes PRMS-simulated snow-covered area (SCA). The accurate simulation of SCA is crucial for reliable streamflow estimates in snowmelt-dominated basins.

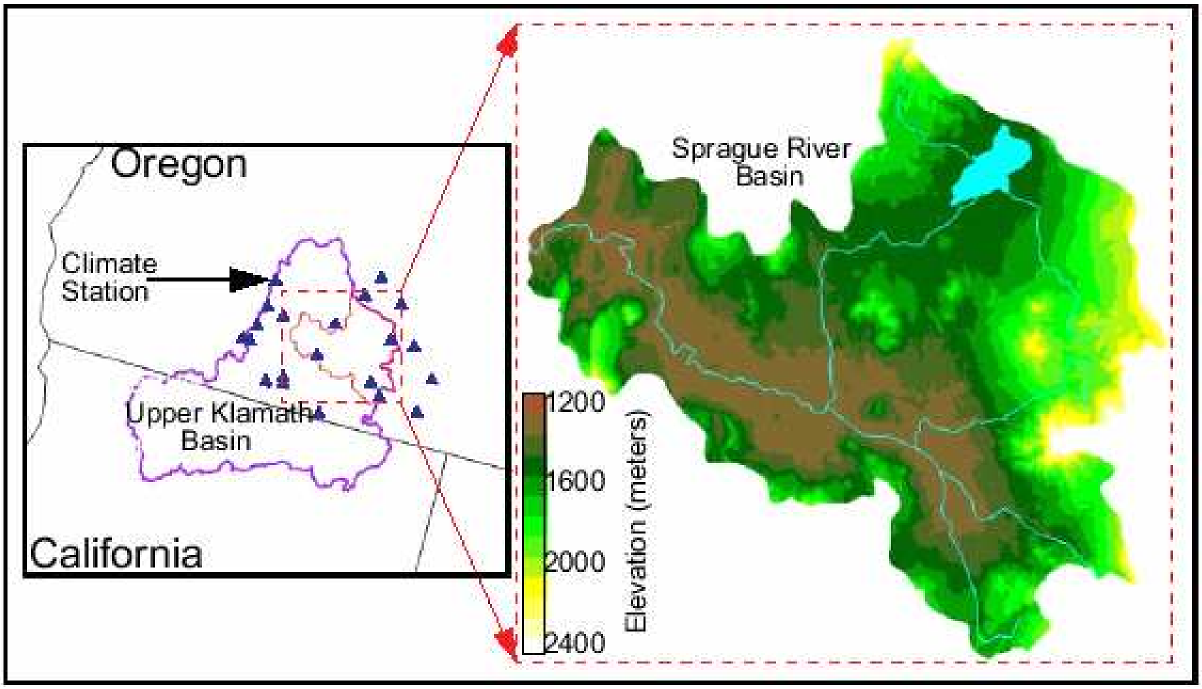

Figure 1. -- Location of the Upper Klamath and the Sprague River basins.

DATA

Climate data Daily maximum and minimum temperatures and precipitation data from stations in and around the Sprague River basin (see Figure 1) were compiled from the National Weather Service Cooperative network of observing stations for the period of record up through water year (WY) 2004. WYs run from October through September. The data were extracted from the National Climatic Data Center's "Cooperative Summary of the Day" web site (http://www.ncdc.noaa.gov/oa/ncdc.html). Snow Telemetry (SNOTEL) data were retrieved from the Natural Resources Conservation Service's web site (http://www.wcc.nrcs.usda.gov). Figure 1 shows the location of the climate stations used in this study (blue triangles).

Snow-covered area data Remotely sensed SCA for model calibration were processed for the Sprague River basin from the MODIS/Terra Snow Cover 5-Min L2 Swath 500m (Hall et al., 2000). These measured-SCA data extend from February 24, 2000 to present. The snow-mapping algorithm classifies each 500-meter pixel as snow, snow-covered lake ice, cloud, water, land, or other. For each day with MODIS output, the percent SCA in the basin was calculated along with an error bound associated with the basin-SCA value. MODIS output reported as cloud or other was used to define the error bound. The sum of each pixel's value of "cloud" and "other" in the MODIS output was added to (or subtracted from) the pixel snow value to give the upper (or lower) error bound. Figure 2 shows processed MODIS-SCA output for the Sprague River basin for the period March 1- May 31, 2000. The black circle indicates days when the error associated with the SCA value was determined to be less than 10 percent. The blue and purple lines indicate the upper and lower values of the error bound, respectively. Note the large uncertainty associated with a large percentage of the MODIS SCA.

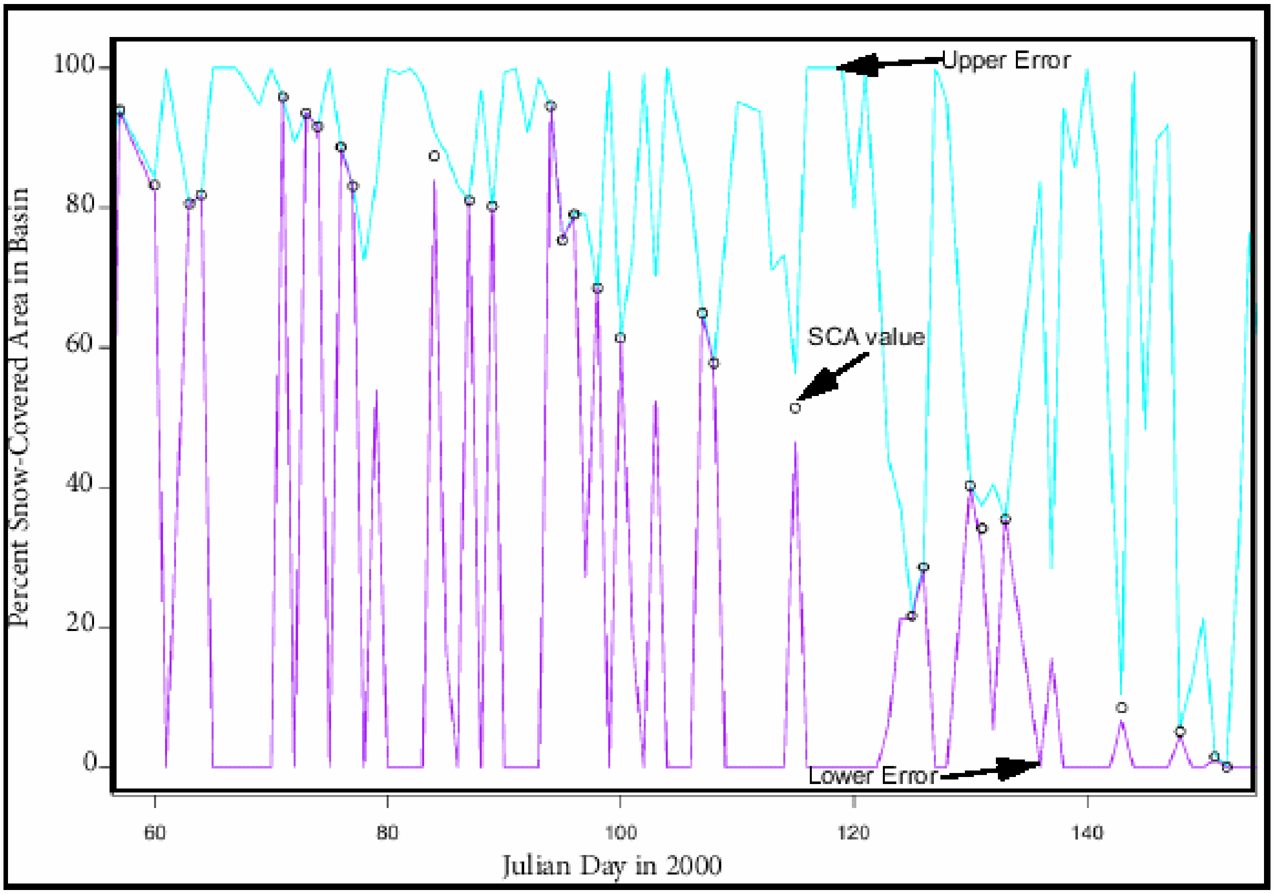

Figure 2. Snow-covered area (SCA) values calculated from MODIS output,
March 1 – May 31, 2000

HYDROLOGIC MODEL

The hydrologic model chosen for this study is the U.S. Geological Survey's Precipitation Runoff Modeling System (PRMS) (Leavesley et al., 1983; Leavesley and Stannard, 1995). PRMS is a distributed-parameter, physically based watershed model. Distributed parameter capabilities are provided by partitioning the watershed into Hydrologic Response Units (HRUs). PRMS is conceptualized as a series of reservoirs (impervious zone, soil zone, subsurface, and groundwater) whose outputs combine to produce runoff. For each HRU, a water balance is computed each day and an energy balance is computed twice each day. The sum of the water balances of all HRUs, weighted by unit area, produces the daily watershed response.

For each HRU, PRMS requires daily inputs of precipitation and maximum and minimum temperature. A multiple linear regression method was used to spatially distribute daily measured precipitation and maximum and minimum temperature data from a group of stations (a single daily mean value) to each HRU in the Sprague River basin based on the longitude (x), latitude (y), and elevation (z) of the HRU. For further details on this XYZ methodology for distributing daily data, please see Hay et al., in press; Hay et al., 2000; and Hay and Clark, 2000.

HYDROLOGIC MODEL CALIBRATION

This study combines the use of different model states for calibration along with the multiple-step approach outlined in Hogue et al (2000). Hay et al. (in press) gives a detailed description of the calibration procedure. For this study, two sets of calibration procedures were run for comparison purposes. A split sample analysis was used for calibration and evaluation of the final PRMS outputs for calibration sets 1 and 2.

Calibration Set 1 The first calibration set used a continuous four-step procedure to calibrate parameters identified as affecting PRMS simulations of: (1) SR; (2) PET; (3) annual water balance; and (4) daily runoff components. This calibration procedure is described in detail in Hay et al. (in press). The WYs 1997-2004 were chosen for model calibration. The WYs 1987-96 were chosen for model evaluation.

Calibration Set 2 The second calibration set included calibration of PRMS-simulated SCA to the multi-step procedure outlined in calibration set 1. Percent SCA was calculated from the MODIS-SCA output on days when there was MODIS coverage. In Figure 2, the distance between the purple and blue lines denotes the uncertainty limits for all MODIS-SCA values. Evident from the plot is the large uncertainty associated with many of the MODIS-SCA values. If the PRMS-simulated SCA value fell within the range of the upper and lower bounds of uncertainty in the MODIS-SCA values, no error was assessed in the objective function.

The final optimized parameter set from calibration set 1 was used to initialize calibration set 2. MODIS-SCA output starts in February of WY 2000. Therefore, approximately four WYs (2000-2004) were available and used for model calibration when using SCA output. Note that WYs 1997-2004 were used when calibrating SR, PET, annual water balance, and daily runoff components in this calibration set. This was necessary since WYs 2001-2004 were unusually low flow years: using low-flow years exclusively in PRMS calibration resulted in abnormally high annual water-balance output during the high flow years (WYs 1996-1999, not shown). A normalized root mean square error objective function that compared PRMS-simulated SCA with MODIS SCA was calculated on days when PRMS-simulated SCA fell outside the error bounds shown in Figure 2.

Optimization Algorithm For this study, the Shuffled Complex Evolution technique (SCE, Duan et. al, 1992; 1993; and 1994) was chosen as the optimization algorithm. The SCE method has been used successfully by a number of researchers (e.g. Yapo et al., 1996; Hogue et al., 2000; and Madsen, 2003; Hay et al., in press). The SCE method selects a population of points distributed randomly throughout the parameter space. The population is partitioned into several complexes. Each of these complexes "evolves" using the downhill simplex algorithm. The population is periodically "shuffled" to form new complexes so that the information gained by the previous complexes is shared. The evolution and shuffling steps repeat until prescribed convergence criteria are satisfied.

RESULTS

Figure 3a-b shows, for calibration sets 1 and 2, measured and simulated basin-mean monthly SR and PET, respectively. Black lines indicate measured values. Results for calibration sets 1 and 2 are shown in magenta and green, respectively. Circle markers with black centers indicate the calibration period (WYs 1997-2004) whereas solid magenta or green circles indicate the evaluation period (WYs 1987-1996). As indicated in Figure 3, both SR and PET are accurately simulated for the calibration and evaluation periods using calibration sets 1 and 2, with set 2 (green) showing slightly higher accuracy over set 1 (magenta).

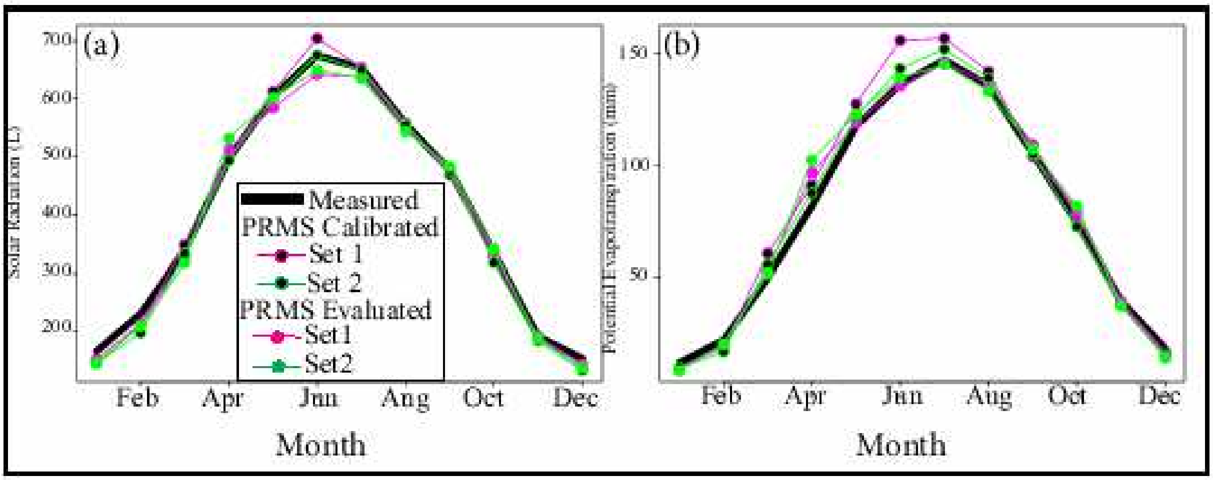

Figure 3.—Measured and PRMS output using calibration sets 1 and 2 for basin mean-monthly values of: (a) solar radiation and (b) potential evapotranspiration.

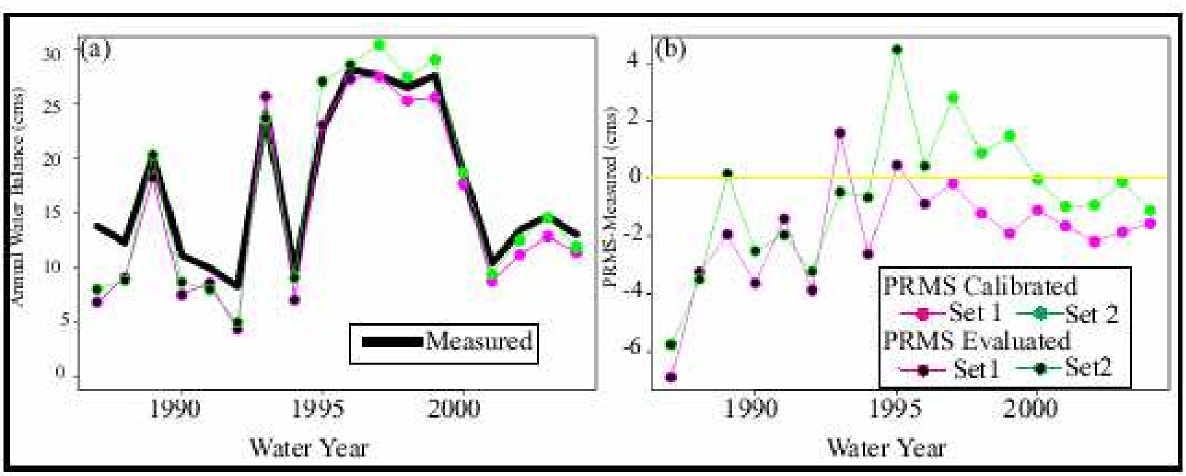

Figure 4.—Annual water balance results by water year for measured and PRMS output using calibration sets 1 and 2: (a) annual water balance values and (b) PRMS – Measured annual water balance values.

Figure 4a shows measured and simulated annual water balance results for calibration sets 1 and 2 by water year. Figure 4b shows the PRMS-simulated minus the measured values for the annual water balance results shown in Figure 4a. SCA calibration was incorporated in the calibration set

2 procedures for WYs 2000-2004. Examination of results for WYs 2001-2004 shows an increase in the accuracy of annual water balance results for calibration set 2 when compared with results from calibration set 1. As noted earlier, WYs 2001-2004 are low-flow years. The increase in accuracy for these low-flow years for calibration set 2 is offset by the decrease in accuracy during high-flow years (see WYs 1996-1999 in Figure 4). In the future, it will help to have a longer period of SCA for model calibration that covers low- and high-flow years.

In general, the Sprague River has daily irrigation withdrawal during the months of April – October. These values are reported as monthly totals, which are then disaggregated to daily values for that month. This means that matching the daily variation in streamflow in the Sprague may not be realistic. MODIS-measured values of daily SCA can be used to examine variation in daily SCA. Figure 5 shows daily MODIS-measured versus the PRMS-simulated SCA by WY for calibration sets 1 and 2. The MODIS-SCA values (black dots) are shown when the uncertainty level is less than 10%. Calibration set 1 (magenta lines) does not reproduce the MODIS-SCA values accurately. Introduction of SCA in the calibration procedure (calibration set 2, green lines), increases the accuracy of the PRMS-simulated SCA, with no evident decrease in the accuracy of SR and PET (Figure 3) or annual water balance (Figure 4).

DISCUSSION AND CONCLUSIONS

This study presented a multiple-objective, step-wise, automated procedure for hydrologic model calibration in the Sprague River basin that included the calibration of basin SCA. Two calibration sets were tested: (1) calibration set 1 included the sequential calibration of PRMS simulated SR, PET, annual water balance, and components of daily runoff and (2) calibration set 2 used the final parameter set from calibration set 1 as initialization for a multi-step procedure that included SR, PET, SCA, annual water balance, and components of daily runoff. Luca: a wizard-style graphical user interface (GUI) has been developed that provides an easy systematic way of building the multiple-objective, step-wise, automated procedure presented in this paper. Umemoto et al. (2006) present detailed instructions for use of this GUI in this issue.

In conclusion, comparison of PRMS-simulated output from the two calibration sets showed that each were able to accurately simulate SR, PET, and the annual water balance. Calibration set 1 did not include SCA in the process, resulting in inaccurate PRMS-simulated SCA. The multi-step calibration process that includes SCA ensures that intermediate model states and fluxes, as well as the annual water balance, components of the daily hydrograph, and snow-covered area are being simulated consistent with measured values.

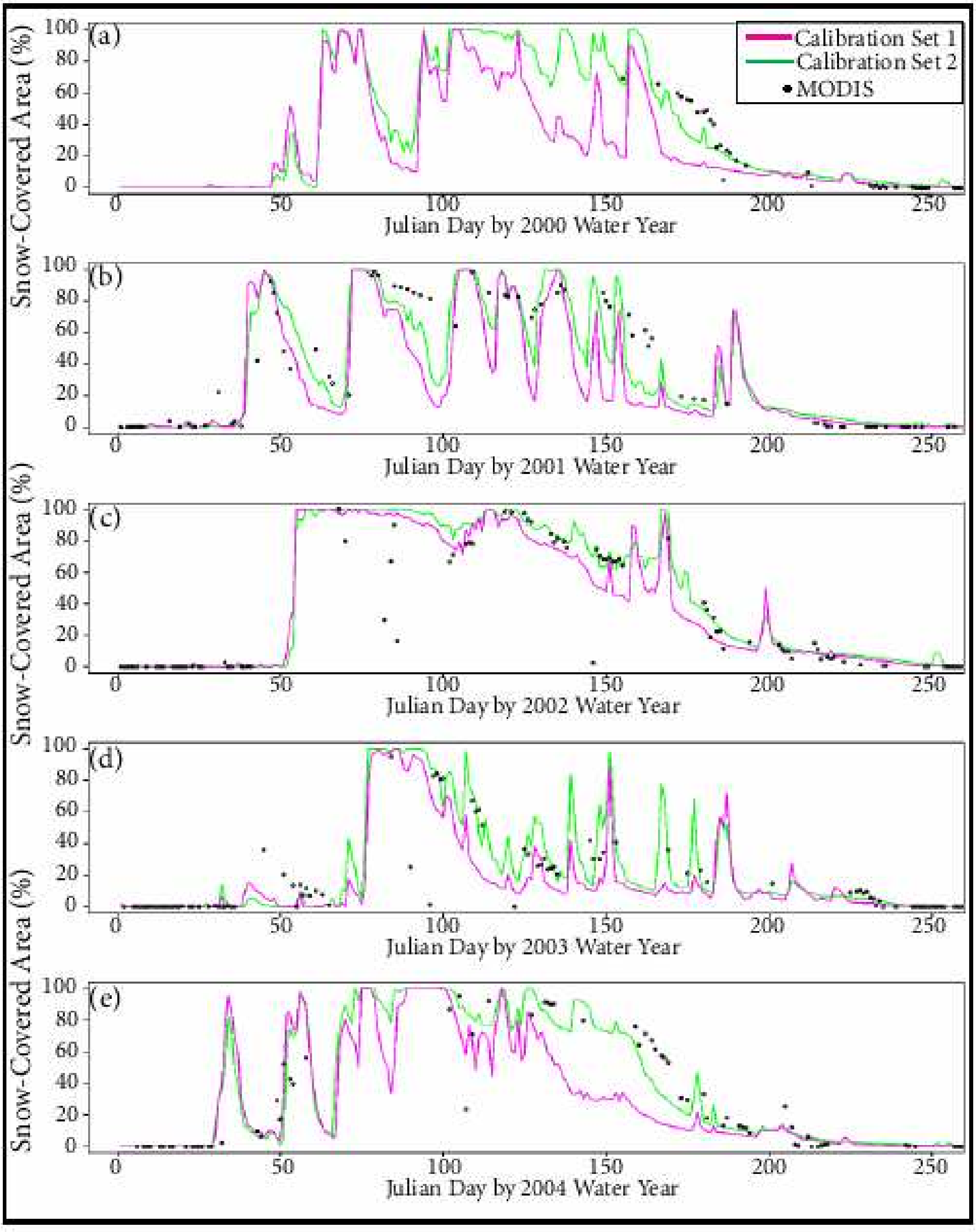

Figure 5.-- Measured and PRMS-simulated snow-covered area by water year: (a) 2000; (b) 2001; (c) 2002; (d) 2003; and (e) 2004.

REFERENCES

Duan, Q., Sorooshian, S. and Gupta, V. (1992). "Effective and efficient global optimization for conceptual rainfall-runoff models," Water Resources Research 28 (4), pp 1015-1031.

Duan, Q., Gupta, V.K. and Sorooshian, S. (1993). "A Shuffled Complex Evolution approach for effective and efficient global minimization," J. of Optimization Theory and its Applications, 76 (3), pp 501-521.

Duan, Q., Sorooshian, S., and Gupta, V.K. (1994). "Optimal use of the SCE-UA global optimization method for calibrating watershed models," Journal of Hydrology, 158, pp 265-284.

Hall, D.K., G.A. Riggs, and Salomonson, V.V. (2000). "MODIS/Terra Snow Cover 5-Min L2 Swath 500m V004, December 2003 to March 2004," Boulder, CO, USA: NSIDC.

Hay, L.E., Wilby, R.L., and Leavesley, G.H. (2000). "A Comparison of Delta Change and Downscaled GCM Scenarios for Three Mountainous Basins in the United States," Journal of the American Water Resources Association, 36, pp 387-397.

Hay, L.E., and Clark, M.P. (2000). "Use of Atmospheric Forecasts in Hydrologic Models in Mountainous Terrain: Part 2- Application to Hydrologic Models." American Water Resources Association's Spring Specialty Conference "Water Resources In Extreme Environments", Anchorage, AK, May 2000.

Hay, L.E., G.H. Leavesley, M.P. Clark, S.L. Markstrom, R. J. Viger, and Umemoto, M. (in press). "Step-wise, multiple-objective calibration of a hydrologic model for a snowmelt-dominated basin," Journal of the American Water Resources Association.

Hogue, T.S., S. Sorooshian, H. Gupta, A. Holz, and Braatz, D. (2000). "A Multi-step Automatic Calibration Scheme for River Forecasting Models," Journal of Hydrometeorology, 1, pp 524-542.

Leavesley, G.H., R.W. Lichty, B.M. Troutman, and Saindon, L.G. (1983). "Precipitation- runoff modeling system: User's manual," U.S. Geological Survey Water Resources Investigation report, 83- 4238.

Leavesley, G.H. and Stannard, L.G. (1995). "The precipitation-runoff modeling system- PRMS," In: Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, CO, edited by V.P Singh, Chapter 9, pp 281-310.

Madsen, H. (2003). "Parameter estimation in distributed hydrological catchment modelling using automatic calibration with multiple objectives," Advances in Water Resources, 26, 205-216.

Umemoto, M., Hay, L.E., Markstrom, S.L., and Leavesley, G.H. (2006). "Luca: Wizard-Style GUI that Provides Easy Systematic Way of Building a Multi-Objective, Step-Wise Calibration Procedure," Joint 8th Federal Interagency Sedimentation Conference and 3rd Federal Interagency hydrologic Modeling Conference, Reno, Nevada, April, 2006.

Yapo, P.O., Gupta, H.V., and Sorooshian, S. (1996). "Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data," Journal of Hydrology, 181, pp 23-48.