STEP WISE, MULTIPLE OBJECTIVE CALIBRATION OF A HYDROLOGIC MODEL FOR A SNOWMELT DOMINATED BASIN[1]

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ABSTRACT: The ability to apply a hydrologic model to large numbers of basins for forecasting purposes requires a quick and effective calibration strategy. This paper presents a step wise, multiple objective, automated procedure for hydrologic model calibration. This procedure includes the sequential calibration of a model's simulation of solar radiation (SR), potential evapotranspiration (PET), water balance, and daily runoff. The procedure uses the Shuffled Complex Evolution global search algorithm to calibrate the U.S. Geological Survey's Precipitation Runoff Modeling System in the Yampa River basin of Colorado. This process assures that intermediate states of the model (SR and PET on a monthly mean basis), as well as the water balance and components of the daily hydrograph are simulated consistently with measured values.
(KEY TERMS: Precipitation Runoff Modeling System; Shuffled Complex Evolution; Colorado; optimization; solar radiation; potential evapotranspiration; water balance; runoff.)

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INTRODUCTION

Runoff from winter snowpack is the main supply of water in the intermountain western United States (U.S.). NOAA National Weather Service (NWS) and USDA National Resources Conservation Service (NRCS) issue runoff forecasts for the western U.S. Both of these agencies are attempting to modernize their runoff forecasting tools by incorporating more spatially distributed hydrologic modeling techniques (e.g. Spatially Distributed Hydrologic Modeling, USDA-NRCS, 1998; Carter, 2005). To this end, the NRCS is currently configuring a version of the U.S. Geological Survey's (USGS) Precipitation Runoff Modelling System (PRMS) for 35 snowmelt dominated basins by 2006 with the possible extension to the entire western U.S. (K. Rojas and F. Geber, NRCS, personnel communication, May 2005). PRMS is a distributed parameter, physically based hydrologic model. The ability to apply a distributed hydrologic model to a large numbers of basins in a timely and efficient manner for runoff forecasting purposes requires a quick and effective calibration strategy.

Traditional approaches to calibration and evaluation of distributed hydrologic models compared observed and simulated runoff at the outlet of the basin. This traditional approach is not sufficient by itself in the evaluation of distributed hydrologic models (Refsgaard, 1997). While incorporation of spatial data into the calibration and evaluation process is ideal, research in this area has occurred mainly in heavily instrumented research basins (Refsgaard, 2000). In general, the data available for calibration and evaluation of distributed hydrologic models are limited for the basins in which NOAA and NRCS are forecasting runoff.

Gupta *et al*. (1998) proclaimed that hydrologic model calibration must consider the multiple objective nature of the problem. The use of multiple objective

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functions in the calibration of hydrologic models has become increasingly popular. For example, Hogue *et al.* (2000) examined recessions and low flows, higher flows, and base flows; Turcotte *et al.* (2000) examined droughts, annual and monthly flow volumes, high flows, high flow synchronization, and snowmelt runoff; Madsen (2000) examined the water balance, hydrograph shape, peak flows, and low flows; and Boyle *et al.* (2000; 2003) examined three components of the hydrograph described as driven, nondriven quick, and nondriven slow. While these studies used multiple objectives, the only data used was runoff – different portions and time steps of the hydrograph were configured for the multiple objective calibrations. Intermediate variables computed by the hydrologic model (such as solar radiation, potential evapotranspiration, snow water equivalent, snow covered area, and soil moisture) could be characterized by parameter values that do not replicate those hydrological processes in the physical system.

Is this paper, a multiple objective calibration strategy that incorporates additional, easily obtainable, data sets is presented. Four variables simulated by PRMS are used as calibration data sets: (1) solar radiation (SR), (2) potential evapotranspiration (PET), (3) water balance, and (4) daily runoff components. The SR and PET datasets are monthly mean values derived from nationwide data sets, making them readily accessible for application in a large number of basins. The parameters influencing each of the model variables are calibrated in a step wise, multiple objective procedure similar to that presented by Hogue *et al.* (2000). This process gives the user higher confidence in the model output by assuring that intermediate states of the model (as described by monthly mean values of SR and PET), as well as the water balance and components of the daily hydrograph are simulated consistently with measured values.

STUDY AREA

The Yampa River basin at Steamboat Springs (USGS streamflow gaging Station 09239500) (USGS 2005a) in northwestern Colorado was chosen as the study area (see Figure 1). The Yampa River basin is a mountainous basin where the runoff is strongly dependent on snowmelt, peaking during May. The basin is 1,430 km^2 in area and ranges in elevation from 2,000-3,800 meters. Figure 2 shows the daily basin mean by month for precipitation and maximum and minimum temperature for two eight-year periods: Water Years (WYs) 1996-2003 and 1988-1995. WYs run from October through September. These two eight-year periods were chosen as the calibration and evaluation periods, respectively. The wettest month for the Yampa River basin is February and the driest month is June. The warmest months are July and August and the coldest are December and January.

The Yampa River basin was included in the Hydro-Climatic Data Network, indicating that the streamflow records prior to 1988 for this USGS streamflow gaging station are considered to be relatively "unaffected by artificial diversions, storage, or other works of man in or on the natural stream channels or in the watershed" (Slack and Landwehr, 1992). In 1987, the Stagecoach Reservoir was completed upstream from Station 0923950. Currently there is moderate regulation of flow during the winter and late summer months (T. Pagano, NRCS, personnel communication). The USGS discharge records are considered good for Station 0923950. Natural flow in the stream can be affected by irrigation diversions (highest during June; http://cwcb.state.co.us), reservoir storage, and pumping of water for snowmaking during the winter (Crowfoot *et al.,* 1996).

CLIMATE DATA

Daily maximum and minimum temperatures and precipitation data from stations in and around the Yampa River basin (see Figure 1) were compiled from the NWS cooperative network of observing stations for the period of record up through September 2003. 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/snow). Figure 1 shows the location of the NWS (white) and SNOTEL (gray) stations used in this study.

To minimize erroneous precipitation and temperature values, quality control of the data was performed for the entire period of record for the time series at all stations. The quality control protocol followed the procedures of Reek *et al.* (1992), Kunkel *et al.* (1998), and Serreze *et al.* (1998, 1999). This includes checks for: (1) extreme values; (2) internal consistency among variables (e.g., maximum temperature less than minimum temperature); (3) constant temperature (e.g., five or more days with the same temperature); (4) excessive diurnal temperature range; (5) invalid relations between precipitation, snowfall, and snow depth; (6) unusual step changes or spikes in temperature time series; and (7) missing values. After completing these checks a serially complete time series was computed: if data values are either (1) not "valid" (as defined above) or (2) lay outside the tolerance

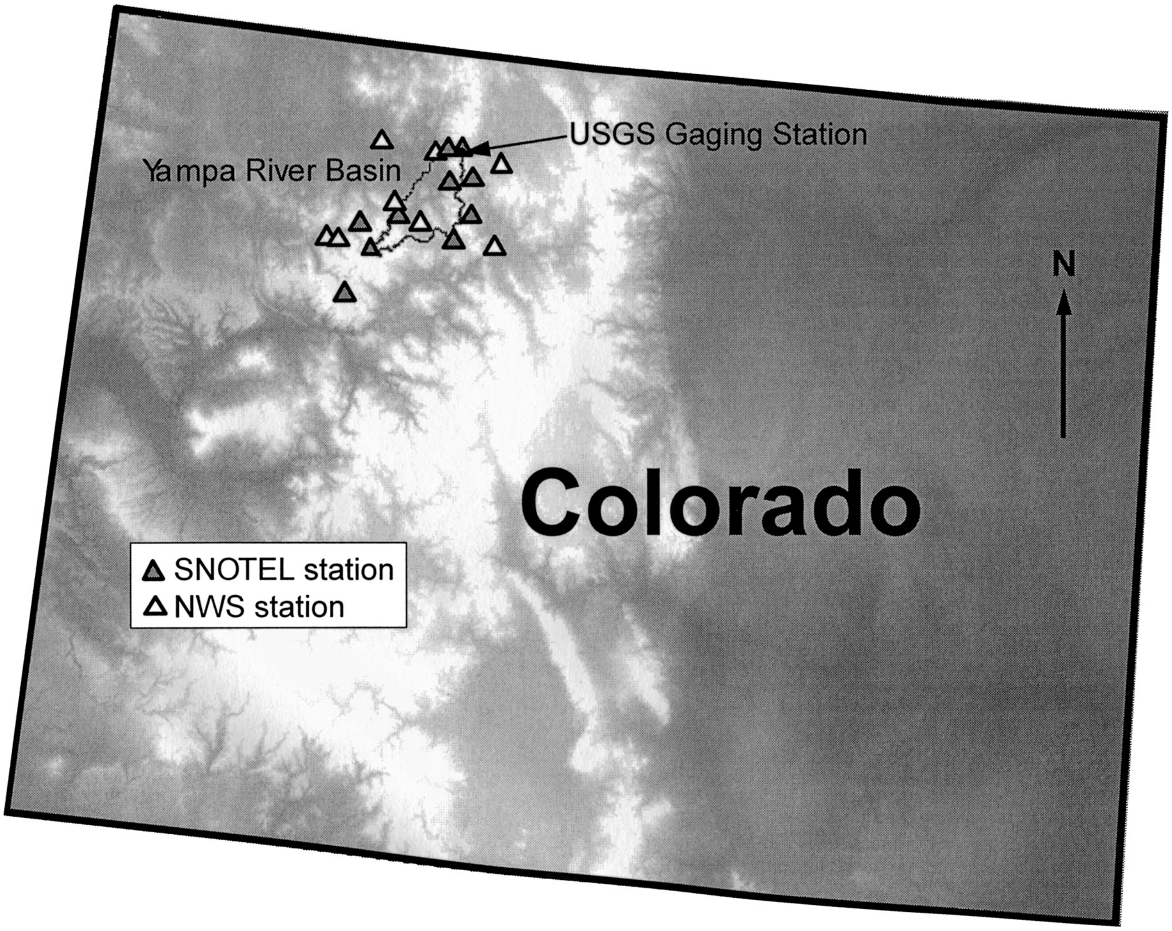

Figure 1. Location of Yampa River Basin (U.S. Geological Survey ID: 09239500) and Climate Stations.

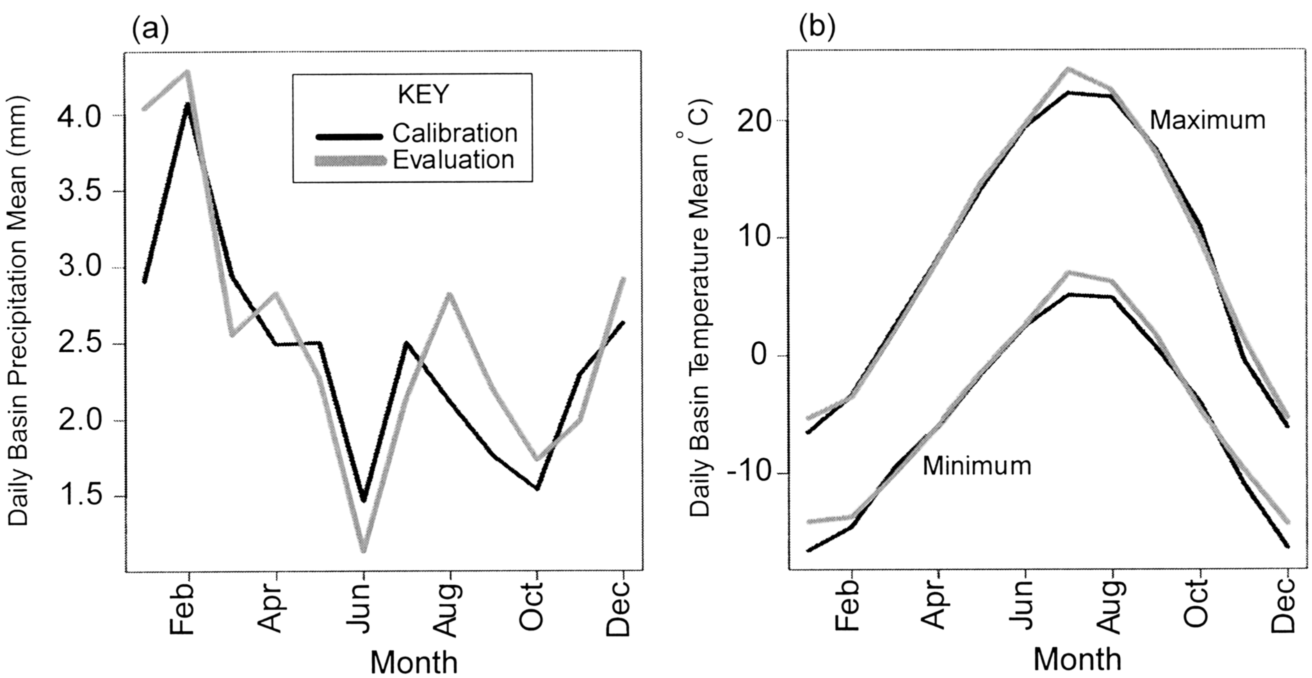

Figure 2. Daily Basin Mean by Month for: (a) Precipitation and (b) Maximum and Minimum Temperature.

limits from the aerial consistency check, then they are replaced with an interpolated value. Suspicious data was replaced with data interpolated from surrounding stations.

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). Each HRU is assumed homogenous with respect to its hydrologic response. PRMS is conceptualized as a series of reservoirs (impervious zone, soil zone, subsurface, and ground water) 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.

HRU delineation, characterization, and parameterization were done using a Geographic Information System (GIS) interface – the GIS Weasel (Viger *et al.,* 1998). For this study, HRUs were delineated for the Yampa River basin by: (1) subdividing the basin into two flow planes for each channel, (2) subdividing the basin using three equal area elevation bands, and (3) intersecting the flow plane map with the elevation band map. This resulted in 68 HRUs for the Yampa River basin (see Figure 3).

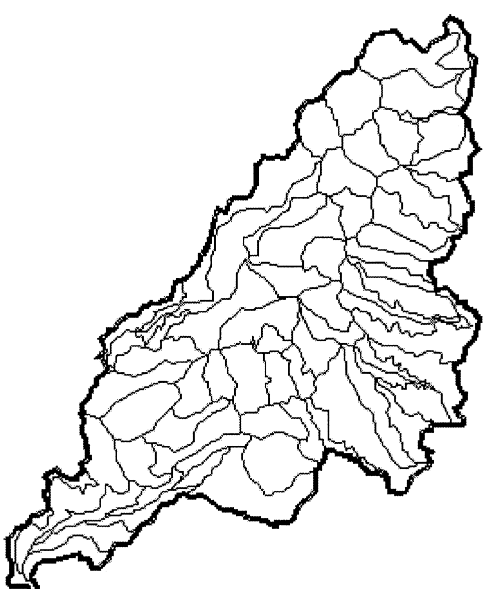

Figure 3. Hydrologic Response Units for the Yampa River Basin.

Hydrologic model parameters describing topographic, vegetation, and soils characteristics were generated using the GIS Weasel for each HRU. The GIS Weasel accesses four digital databases: (1) USGS 3-arc second digital elevation model (USGS, 2004); (2) state soils geographic (STATSGO) 1-km gridded soils data (U.S. Department of Agriculture, 1994); (3) U.S. Forest Service 1-km gridded vegetation type and density data (U.S. Department of Agriculture, 1992); and (4) USGS 1-km gridded Land Use/ Land Cover data (Anderson *et al.,* 1976). When an HRU contained more than one soil or vegetation type, the dominant soil or vegetation type was used.

PRMS uses daily values of precipitation and maximum and minimum temperature at each HRU. A multiple linear regression (MLR) method was used to distribute daily measured precipitation and maximum and minimum temperature data from a group of stations (a single daily mean value) to each HRU in a basin based on the longitude (x), latitude (y), and elevation (z) of the HRU. This xyz methodology is described in detail in Hay *et al.* (2000a,b).

HYDROLOGIC MODEL CALIBRATION

A step wise, multiple objective calibration scheme was used to calibrate PRMS for the Yampa River basin. For this study, four steps were used in the calibration procedure. Table 1 lists the calibration step and associated: calibration data set(s), objective functions(s), and model parameters. For each of the four calibration steps, the following calibration data set(s) were developed to compare with PRMS outputs: (1) mean monthly SR, (2) mean monthly PET, (3) water balance configurations, and (4) daily runoff components. The parameters listed in Table 1 for each calibration step were determined from a single parameter sensitivity analysis conducted using Monte Carlo techniques.

To start the calibration procedure an initial parameter file containing all PRMS parameters is defined. In each calibration step, the parameters designated in Table 1 are calibrated. These calibrated parameter values replace the respective parameter values in the parameter file and this parameter file is used as the initial parameter file for the next calibration step. Completion of the four calibration steps constitutes a round. Once a parameter is calibrated, its value is set for the remainder of that calibration round. This process is repeated until no further increase in model accuracy is seen. The following section describes the four calibration steps in detail and the optimization algorithm chosen for this study.

TABLE 1. Parameters Calibrated in Each Step of the Calibration Process.

Step	Calibration Data Set	Objective Function	Parameters Used to Calibrate Model State	Parameter Description
1	Basin mean monthly solar radiation (SR)	Sum of the absolute difference in the logarithms of observed and simulated SR	dday_intcp	Intercept in temperature degree-day relationship
			tmax_index	Index temperature used to determine precipitation adjustments to solar radiation
2	Basin mean monthly potential evapotranspiration (PET)	Sum of the absolute difference in the logarithms of observed and simulated PET	jh_coef	Coefficient used in Jensen-Haise PET computations
3	Water balance: 1. Annual 2. April-September 3. February-July 4. High	Sum of the absolute value of the Normalized Residuals (ANR)	adjust_rain	Precipitation adjustment factor for rain days
			adjust_snow	Precipitation adjustment factor for snow days
			psta_nuse	Binary indicator for using station in precipitation distribution calculations
		ANR computed for each of the four water balance components and summed	psta_freq_nuse	Binary indicator for using station in precipitation frequency calculations
4	Daily flow: 1. All flows 2. Low flows 3. Peak flows	Normalized Root Mean Square Error (NRMSE)	adjmix_rain	Factor to adjust rain proportion in mixed rain/snow event
			tmax_allrain	If HRU maximum temperature exceed this value, precipitation assumed rain
		NRMSE is computed for each of the three daily flow components and summed	tmax_allsnow	If HRU maximum temperature is below this value, precipitation assumed snow
			tsta_nuse	Binary indicator for using station in temperature distribution calculations
			cecn_coef	Convection condensation energy coefficient
			emis_noppt	Emissivity of air on days without precipitation
			freeh2o_cap	Free water holding capacity of snowpack
			potet_sublim	Proportion of PET that is sublimated from snow surface
			smidx_coef	Coefficient in nonlinear surface runoff contributing area algorithm
			smidx_exp	Exponent in nonlinear surface runoff contribution area algorithm
			gwflow_coef	Ground water routing coefficient
			ssrcoef_sq	Coefficient to route subsurface storage to streamflow
			soil2gw_max	Maximum rate of soil water excess moving to ground water
			soil_moist_max	Maximum available water holding capacity of soil profile
			soil_rechr_max	Maximum available water holding capacity for soil recharge zone

Calibration Step 1 -- Solar Radiation (SR)

The first step in the calibration procedure used mean monthly SR values. The snowmelt and evapotranspiration computations in PRMS require daily values of SR. For this study, daily SR values were calculated in PRMS from daily air temperature data (Leavesley *et al.,* 1983). Where available, daily SR can be input directly into PRMS, but in general, these data are not available.

Measured monthly SR values are available for 217 stations in the U.S. (http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/mon2/). A data set of mean monthly SR values at each of the climate station sites (SNOTEL and NWS) in the U.S. was developed. A multiple linear regression (MLR) was developed between measured monthly SR values at the 217 stations and independent variables (climate statistics calculated using climate stations co-located with the measured solar radiation). For each month a separate MLR equation was developed, choosing from the following independent variables: latitude, longitude, elevation, mean precipitation (days > 0°C), mean precipitation, number of rain days, mean maximum temperature, and the difference between mean maximum and mean minimum temperature. Adjusted R^2 values ranged from 0.83-0.98. Mean monthly SR values were calculated at each SNOTEL and NWS climate station site using the monthly MLR equations.

As noted earlier in this paper, there is a lack of additional data sources for model calibration and evaluation in nonresearch oriented basins. Mean monthly values of SR are used for calibration and evaluation purposes in this study because these values are available for the entire U.S. and the ability to apply this calibration procedure to numerous basins across the U.S. depends on having a data source for SR in each of these basins.

SR output from the station closest to the centroid of the Yampa River basin (23 km) was used as the calibration data set for the first step in the calibration process. These SR values are referred to as interpolated values in the text.

A PRMS parameter sensitivity analysis showed three parameters influencing the SR calculations in PRMS. Two of these parameters are the slope and the y-intercept of the line that expresses the relation between monthly maximum air temperature and a degree day coefficient. For this study, the slope was calculated using the interpolated SR output at the station closest to the Yampa River basin centroid and the y-intercept was calibrated. This left two parameters for calibrating SR (Table 1). These parameters also influence the other PRMS outputs tested in this study, but their purpose is in calculating SR and therefore their values are set in the first calibration step.

The objective function used to calibrate the mean monthly SR values produced in PRMS is described as:

$$OF_{sr} = \sum_{m=1}^{12} abs\left(\log\left(INT_m\right) - \log\left(SIM_m\right)\right) \tag{1}$$

where OF_{sr} is the objective function, m is the month, and INT and SIM are the mean monthly interpolated and simulated SR values, respectively.

Note that the choices of objective functions in this paper were made based on the authors past experience with PRMS. Choice in objective function should be based on the purpose of the study. There are 12 monthly values used in the SR objective function computation. The sum of the absolute difference in the logarithms of monthly interpolated and simulated SR was chosen because it gave a more proportional measure of error for low and high values.

Calibration Step 2 – Potential Evapotranspiration (PET)

The second step in the calibration procedure used a calibration data set consisting of mean monthly PET values for the Yampa River basin. The basin mean monthly PET values were calculated from PET maps provided by the NWS. The NWS derived the PET values from the free water evaporation atlas of Farnsworth *et al.* (1982). These PET maps were used for calibration and evaluation purposes in this study because these values are available for the entire U.S. and the ability to apply this calibration procedure to numerous basins across the U.S. depends on having a data source for PET.

Daily estimates of PET in PRMS are produced from SR using a procedure developed by Jensen and Haise (1963). This procedure uses one parameter, which is described in Table 1. This parameter also influences other PRMS outputs, but its purpose is in calculating PET and therefore its value is set in this step of the calibration.

The objective function, OF_{PET}, is calculated in a manner similar to that for SR

$$OF_{PET} = \sum_{m=1}^{12} abs\left(\log\left(INT_m\right) - \log\left(SIM_m\right)\right) \tag{2}$$

where INT is the mean monthly PET value interpolated for the Yampa River basin from the PET maps and SIM is the mean monthly PET value simulated for the Yampa River basin.

Calibration Step 3 -- Water Balance

The third step in the calibration procedure used four calibration data sets calculated from USGS streamflow gaging Station 0923950. Table 1 lists the four parameters influencing the water balance calculations in PRMS. The first calibration data set used annual runoff volumes (based on water year). The three additional calibration data sets were included because the Bureau of Reclamation is interested in these runoff volumes for forecasting (Tom Hicks, Bureau of Reclamation, personnel communication, January 2005). These include volumes calculated from daily flow values that occurred between April and September and February and July and volumes calculated when daily flow values were greater than a selected low flow value (Q_{low}). Figure 4 shows a schematic of the Q_{low} calculation. In Figure 4, measured daily runoff values were sorted and plotted. The location where the grey lines in Figure 4 intersect was assigned the Q_{low} value.

The water balance objective function (OF_{WB}, Equation 3) is the sum of the four objective functions: (1) OF_{ann} (annual water volumes); (2) OF_{as} (volumes computed for April-September); (3) OF_{fj} (volumes computed for February-July); and (4) OF_{high} (volumes computed from daily flow values greater than designated Q_{low} value).

$$OF_{wb} - OF_{ann} + OF_{as} + OF_{fj} + OF_{high} \tag{3}$$

OF_{ann}, OF_{as}, OF_{fj}, and OF_{high} are computed using the sum of the absolute value of the normalized residuals (ANR)

$$ANR = \sum_{n=1}^{nyr} abs\left(\left(MSD_n - SIM_n\right) / MSD_n\right) \tag{4}$$

where n is the year, nyr is the total number of years, and MSD and SIM are the measured and simulated runoff volumes associated with OF_{ann}, OF_{as}, OF_{fj}, or OF_{high}.

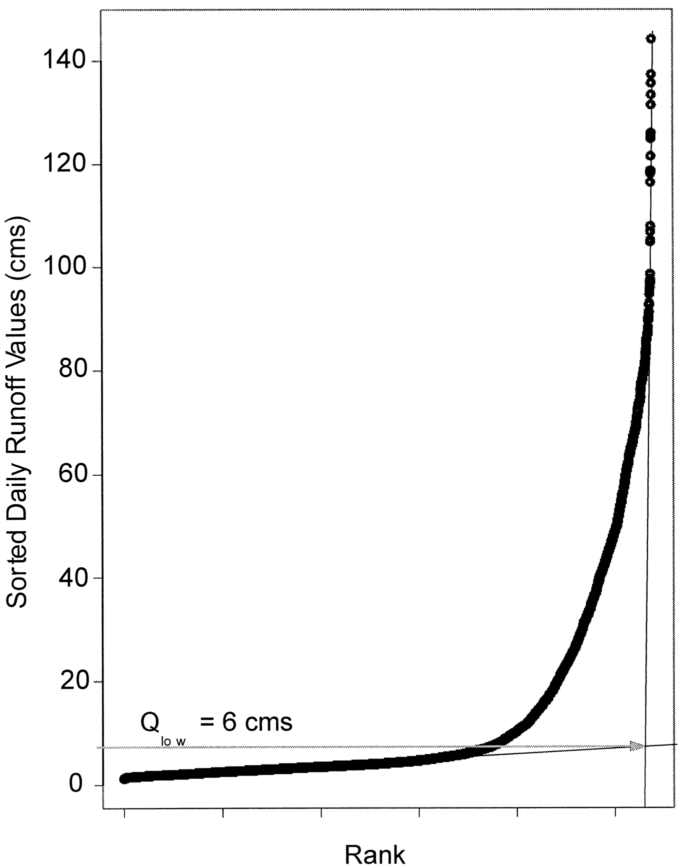

Figure 4. Cutoff Value for Q_{low} Calculated Using Daily Runoff Sorted by Magnitude.

It was assumed that the errors in measured flow volumes were small when compared with other sources of error such as climate inputs or model structure. Based on this assumption, ANR was chosen as the objective function.

Calibration Step 4 – Daily Runoff

The fourth step in the calibration procedure used calibration data sets calculated using three components of daily runoff: (1) all flows, (2) low flows, and (3) peak flows. Table 1 lists the 15 parameters influencing the components of daily runoff.

The daily runoff objective function (OF_{RO}) was calculated as the sum of three objective functions

$$OF_{RO} = OF_{daily} + OF_{low} + OF_{peak} \tag{5}$$

where OF_{daily} is an objective function calculated using all daily measured flow values; OF_{low} is an objective function calculated on days when measured daily flow values were less than Q_{low} (described earlier, see Figure 4); and OF_{peak} is an objective function calculated using daily flows that were determined to be "peak" runoff values. Figure 5 shows "peak" flow value designation for one year of measured flow data. The flow values with circles were determined to be "peak" values for the calibration data set and OF_{peak} objective function calculations.

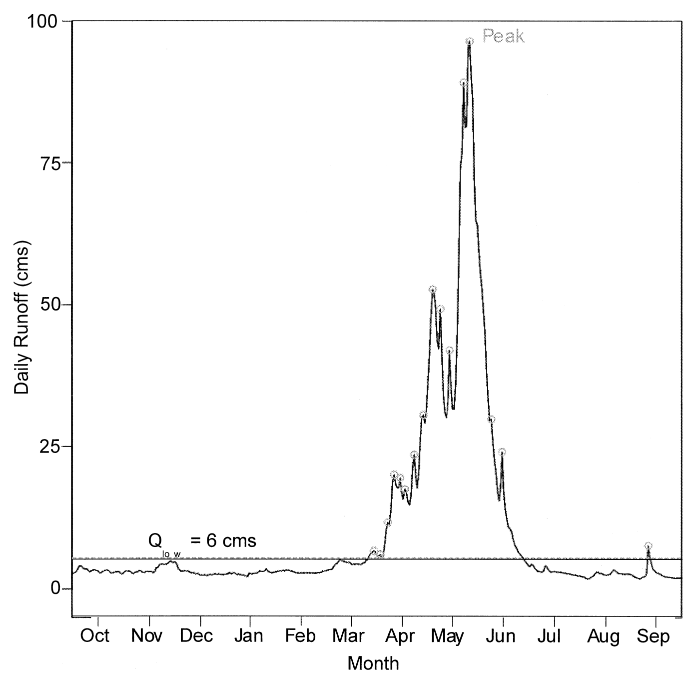

Figure 5. Daily Hydrograph Showing Peak Flow Definitions (gray circles).

OF_{daily}, OF_{low}, and OF_{peak} were calculated using the normalized root mean square error (NRMSE)

$$\mathrm{NRMSE} = \left(\sum_{n=1}^{\mathrm{ndays}} \left(\mathrm{MSD}_n - \mathrm{SIM}_n\right)^2 / \sum_{n=1}^{\mathrm{ndays}} \left(\mathrm{MSD}_n - \mathrm{MN}\right)^2 \right)^{1/2} \tag{6}$$

where n is the day; ndays is the total number of days; and MSD, SIM, and MN are the measured, simulated, and mean daily values associated with OF_{daily}, OF_{low}, or OF_{peak}. If NRMSE = 0, then the measured values are equal to the simulated values (MSD = SIM). A value of NRMSE > 1 indicates that simulated values are as good as using the average value of all the measured data.

Optimization Algorithm

For this study, the Shuffled Complex Evolution technique (SCE) (Duan *et al.,* 1992,1993,1994) was chosen as the optimization algorithm. The SCE method has been used successfully by a number of researchers (e.g., Yapo *et al.,* 1996; Kuczera, 1997; Hogue *et al.,* 2000; and Madsen, 2003). 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. Further detailed explanation of the method is given in Duan *et al.* (1992,1993, 1994).

RESULTS

The step wise, multiple objective automated procedure described above was used to calibrate the hydrologic model PRMS in the Yampa River basin. Yapo *et al.* (1996) found that approximately eight years of data were needed to achieve model calibrations that are insensitive to the period selected. For this study, a split sample test was used for calibration and evaluation of PRMS. Eight WYs (1996-2003) were chosen for model calibration. WYs 1996-2003 included a high flow year (WY 97) as well a low flow year (WY 2002). Eight WYs (1988-1995) were chosen for model evaluation.

Four hydrologic model outputs were calibrated: (1) monthly mean SR, (2) monthly mean PET, (3) annual water balance components, and (4) daily runoff components. Four rounds of the step wise calibration procedure were needed to reach a minimum in each objective function tested.

Solar Radiation (SR)

Calibration of SR is the first step in the step wise procedure. Figure 6 shows the basin mean SR values by month for interpolated (gray line), calibrated (black solid line), and evaluated (black dashed line) SR values. The calibrated values (WYs 1996-2003) are almost identical to those shown for interpolated SR. The evaluated values (WYs 1988-1995) show close agreement with interpolated values as well.

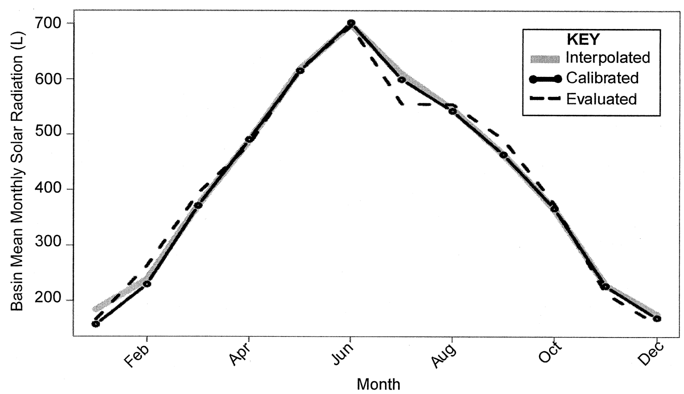

Figure 6. Basin Mean Monthly Solar Radiation: Interpolated, Calibrated (WYs 1996-2003), and Evaluated (WYs 1977-1995).

Potential Evapotranspiration (PET)

Calibration of PET is the second step in the step wise procedure. Figure 7 shows the basin monthly PET values by month for "measured" (gray line), calibrated (black sold line), and evaluated (black dashed line) PET values. The calibrated values (WYs 1996-2003) are almost identical to those shown for measured PET. PET values for the evaluation period (WYs 1988-1995) show a large discrepancy in July. Closer examination of SR for this month (Figure 6) shows the greatest discrepancies during July as well. Figure 2b shows the maximum and minimum daily basin mean temperatures by month for the calibration and evaluation periods. The temperature differences between the calibration and evaluation periods in July directly affect the PRMS simulated SR and PET in July.

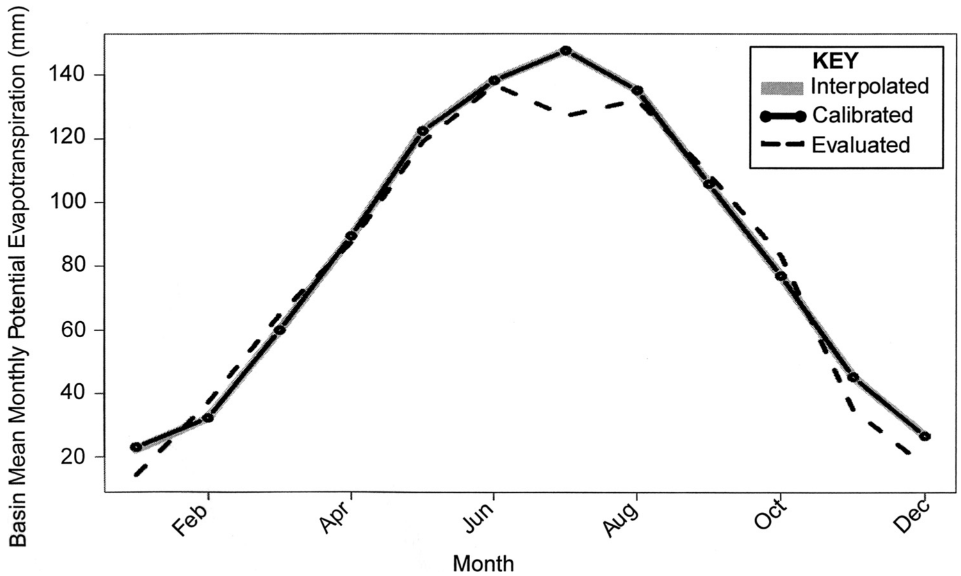

Figure 7. Basin Mean Monthly Potential Evapotranspiration: Measured, Calibrated (WYs 1996-2003), and Evaluated (WYs 1977-95).

Water Balance

Calibration of the water balance is the third step in the step wise procedure. The water balance was calibrated using the sum of four objective functions, which examined four water balance categories: (1) annual water balance, (2) February-July water balance, (3) April-September water balance, and (4) water balance comprised of daily flow values greater than the designated Q_{low} value (see Figure 4). Figure 8 shows the measured (gray line) and PRMS simulated (dots) annual values for each of these categories. The white dots indicate PRMS results for the calibration period (WYs 1996-2003) and the black dots indicated PRMS results for the evaluation period (WYs 1988-1995). In general, measured and simulated water balances show good agreement. There is a slight tendency for underestimation during the calibration period.

Daily Runoff

Calibration of the daily runoff is the fourth and final step in the step wise procedure. Daily runoff was calibrated using the sum of three objective functions, which examined three categories of daily flow: (1) all, (2) low, and (3) peak daily flow values. Figure 9 plots the measured versus simulated daily flow values for each of these categories. Each row of two plots shows results for calibration and evaluation periods. Visual inspection of the daily plots shows a good one-to-one fit between measured and simulated values with the exception of Figure 9d, which shows overestimation of low flows during the evaluation period.

The Nash-Sutcliffe goodness of fit (NS) was chosen to evaluate the performance of the PRMS calibration for the three daily flow categories (Nash and Sutcliffe, 1970). The NS value is calculated as

$$NS = 1.0 - \sum_{n=1}^{ndays} \left(MSD_n - SIM_n\right)^2 / \sum_{n=1}^{ndays} \left(MSD_n - MN\right)^2 \tag{7}$$

where MSD are the measured daily runoff values, SIM are the simulated daily runoff values, MN is the average of the measured values, and n is the number of values out of a total of ndays. An NS value of one indicates a perfect fit between measured and simulated. A value of zero indicates that the fit is as good as using the average value of all the measured data.

Figure 10a shows the yearly NS statistic values by water year (white dots indicate calibration period and black dots indicate evaluation period). Figures 10b, 10c, and 10d show the NRMSE for all, peak, and low flows, respectively. The NS results in Figure 10a show yearly NS values greater than 0.80 for the calibration and evaluation years when using all daily flow values. Figure 10b shows the corresponding NRMSE that are consistent for the calibration and evaluation periods. When the daily flows are subdivided by peak and low flows (Figures 10c and 10d), there are NRMSE values greater than 1.0, indicating that the simulated values

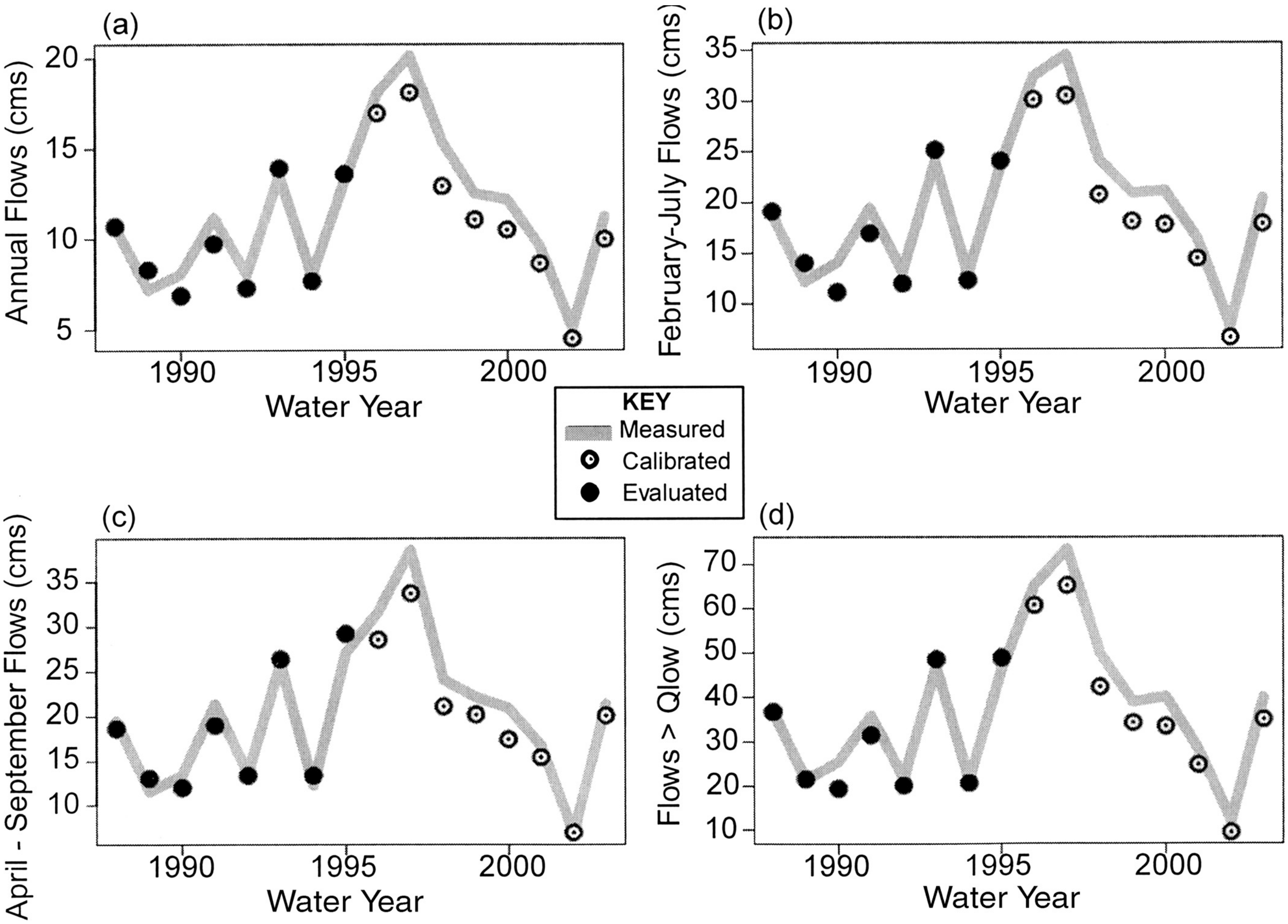

Figure 8. Water Balance: Measured, Calibrated (WYs 1996 to 2003), and Evaluated (WYs 1988 to 1995) for (a) Annual Flows, (b) February-July Flows, (c) April-September Flows, and (d) Flows > Q_{low}.

can be considered inferior to using a mean value. This is especially true for the low flows (Figure 10d). Much of the fluctuation in the summer low flow values for the Yampa River basin can be attributed to diversions and returns during the summer months. Without detailed information on these diversions, it is unrealistic to be able match the daily variability in the low flows. The lowest flow year (2002) also shows the lowest NS value (0.80). As indicated by Figure 8d, the annual low flow volumes are simulated accurately.

DISCUSSION

The step wise, multiple objective, automated calibration procedure may not actually improve the final runoff simulations when compared with a single objective calibration procedure. To demonstrate this, a single objective function calibration procedure was performed in which all parameters listed in Table 1 were calibrated simultaneously with one objective function (OF_{daily} using NRMSE from Equation 6). Figure 11 compares calibration period results (WYs 1996-2003) from the single objective automated calibration procedure and the multiple objective, step wise, automated calibration procedure. Figures 11a and 11b show mean monthly SR and PET results from single objective (dashed black line) and multiple objective (black line) procedures. Figure 11c shows annual water volumes calculated from measured data (gray line) and single objective (white dots) and multiple objective (black dots) procedures. Figure 11d shows the annual Nash-Sutcliffe goodness of fit statistic calculated with daily flow values simulated using single objective (white dots) and multiple objective (black dots) procedures. Single objective and multiple objective results for annual water volumes and Nash-Sutcliffe values are similar (Figures 11c and 11d). Single objective results for SR and PET are not

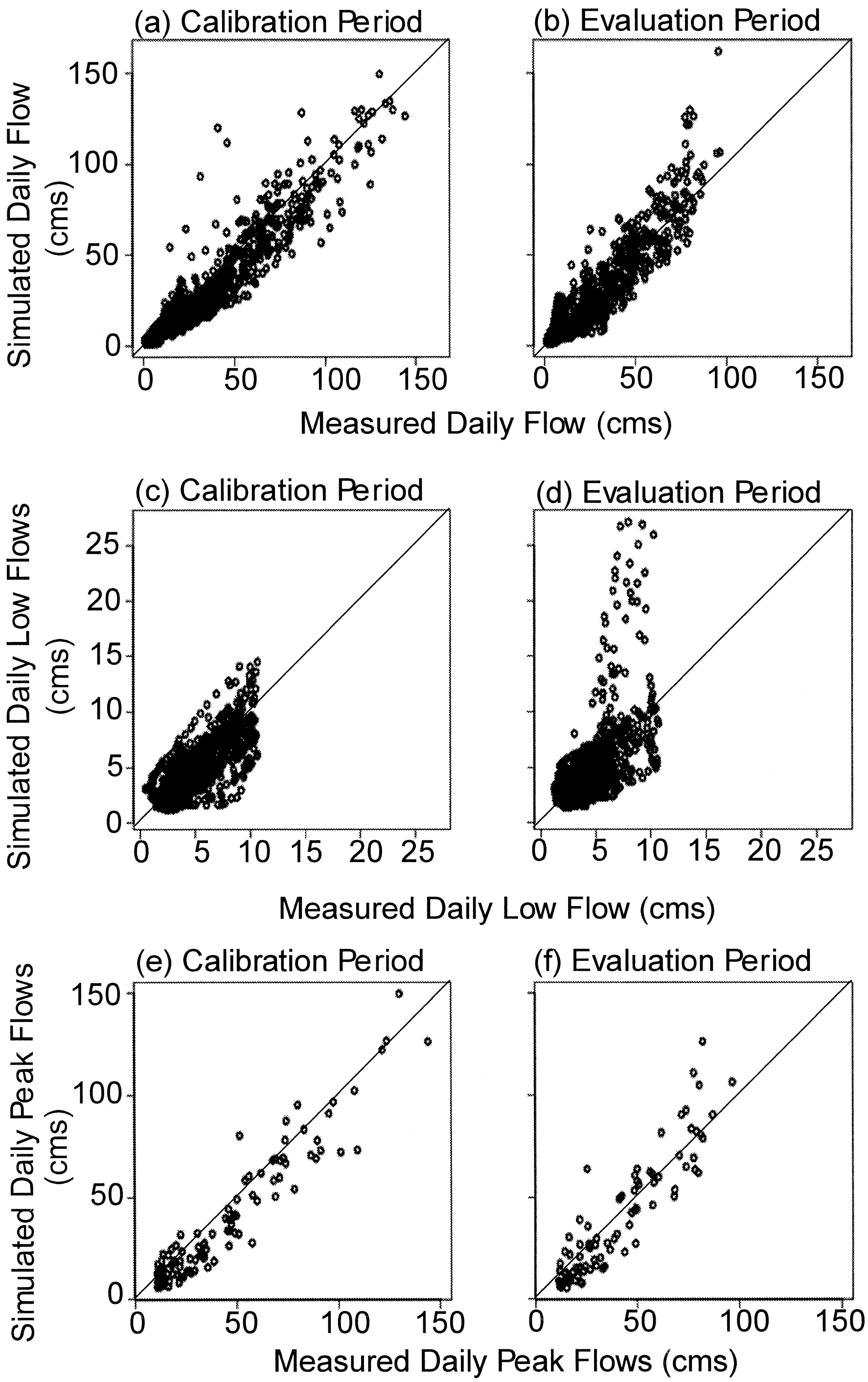

Figure 9. Simulated Versus Measured Daily Flows: (a) All Flows (WYs 1996 to 2003); (b) All Flows (WYs 1988 to 1995); (c) Low Flows (WYs 1996 to 2003); (d) Low Flows (WYs 1988 to 1995); (e) Peak Flows (WYs 1996 to 2003); and (f) Peak Flows (WYs 1988 to 1995).

comparable with measured or multiple objective results (Figures 11a and 11b). These results demonstrate that although you can achieve the same final, seemingly accurate, results with a single objective function (Figures 11c and 11d), the intermediate states are not accurately represented (Figures 11a and 11b). The multiobjective results improved simulations of the intermediate model states, giving more credibility to the simulation.

The step wise, multiple objective, automated calibration procedure is available in an extensible framework being packaged as part of the Object User

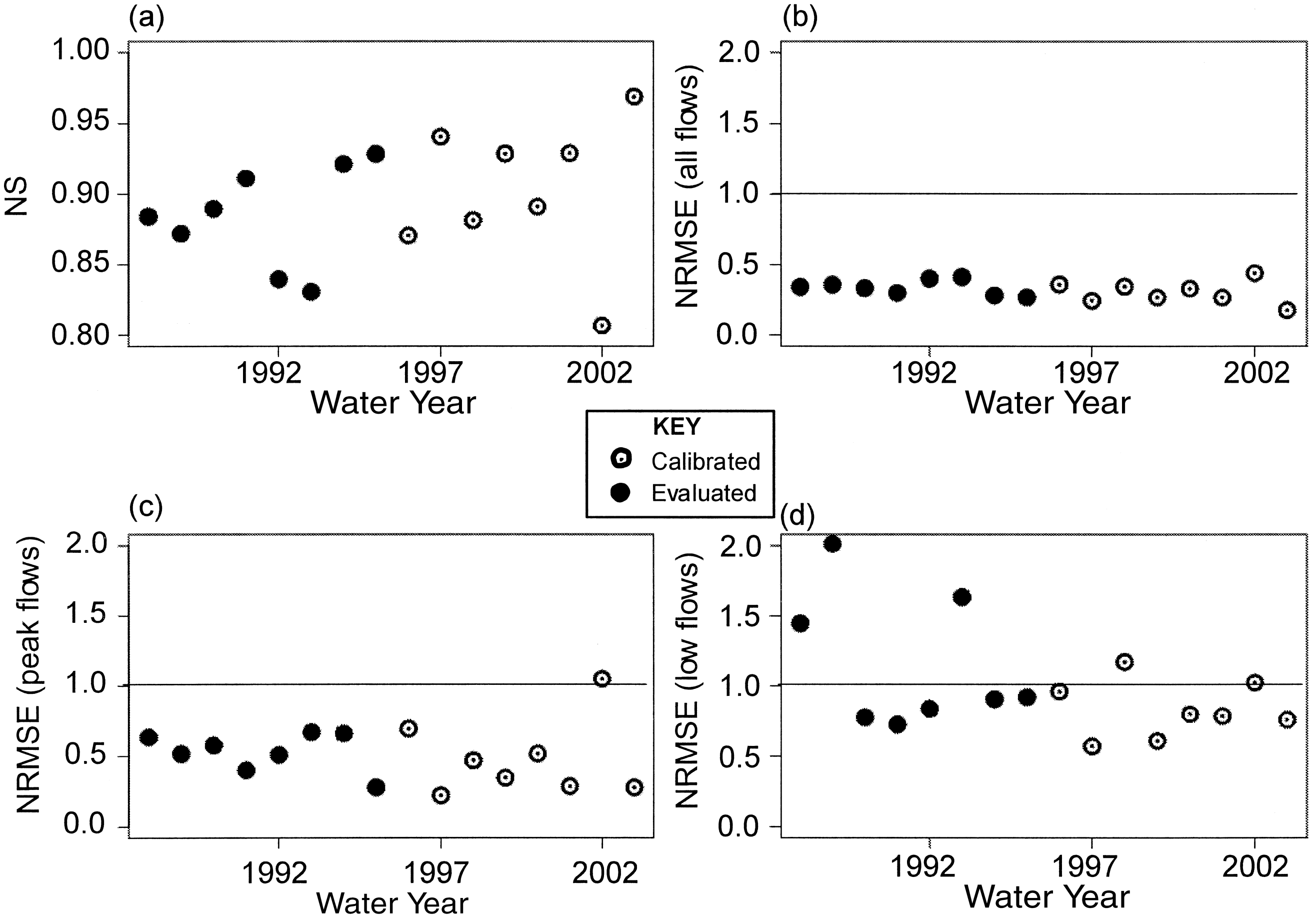

Figure 10. Evaluation of Daily Flow Values by Water Year: (a) Nash-Sutcliffe (NS) Goodness of Fit Test; (b) Normalized Root Mean Square Error (NRMSE) for All Flows; (c) NRMSE for Peak Flows; and (d) NRMSE for Low Flows.

Interface (OUI) modeling framework (USGS, 2005b). OUI is a map-based modeling framework for models, modeling data, and associated tools. It provides a common interface for running models as well as acquiring, browsing, organizing, and selecting spatial and temporal data. This allows users to modify the calibration procedure to their own models, data, objective functions, and calibration steps.

For example, a modification for a snowmelt dominated basin might include calibration steps for PRMS simulated snow covered area (SCA) or snow water equivalent (SWE). SCA and SWE data sets are available from the National Operational Hydrologic Remote Sensing Center (NOHRSC). The SCA and SWE NOHRSC products may not be appropriate for data assimilation purposes in PRMS due to data accuracy issues, but they may prove to be a valuable tool in documenting these intermediate model states.

Many of the data sets that could be used for intermediate model state identification are processed from other data sources and therefore not available in real time. The most appropriate use of these data sets would be for model calibration. In addition, when there is no runoff data available for calibration purposes (ungaged basin), intermediate model states can be calibrated and only the parameters associated with runoff calibration steps need to be identified.

CONCLUSIONS

This paper presented an application of a calibration procedure that used a multiple objective, step wise, approach. The procedure used the Shuffled Complex Evolution global search algorithm to calibrate the Precipitation Runoff Modeling System (PRMS) in the Yampa River basin of Colorado. The base application included the sequential calibration of: (1) mean monthly solar radiation, (2) mean monthly potential evapotranspiration, (3) annual water balances, and (4) components of daily runoff simulated by PRMS. The calibration procedure is available in an extensible framework, allowing for modification of the

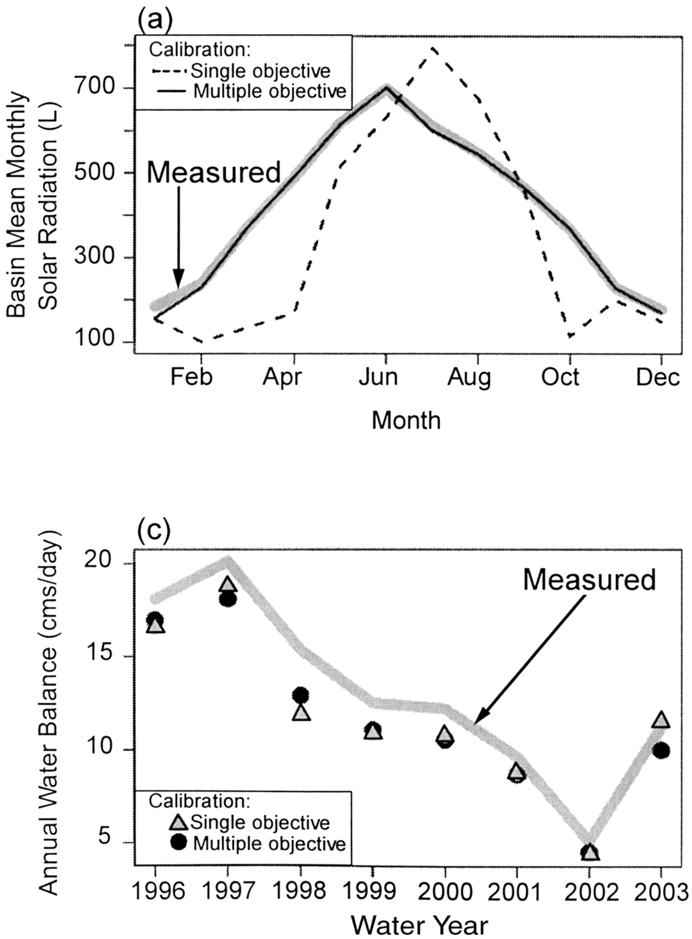

Figure 11. Comparison of Calibration Results From Single Objective and Multiple Objective Calibration Procedures: (a) Basin Mean Monthly Solar Radiation; (b) Basin Mean Monthly Potential Evapotranspiration (PET); (c) Annual Water Balance; and (d) Nash-Sutcliffe Goodness of Fit Statistic Using Daily Flow Data.

models, data, objective functions, and calibration steps based on the users needs. For this paper, the procedure not only produced realistic runoff, but it also documented intermediate states of the model on a monthly mean basis not normally calibrated in hydrologic models.

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