Comparison and semi-automatic calibration of two rainfall-runoff models used in NWS river forecasting operations

KATHRYN GOODWIN

Dept. of Civil and Environmental Engineering, Pennsylvania State University, 212 Sackett Building,
University Park, PA 16802

Abstract Two structurally different rainfall-runoff models are used by the National Weather Service (NWS) River Forecast Centers (RFCs) to generate daily forecasts of river conditions – the Sacramento Soil Moisture Accounting model (SAC-SMA) and the Continuous-API model (CONT-API). The SAC-SMA is conceptual and widely used in research and operations, while the CONT-API is empirically-based and rarely tested with developing hydrologic modeling tools. In this study, a recent semi-automatic calibration scheme is applied and its utility for the CONT-API model is evaluated. A comparison is also presented between the CONT-API and SAC-SMA when both models are coupled with a snow model (SNOW-17). Results indicate that the MACS procedure is an effective option to increase calibration efficiency for CONT-API, though some parameters should be excluded and defined manually. Overall model results were somewhat better for SAC-SMA than CONT-API. The improvement, however, was minimal and CONT-API produced results comparable to SAC-SMA results when parameters are estimated by semi-automatic calibration.

INTRODUCTION

The NWS RFCs are responsible to produce daily short-term forecasts of river conditions at hundreds of points throughout the United States. The theory and technology used by the RFCs to accomplish this task has evolved over time with advancements in hydrologic science and modeling. Before the development of continuous, conceptual hydrologic models, such as SAC-SMA, event-based API models were widely used at RFCs (Lindsey *et al.*, 1949). In recent years, 12 RFCs have migrated to SAC-SMA, while one RFC continues to use an API-based model

(CONT-API). Though the SAC-SMA model is typically considered a superior model for forecasting applications (Smith *et al*., 2000), few direct comparisons have been published and none were found in which the rainfall-runoff models are coupled with a snow model.

The SAC-SMA and CONT-API are both complex models (16 and 23 parameters, respectively) for which calibration can be prohibitively difficult and time-consuming. In recent years, substantial research has focused on ways to fully automate the calibration process. However, automatic methods have not been widely accepted by the NWS RFCs due to biased or unsatisfactory results (Boyle *et al.,* 2000). In efforts to avoid the limitations of fully automated and single criterion methods, other strategies have been developed that are semi-automatic (Brazil, 1988; Boyle *et al*., 2000; Hogue *et al.,* 2000) and multi-criteria (Gupta *et al*., 1998) in nature. These strategies have been tested (in large part) for the SAC-SMA model with good results, but they have not been applied (to our knowledge) for the CONT-API model.

The objectives of the work presented here are twofold. The first is to assess the utility of a Multi-step Automated Calibration Scheme (MACS) for use as an alternative to manual calibration of the CONT-API model coupled with the SNOW-17 model. The second objective is to compare model performance of the CONT-API and the SAC-SMA in basins where snow is a factor and the CONT-API is currently used for operational forecasting by the Mid Atlantic RFC (MARFC). Hydrographs and quantitative performance measures are calculated and compared for three study basins.

METHODS

Study Basins

The Juniata Watershed is located in the ridge and valley region of the Appalachian Mountains and is within the MARFC area of forecast responsibility. Three headwater sub-basins were selected from this area for the study. The corresponding NWS segment identifiers are SXTP1, WLBP1, and SLYP1. Sub-basin areas and mean annual flows are listed in Table 1. Historical data and manually calibrated CONT-API parameter sets were provided by the NWS Hydrology Lab.

Table 1 Study basin areas, mean flows, and variance of flow

Sub-basin	Area (km^2)	Mean Flow (cms)	Variance (cms)
SXTP1	1220	29.7	2589
WLBP1	470	12.2	403
SLYP1	485	11.8	711

Models

SNOW-17 The NWS snow accumulation and ablation model, SNOW-17 (Anderson, 1973) is a conceptual model that simulates the energy balance of a snowpack using a temperature index method. The model includes 12 total parameters, 6 of which have a significant effect on snowmelt (“major” parameters). Major parameters and their descriptions and listed in Table 2, along with the allowable range (Anderson, 2002) and the typical range of manually-calibrated values for the Juniata basins.

Table 2 Major SNOW-17 parameters, allowable ranges, and typical ranges in the Juniata basin

Parameter	Description	Allowable Range	Juniata Range
SCF	Gage catch deficiency adjustment factor	1.0 – 1.3	1.03 - 1.17
MFMAX	Maximum melt factor	0.5 – 1.2	0.6 - 0.82
MFMIN	Minimum melt factor	0.1 – 0.6	0.3 - 0.63
UADJ	Ave. wind function for rain-on-snow	0.02 – 0.2	0.04 – 0.09
SI	Mean WE above which 100% cover exists	10 - 120	39 - 102

CONT-API The CONT-API model is based on empirical relationships linked by a four-quadrant graphical structure (Sittner *et al.*, 1969). Beginning with the API value, calculations progress through the quadrants, accounting for seasonality and surface moisture (quadrants 1 and 2), then computing surface runoff and groundwater storage inflow (quadrants 3 and 4). Baseflow runoff is calculated from groundwater storage using the equations of the Stanford Watershed Model (Crawford & Linsley, 1966), which represents baseflow as two components in a manner similar to baseflow representation in the SAC-SMA. The CONT-API model has 23 parameters, 9 of which are typically calibrated (Table 3). The others are normally calculated from observed data or set to standard values. Parameters that control baseflow are shaded gray.

Table 3 Calibrated CONT-API parameters, allowable ranges, and ranges for the Juniata basins

Parameter	Description	Allowable Range	Juniata Range
AIXW	Wet curve intercept	1 – 15	2.9 – 4.0
AIXD	Dry curve intercept	10 – 40	22 – 27.5
CW	Wet curvature constant	0.1 – 0.9	0.5 – 0.63
CD	Dry curvature constant	0.2 – 0.9	0.59 – 0.67
SMIX	Maximum value of soil moisture index (SMI)	0.5 – 2.0	0.8 – 1.2
FRSX	Maximum percent runoff	0.3 – 1.0	0.75 – 0.84
BFIM	Baseflow weighing factor	1 – 13	3.0 – 6.5
ACIR	Critical index below which all infiltration goes to groundwater storage	1 – 6	3.1 – 3.4
CG	Groundwater inflow curvature constant	0.3 – 0.9	0.53 – 0.65

SAC-SMA The SAC-SMA is a conceptual model that represents the soil column by an upper and lower zone of multiple storages (Burnash, 1973). SAC-SMA has been used extensively in both research and operational applications (Brazil, 1988; Hogue *et al.,* 2000, Boyle *et al*., 2000). Of the 16 model parameters, 5 are often set to standard values. Table 4 lists the 11 typically-calibrated parameters of SAC-SMA, with allowable ranges (Anderson, 2002) and lower zone parameters shaded gray.

Table 4 Calibrated SAC-SMA parameters and ranges for the Juniata basins

Parameter	Description	Allowable Range
UZTWM	Upper zone tension water max. storage (mm)	25 – 125
UZFWM	Upper zone free water max storage (mm)	10 – 75
UZK	Upper zone free water withdrawal rate (day^{-1})	0.2 – 0.5
ZPERC	Maximum percolation rate (dimensionless)	20 – 300
REXP	Percolation equation exponent (dimensionless)	1.4 – 3.5
LZTWM	Lower zone tension water max storage (mm)	75 – 300
LZFPM	Lower zone free water primary max storage (mm)	40 – 600
LZFSM	Lower zone free water supplementary max storage (mm)	15 – 300
LZPK	Lower zone primary withdrawal rate (day^{-1})	0.001 – 0.015
LZSK	Lower zone supplementary withdrawal rate (day^{-1})	0.03 – 0.2
PFREE	% of water percolating directly to lower zone free water	0 – 0.5

MACS Procedure

The Multi-step Automated Calibration Scheme (MACS), developed by Hogue *et al.* (2005), is a three step method that attempts to mimic the manual calibration procedures used at the NWS RFCs. In each step an optimization algorithm is run for a specified parameter group and objective function, as depicted in Fig.1. The LOG criterion is used to emphasize the lower zone parameters and DRMS function to emphasize the upper zone parameters.

$$LOG = \sum_{t=1}^{n} \left(LOG_{Q_{s,t}} - LOG_{Q_{o,t}} \right)^2 \tag{1}$$

where $Q_{s,t}$ = simulated flow and $Q_{o,t}$ = observed flow at time step t, and *n*=number of time steps.

$$DRMS = \sqrt{\frac{1}{n}\sum_{t=1}^{n} \left(Q_{s,t} - Q_{o,t} \right)^2} \tag{2}$$

where $Q_{s,t}$ = simulated flow and $Q_{o,t}$ = observed flow at time step t, and *n*=number of time steps. Gray shading in Tables 2 & 3 indicates which parameters are considered lower zone. In this study, MACS was applied to estimate parameters of the SNOW-17 and CONT-API coupled model and the SNOW-17 and SAC-SMA coupled model for the three study sub-basins. The steps of MACS were performed using the NWS OPT-3 automatic calibration program with the Shuffled Complex Evolution (SCE-UA) algorithm (Duan *et al.*, 1993).

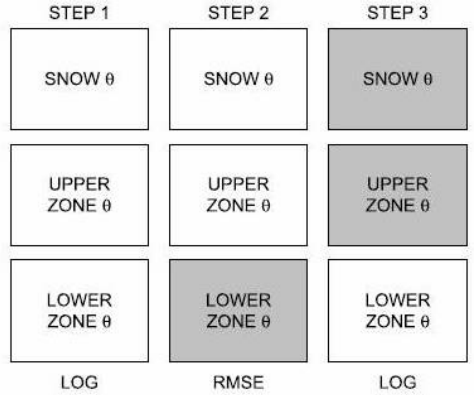

Fig. 1 MACS 3-step procedure for optimization, with inactive (non-optimized) parameter groups shaded gray and optimization criterion below the column (from *Hogue et al.*,2005)

Model Performance Measures

In order to quantitatively assess the performance of each model, several statistical measures were calculated for a 10-yr historical period. Using multiple performance measures, rather than a single measure, ensures the inclusion of different hydrograph components and a more complete evaluation of model performance (Sorooshian and Gupta, 1983; Yapo et al. 1997). The performance measures used in this study for model comparison include the LOG and DRMS functions, defined in equations (1) and (2) above, as well as the Nash-Sutcliffe Efficiency (NSE) and % Bias. NSE is derived as follows

$$\mathrm{NSE} = 1 - \left(\sum_{i=1}^{n} \left(Q_{s,t} - Q_{o,t} \right)^2 / \sum_{i=1}^{n} \left(Q_{o,t} - \overline{Q}_o \right)^2 \right) \tag{3}$$

where $Q_{s,t}$ = simulated flow and $Q_{o,t}$ = observed flow at time step t, Q_o= mean observed flow and *n* = number of time steps. The % Bias is a measure of total volume error by the equation

$$\%Bias = \left(\sum_{i=1}^{n} \left(Q_{s,t} - Q_{o,t} \right) / \sum_{i=1}^{n} Q_{o,t} \right) \times 100 \tag{4}$$

where $Q_{s,t}$ = simulated flow and $Q_{o,t}$ = observed flow at time step t, and *n* = number of time steps.

RESULTS

Parameter estimates

The parameter values resulting from the MACS procedure for the SNOW-17 and CONT-API coupled model were normalized and compared to manually-calibrated parameters (Fig. 2). The purpose of this comparison is to assess how similar (or different) are the two parameters sets, as well as to find any trends associated with the MACS procedure. Studies have shown that one “best” parameter set does not often exist for hydrologic models (Gupta *et al.*, 1998), but rather many sets may exist that provide similarly reliable results. Therefore the quality of the

MACS results are not judged solely based on closeness to manual parameter values. Hydrographs and quantitative performance measures are also reviewed in a later section.

The results in Fig. 2 demonstrate a strong dependence on the allowable range assigned for each parameter. Particularly for the SNOW-17 parameters, several of the MACS parameter values were equal to the maximum (or minimum) of the allowable range. This could imply that the range used for the parameter is too narrow (although a larger range could drive the MACS value further from the manually-calibrated value), or that insufficient information exists in the data to optimize the parameter. When the remaining parameters (those not equal to a range limit) are compared, there is some agreement between the MACS and Manual values. These values are emphasized in Fig. 2 by open and filled circles. Results of the MACS procedure for the SNOW-17 and SAC-SMA coupled model for each basin are given in Fig. 3. The SNOW-17 parameters show a similar pattern to Fig. 2 and some resulting SAC-SMA parameters (UZTWM, LZTWM, LZSK) are also equal to a range limit.

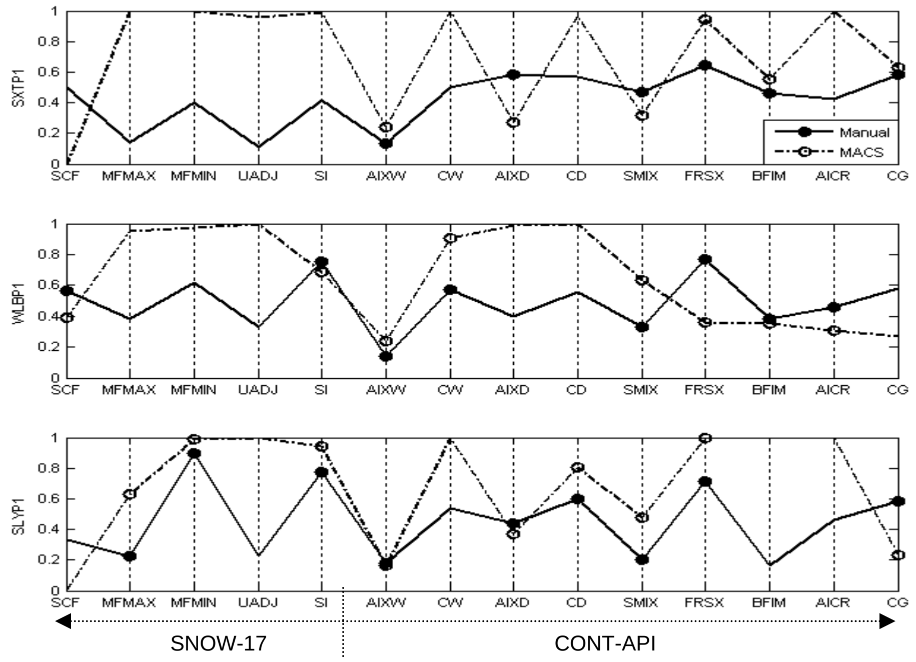

Fig 2 Manual and MACS normalized parameter values for SNOW-17 and CONT-API

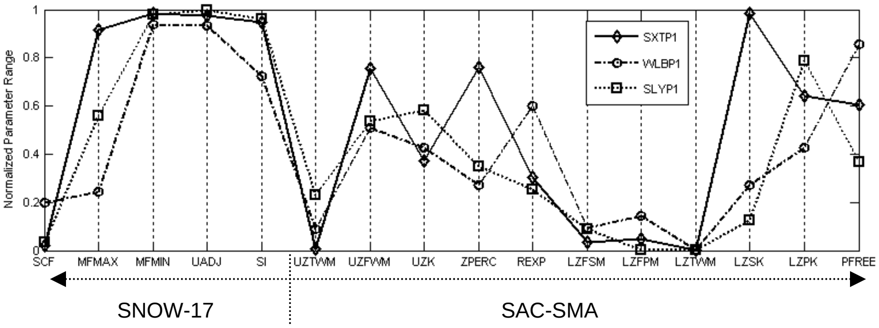

Fig 3.MACS normalized parameters for SNOW-17 and SAC-SMA

Hydrographs

Hydrographs resulting from three model simulations (referred to as API-manual, API-MACS, SAC-MACS) are plotted with observed data for water year 1997 in Figs. 4-6. An arithmetic scale is used to analyze high flows and a logarithmic scale to highlight low flows. The overall results show that for each model the quality of the simulations (in terms of closeness to observations) varies with basin and flow regime.

In comparing API-MACS and API-Manual, both models performed reasonably well for sub-basin SXTP1 (Fig. 4) with some minor differences. API-Manual simulates the mid-to-low peaks better (i.e., April-June), but over-simulates the high peak in November. Low flow simulations are fairly good for both models in SXTP1. Basin WLBP1 results (Fig. 5) show that API-Manual over-simulates nearly all events, particularly during the summer recession (June-Sept), while API-MACS simulates fairly well. The two model results are somewhat similar in basin SLYP1 (Fig. 6), though API-Manual is again too high during the summer recession and API-MACS winter recessions are too steep and low (Dec-Jan). In comparing API-MACS and SAC-MACS hydrographs for all three basins, both models perform similarly well for the peaks and low flows with only short periods of over- or under-simulation.

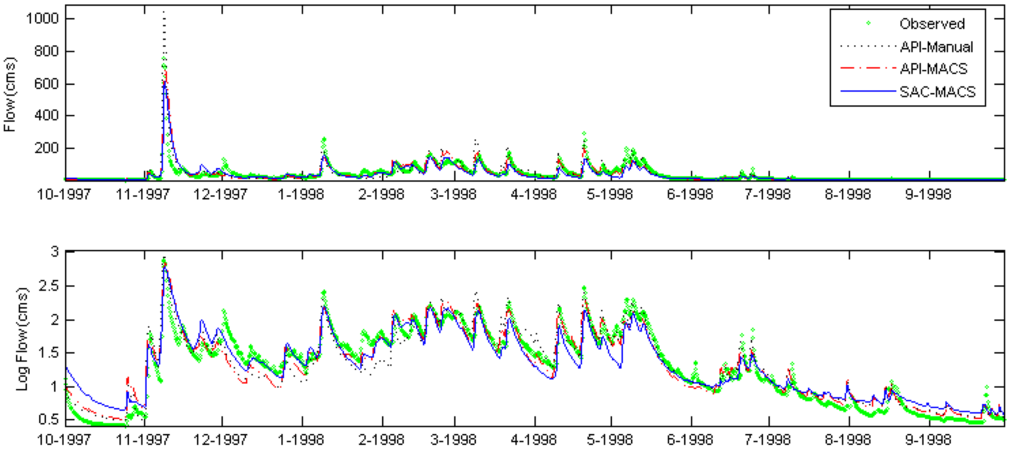

Fig 4 Hydrographs on arithmetic and log scale for basin SXTP1 and WY 1997

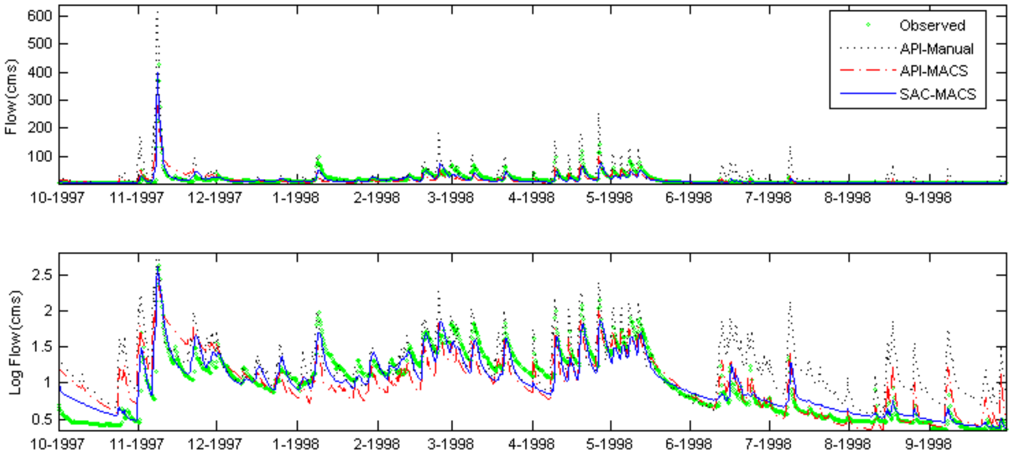

Fig 5 Hydrographs on arithmetic and log scale for basin WLBP1 and WY 1997

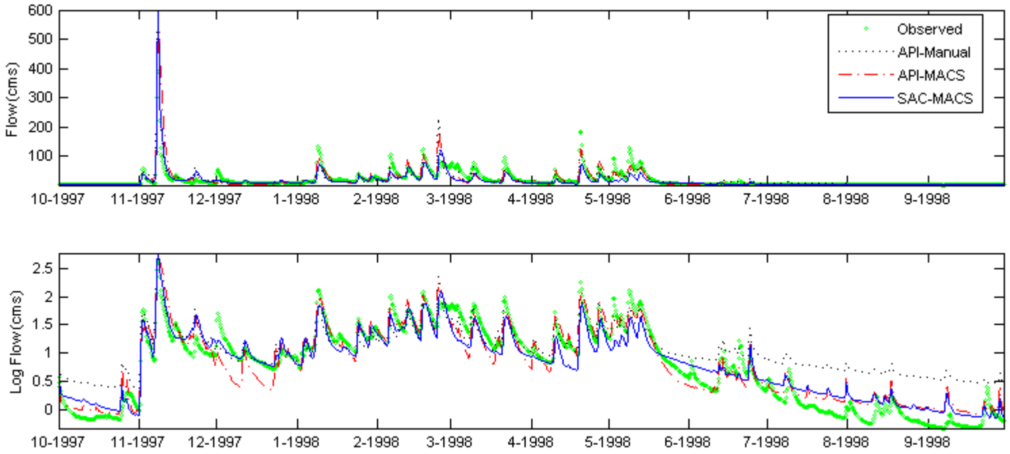

Fig 6 Hydrographs on arithmetic and log scale for basin SLYP1 and WY 1997

Statistics

Plots of statistical performance measures are given in Fig 7. The API-Manual and API-MACS values of NSE, DRMS, and % Bias were similar (though API-MACS slightly better) for basins SXTP1 and SLYP1. The LOG value for basin SLYP1 reflects the poor low flow simulations that were seen in Fig. 5. API-MACS values of all measures for basin WLBP1 were substantially better than API-Manual values, which is consistent with poor simulations by API-Manual for all portions of the hydrograph seen in Fig. 6.

The SAC-MACS model performed the best for each basin with respect to the NSE and DRMS values, though differences with API-MACS values were small. Conversely, the % Bias was worse for SAC-MACS (compared to API-MACS) in all basins. The LOG values were nearly the same in basin SLYP1, better for SAC-MACS in basin WLBP1, and slightly better for API-MACS in basin SXTP1.

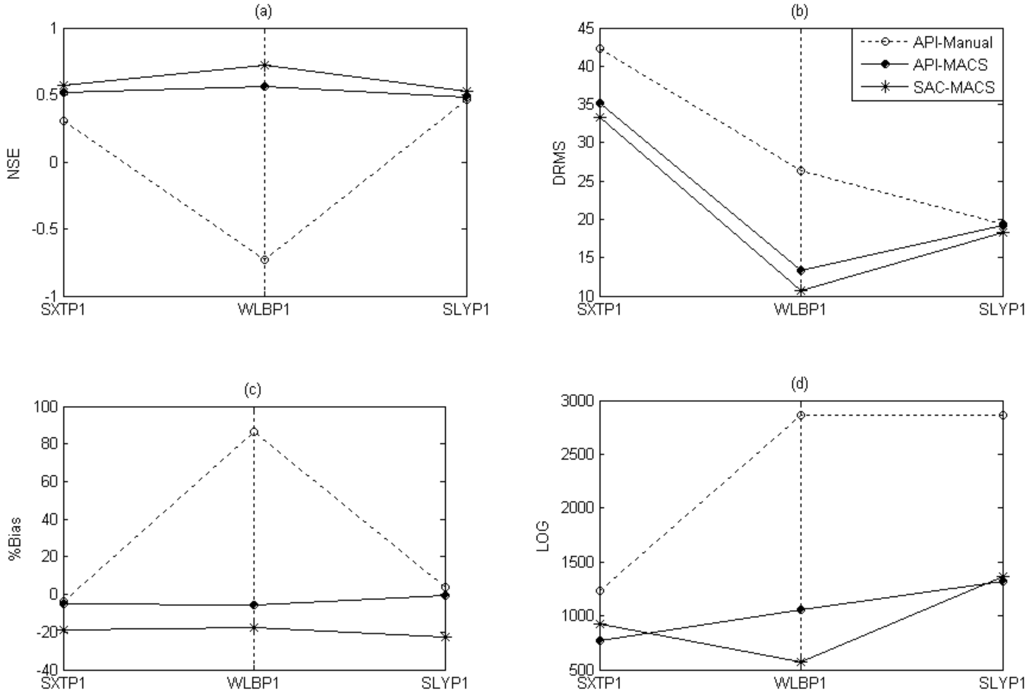

Fig. 7 (a) NSE (b) DRMS (c) %Bias and (d) LOG values for the three sub-basins and three model combinations.

DISCUSSION AND CONCLUSIONS

The results presented here demonstrate that a semi-automatic calibration procedure known as MACS could be a useful tool for RFCs to increase calibration efficiency of the CONT-API model, but some parameters should be excluded. When the procedure was tested for CONT-API coupled with SNOW-17, some of the resulting parameter values were reasonable, while others were set to a limit of the allowable range. Similar results were found when the procedure was tested for the same sub-basins with a SAC-SMA and SNOW-17 coupled model. Consistency in the unidentifiability of the SNOW-17 parameters suggests that a lack of information exists in the data to activate or isolate those parameters. Thus coupling with CONT-API (and parameter interaction) is not the cause of SNOW-17 parameter unidentifiability by MACS. Furthermore the SAC-SMA parameters UZTWM and LZTWM (both equal to a range limit in some cases) are reported by Anderson (2002) to be difficult to isolate for wet climates. It can reasonably be concluded that the CONT-API parameters that were set to range limits can also not be estimated given the data and should likely be excluded from the MACS procedure.

The hydrographs and performance measures revealed that despite some significant differences in parameter values, the API-MACS models actually performed as good as or better than the API-Manual models, further demonstrating the success of MACS. Future work should investigate how results are affected by excluding and manually defining the unidentifiable SNOW-17 and CONT-API parameters. This preliminary study however, provides evidence that the MACS procedure is useful to estimate a subset of the parameters included in this analysis for each basin.

As a second objective, model performance of a SNOW-17 and CONT-API coupled model with MACS-derived parameters (API-MACS) was compared to a SNOW-17 and SAC-

SMA coupled model (SAC-MACS) for the three study sub-basins. Hydrograph analysis did not reveal significant superiority of one model over the other, though some areas of over- and (particularly) under-simulation were evident for both models. Performance measures reaffirmed the overall similar performance of the two models. Detailed comparison showed that the SAC-SMA model performs slightly better for peaks (NSE, DRMS) and worse for volume (%Bias), than the CONT-API. The low flow results (LOG) varied by sub-basin. For all measures the differences are not large and the CONT-API model produces results similar to the SAC-SMA, when both models are coupled with SNOW-17 and their parameters are estimated by MACS.

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