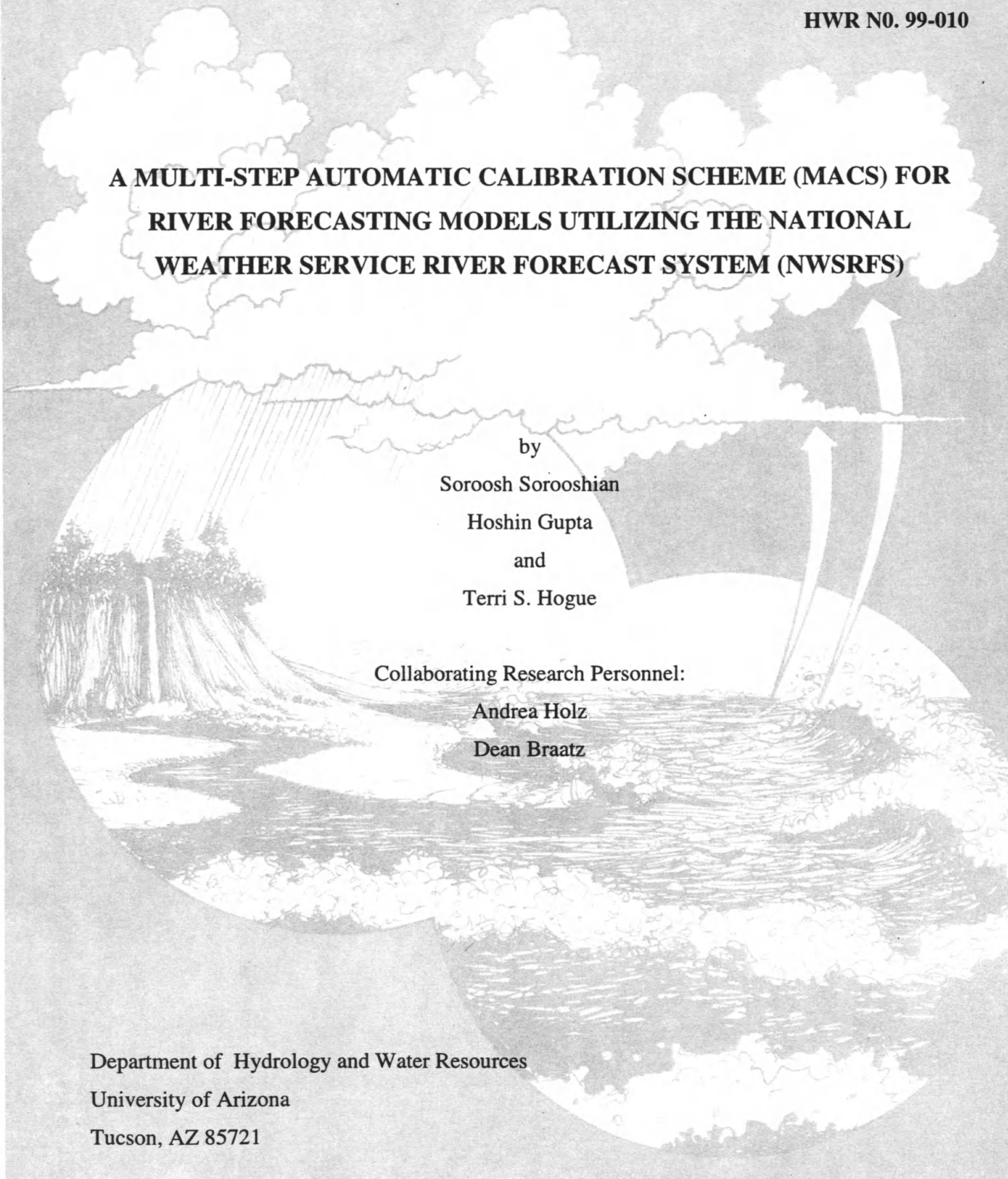

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A MULTI-STEP AUTOMATIC CALIBRATION SCHEME (MACS) FOR RIVER FORECASTING MODELS UTILIZING THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM (NWSRFS)

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ABSTRACT

Traditional model calibration by National Weather Service (NWS) River Forecast Center (RFC) hydrologists involves a laborious and time-consuming manual estimation of numerous parameters. The National Weather Service River Forecasting System (NWSRFS), a software system used by the RFCs for hydrologic forecasting, includes an automatic optimization program (OPT3) to aid in model calibration. The OPT3 program is not used operationally by the majority of RFC hydrologists who perform calibration studies. Lack of success with the traditional single-step, single-criterion automatic calibration approach has left hydrologists more comfortable employing a manual step-by-step process to estimate parameters. This study develops a Multi-step Automatic Calibration Scheme (MACS), utilizing OPT3, for the river forecasting models used by the RFCs: the Sacramento Soil Moisture Accounting (SAC-SMA) and SNOW-17 models. Sixteen parameters are calibrated in three steps, replicating the progression of manual calibration steps used by NWS hydrologists. MACS is developed by minimizing different objective functions for different parameters in a step-wise manner. Model runs are compared using the MACS optimized parameters and the manually estimated parameters for six basins in the North Central River Forecast Center (NCRFC) forecast area. Results demonstrate that the parameters obtained via the MACS procedure generally yield better model performance than those obtained by manual calibration. The MACS methodology is a time-saving approach that can provide prompt model forecasts for NWS watersheds.

1. INTRODUCTION AND SCOPE

a. Background

The National Weather Service (NWS) River Forecast Centers (RFCs) are currently in the midst of a national modernization effort, with the goal of improving hydrologic forecasts and mitigating the loss of life and property caused by flooding. Implementation of the proposed Advanced Hydrologic Prediction System (AHPS) will provide forecasts with lead times of a few days to several months. As part of the AHPS updating, many of the 13 RFCs located across the United States are in the process of implementing several modules of the NWSRFS, including the Sacramento Soil Moisture Accounting Model (SAC-SMA) and a Snow Accumulation and Ablation Model (SNOW-17). Implementation of these models requires calibration to forecast points within each of the RFCs. Calibration, in the traditional sense, involves using hydrologic inputs of a watershed and adjusting parameters to match model simulations with observed historical data. With over 4000 river basins located across the United States (Ingram, 1996), calibration of the complex SAC-SMA and SNOW-17 models has become a labor-intensive and time-consuming portion of the RFC hydrologists' duties. Although a great deal of research has been devoted to the development of automatic optimization techniques, most NWS hydrologists still prefer to use manual methods to estimate the numerous parameters of the models.

Since 1985, the majority of RFCs have been using a highly integrated, centralized software system known as the NWSRFS (Page, 1996). The system is a highly interdependent batch-operating system containing various models and algorithms to aid the RFCs in their hydrologic forecasting responsibilities. The system consists of three main components: a Calibration System (CS), an Operational Forecast System (OFS), and an Extended Streamflow Prediction (ESP).

The OFS contains several river-forecasting models that the RFC may use, including the Antecedent Precipitation Index (API) and the SAC-SMA, along with a snowmelt model, SNOW-17. The Calibration System within NWSRFS contains manual and automatic calibration programs that can be used in conjunction with an Interactive Calibration Program (ICP) to aid in the estimation of parameters for the hydrologic models. The majority of hydrologists within the NWS use the Manual Calibration Program (MCP3), along with the interactive visual interface, ICP, to manually estimate parameters for the SAC-SMA and SNOW-17 models. The Calibration System also contains an Automatic Optimization Program (OPT3) that can be used to automatically estimate parameters for watersheds.

Calibration of the 16-parameter SAC-SMA, in conjunction with the 12-parameter SNOW-17 model, requires a thorough knowledge of the model structure and an understanding of the effects which various parameters have on model output. The RFC hydrologists are trained in calibration procedures via workshops and seminars presented by experienced modelers and calibrators within the NWS organization. Many of the RFCs are just beginning to implement and operate the SAC-SMA, and the effort required to train hydrologists on the workings of the model and have them be proficient manual calibrators is immense. Several of the RFCs are faced with imminent deadlines and numerous basins to calibrate for implementation of the SAC-SMA and SNOW-17 models as part of their forecasting regime. The NCRFC, one of the NWS's largest river forecast centers, is in the process of calibrating the NWSRFS models for approximately 900 basins. The NCRFC has recently elevated the priority of calibrating the SAC-SMA and SNOW-17 models. Of the 900 basins within their forecast area, approximately 225 are completed. The NCRFC hopes to implement the SAC-SMA by the year 2005 and has been using manual calibration methods to estimate parameters. NCRFC hydrologists report the typical length of time spent on calibration of a forecast point is 15-20 hours. Presentation of previous work by Hogue (1998) involving use of the OPT3 for calibration of NWS basins in the Mid-Atlantic River Forecast region generated interest by the NCRFC in automatic optimization techniques. With approaching deadlines, the NCRFC is looking for ways to speed up the calibration process for the remaining 675 basins. This study evolved from a cooperative agreement between the NWS Hydrologic Research Laboratory (HRL) and the Department of Hydrology and Water Resources at the University of Arizona to investigate the feasibility of RFCs using OPT3 as a tool in their calibration efforts.

b. Automatic Calibration

Fueled by the time-consuming and difficult nature of manual calibration, the last few decades have seen a great deal of research focus on the development of automatic calibration methods. The evolution of these methods has been motivated by several factors: (1) the need to speed up the calibration process, (2) the need to assign objectivity and confidence to the calibration process (and hence, model predictions), and (3) the lack of numerous "expert" calibrators available for each watershed model (Sorooshian and Gupta, 1995).

Automatic calibration methods have evolved significantly since early endeavors reported by Dawdy and O'Donnell (1965), Nash and Sutcliffe (1970), Ibbitt (1970), Ibbitt and O'Donnell (1971), Monroe (1971), and Johnston and Pilgrim (1976). Early problems in automatic calibration evolved around several issues: conceptually unrealistic parameter values, poor model performance on validation period (vs. calibration period), and the inability of the algorithms to find a “single” best parameter set (Gupta and Sorooshian, 1994). More recent research has seen the development of global search procedures (Brazil and Krajewski, 1987; Brazil, 1988; Duan et al., 1992; Duan et al., 1993; Sorooshian et al., 1993)) and multi-criteria optimization schemes (Gupta et al., 1998; Yapo et al., 1998), giving calibrators increased confidence in obtaining a “best” parameter set for their watershed models.

The basics of an automatic calibration procedure include:

1. the choice of an objective function
2. choice of an algorithm to search the parameter space
3. a period of historical data to calibrate the model against
4. termination criteria used to determine when to stop the search

The objective function chosen by the modeler represents the computation of a numerical measure of the difference between the simulated output and the observed or measured values. The goal of automatic calibration is to optimize (maximize or minimize) this objective function. Traditional measures used in single-objective optimization include Least Squares (or Daily Root Mean Square) and more recently, Maximum Likelihood functions. The current version of OPT3 is a single-objective calibration procedure, allowing the user a choice of six objective functions to use as the optimization criterion. The Daily Root Mean Square (DRMS) function has traditionally been chosen as the objective function for NWS calibrations. OPT3 allows the estimation of 16 model parameters in one single-objective optimization run. These limitations of OPT3 were primary factors constraining the development of the methods used in this study.

Once a response surface is generated from calculation of the objective function, an optimization algorithm or search procedure is used to search this surface, constrained by user-defined parameter ranges. The algorithm looks for the parameter values that minimize or maximize the chosen objective function. Optimization methods have been categorized as local search, such as the Pattern Search method (Hooke and Jeeves, 1961), the Rosenbrock method (Rosenbrock, 1960), and the Simplex method (Nelder and Mead, 1965), or as global search strategies, including Random Search method (Karnopp, 1963), Adaptive Random Search (Masri et al., 1978: Pronzato et al., 1984), and more recently, the Shuffled Complex Evolution method (SCE-UA) (Duan et al., 1992). The Shuffled Complex Evolution method, a global search procedure based on the nonlinear simplex method, uses concepts from the random search procedures, along with the strength of the downhill simplex method. The OPT3 algorithm within NWSRFS contains three of the established optimization strategies, the Pattern Search algorithm, the Adaptive Random Search algorithm, and the Shuffled Complex Evolution algorithm.

As part of the automatic calibration process, one must also select a historical period of data against which to calibrate the model. In selecting a calibration period, the goal is to choose a data set representative of the various hydrologic phenomena experienced by the watershed. Results and parameters obtained during calibration should be insensitive to the period of data that was selected if an adequate calibration period is selected. Research in this area by Yapo et al., (1996) found that approximately eight years of data, specifically including some of the wettest years, are adequate to ensure a quality calibration.

Termination criteria are needed to determine when to stop the search algorithm during an automatic calibration. Methods that have been used include parameter convergence, function convergence, or a maximum number of iterations. When an algorithm is unable to appreciably change parameter values and improve the objective function value, parameter convergence is achieved. Function convergence occurs when the algorithm is unable to improve the objective function beyond a predefined increment in one or more iterations. A calibrator also may set a maximum number of iterations to stop the search procedure, ensuring that the algorithm does not enter an endless loop. The OPT3 program allows the modeler to define a function convergence value, typically 0.1% change, and a maximum number of desired iterations.

c. Scope

The focus of this study is to investigate the practicality of using the automatic optimization algorithm, OPT3, to aid in calibration of the SAC-SMA and SNOW-17 models. Unlike optimization routines used in research and other operational settings, the OPT3 program available to RFC hydrologists has distinct choices available for search algorithms, objective functions, and the number and choice of parameters to calibrate. Limitations of the OPT3 program influenced the methods that were developed in this study: use of a single-criterion or single-objective function and a 16-parameter optimization limit. Although recent calibration research has taken a turn toward multi-objective or multi-criteria optimization studies, this analysis used only the options currently available to the RFC hydrologists. This paper, therefore, addresses how to incorporate the features and limitations of OPT3 into a functional optimization scheme that can give comparable results to an RFC hydrologists' manual calibration.

2. STUDY AREA

The NCRFC's area of forecasting responsibility, located in the upper Midwest, covers all of Minnesota, Wisconsin, and Michigan, portions of North Dakota, South Dakota, Iowa, Illinois, and Indiana, along with portions of southern Canada. Major drainages include the Upper Mississippi River, St. Lawrence River, and Hudson Bay. The basins selected by the NCRFC for this calibration study were all located within the Upper Mississippi River drainage and included four headwater basins of the Des Moines River: AKWI4, BSSI4, IDNI4, and NRWI4 and two headwater basins of the Minnesota River: MMLM5 and RPDM5 (Figure 1). Study basins, along with relevant data, are listed in Table 1.

Precipitation and streamflow records from 1948 to 1993 were obtained from the NCRFC for all of the basins. Average mid-month evapotranspiration (ET) values also were obtained to estimate the ET-demand curve in the SAC-SMA. For calibration of the models, an 11-year period, 1970 to 1981, was selected. Evaluation of the model was performed on data for the entire 1948 to 1993 period.

3. MODELS

a. SAC-SMA

The NWSRFS SAC-SMA is a continuous, physically based model that uses two soil-moisture layers to account for flow through the subsurface (Figure 2). The upper zone represents surface soil regimes and interception storage, while the lower zone represents deeper soil layers containing the majority of the soil moisture and groundwater storage (Brazil and Hudlow, 1981). Percolation of water from the upper to the lower zone is controlled by a complex nonlinear process dependent on the contents of upper zone free water and the deficiencies in lower zone storages. When rainfall exceeds interflow and percolation capacities, upper zone storage will be full, and saturated or overland flow will occur. The model has 16 parameters, an evapotranspiration demand curve (or adjustment curve), along with a unit hydrograph to convert channel inflow to streamflow. Inputs to the model include mean areal precipitation (MAP) (mm/6 hr) and potential evapotranspiration (mm/day). Outputs are estimated evapotranspiration (mm/day) and channel inflow.

b. SNOW-17

The NWSRFS SNOW-17 model uses the temperature index method to simulate the energy balance of a snowpack and model accumulation and ablation of the snow cover. SNOW-17 models the energy exchange at the snow surface, heat storage and heat deficit within the snowpack, liquid water retention and transmission through the snowpack, and heat exchange at the ground surface (Anderson, 1973). The model uses an areal depletion curve to estimate the extent of snow cover in a basin and subsequently determine rain-on-snow or rain-on-bare ground model simulations. Inputs to the SNOW-17 model include mean areal precipitation (mm/6hr) and temperature (°C/6 hr. or °F/6 hr.) and a Snow Water Equivalent (SWE) series (mm), if available. Outputs include a rain-melt time series (mm/6 hr) and SWE (mm) of the snowpack. When used in conjunction with the SAC-SMA, input to the SAC-SMA is the rain-melt output from the SNOW-17 model. The model has 12 parameters, of which six are considered major parameters (more of an effect on simulations) and six are minor parameters (less of an effect). Parameters for both the SAC-SMA and SNOW-17 model are listed in Table 2.

Along with the SNOW-17 and SAC-SMA models used by the NCRFC, the forecast center also has implemented a Frozen Ground Model developed specifically for the region. The model computes a Frost Index that reduces percolation to the lower zone and decreases lateral interflow in the SAC-SMA during periods of deep ground frost. Because the Frozen Ground Model is currently not one of the OPT3 calibration options, the model was not optimized, but was run as part of the system with parameter values used by the NCRFC. Unit Hydrograph ordinates for each basin also were obtained from the NCRFC and were not calibrated during this study.

Without including the Frozen Ground Model parameters and the Unit Hydrograph ordinates, there are 28 parameters that need to be estimated: 16 for the SAC-SMA and 12 for the SNOW-17. Of the 16 SAC-SMA parameters, three of the parameters, RIVA, SIDE, and RSERV, can be fixed at established values from literature and local hydrologic knowledge. RSERV and SIDE typically are set to 0.3 and 0.0, respectively. RIVA was set equal to 0.0 for five of the basins and to 0.005 for basin MMLM5. The PCTIM parameter also can be established from regional maps and local hydrologic information. For the SNOW-17 model, the minor parameters, along with the areal depletion curve, were set at values obtained from the NCRFC and were not optimized.

These parameters can be estimated from model documentation (Anderson, 1973, 1978) or obtained from historical snow data for the basin. Two additional parameters, EFC and PXADJ, were not optimized, with EFC and PXADJ set to 0.0 and 1.00, respectively, for all basins. For this study, the UADJ parameter was not optimized and was set to an established value of .100, based on values used in other areas of the NCRFC. In summary, 12 of the SAC-SMA parameters, along with four major snow model parameters, SCF, MFMAX, MFMIN, and SI, will be considered for optimization in this study (Table 2).

c. SCE Optimization Method

The SCE-UA, part of the NWSRFS OPT3, is a global search optimization algorithm designed to handle problematic, nonlinear response surfaces encountered in the calibration of conceptual watershed models. The SCE-UA algorithm has been tested extensively in the last few years (Duan et al., 1992, 1993; Sorooshian et al., 1993; Gan and Biftu, 1996; Kuczera, 1997; Cooper et al., 1997; Franchini et al., 1998; Freedman et al., 1998; Thyer et al., 1999) and has demonstrated its ability to efficiently and consistently find a global optimum. A detailed description of the method appears in Duan et al. (1992). A summary of the algorithm is presented here:

(1) A "population" of points is selected randomly from the feasible parameter space.

(2) The population is partitioned into several complexes, each with 2n+1 points, where n is the number of parameter to be optimized.

(3) Each complex is evolved independently based on the downhill simplex method.

(4) The population is periodically shuffled to share information, and new complexes are formed.

(5) Evolution and shuffling are repeated until the entire population until the specified convergence criteria are satisfied.

In this study, 13 complexes were used (this gave a population size of 13 x ((2 x 16) + 1)) = 429 points), with a convergence criterion of .1% (change in objective function) in 5 loops. The search was terminated after 20,000 iterations (if an optimum was not reached).

4. MULTI-STEP AUTOMATIC CALIBRATION SCHEME (MACS)

a. Introduction

Although available to NWS hydrologists, the OPT3 program within the NWSRFS is not operationally used by RFC hydrologists. Problems with the classical single-step, single-objective approach have led modelers to question the abilities of automatic calibration methods. The traditional approach of single-step automatic optimization has been to apply the DRMS objective function, calibrate all possible parameters, and run a single optimization. As observed in our research, this approach generally leads to a good overall DRMS statistic, but model results do not reasonably match the observed hydrograph: low flows and the recession limbs of the hydrograph are not well-simulated. With these problems in mind, the objective of our research was to develop a method that would utilize the OPT3 program, but would take into account differing objective functions for various parts of the hydrograph. To accomplish this, two objective functions were chosen from the available options in OPT3 that would emphasize the various parts of the hydrograph to be calibrated. A LOG function was chosen to calibrate baseflow and recession parameters, and the DRMS function was chosen when parameters affecting higher flow events were to be calibrated. These are defined as follows:

$$LOG = \sum \left(LOG_{Q_{sim,t}} - LOG_{Q_{obs,t}} \right)^2 \tag{1}$$

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

where $Q_{sim,t}$ = simulated flows, and $Q_{obs,t}$ = observed flows at timestep, t.

The principles behind the MACS process developed in this paper are not new: other researchers have developed automatic step-by-step schemes to calibrate hydrologic models. Harlin (1991) developed a Process Oriented Calibration (POC) automatic calibration scheme to apply to the HBV model. The POC method incorporated a two-step automatic calibration scheme, minimizing different parameters with different objective functions over relevant subperiods of the data. Brazil (1988) developed an interactive multi-stage semi-automated (manual) method to calibrate the SAC-SMA. However, from interactions with the NWS RFC hydrologists, it is apparent that traditional manual calibration methods still are the norm. The MACS method developed in this paper uses technology currently available to NWS hydrologists, with the goal of encouraging more usage of automatic calibration techniques within routine RFC calibration operations.

The development of MACS was designed to mimic the process used by NWS hydrologists in their manual calibration of basins. In the initial calibration phase of a basin, the modeler attempts to match baseflow (lower zone) parameters of the SAC-SMA. MACS imitates this process by first running an optimization to model recessions and lower flow values. The second step of the calibration process attempts to estimate parameters that influence higher flow events. The MACS method holds baseflow parameters (found in step 1) constant and calibrates upper zone SAC-SMA and the SNOW-17 model parameters. Once parameters are obtained in the second step, a third calibration is run to refine the baseflow parameters. An optional fourth step in the MACS process is to manually adjust monthly ET parameters in order to minimize monthly flow biases.

The NWS RFCs use several statistics, along with visual inspection of modeled vs. simulated hydrographs, to evaluate model calibrations. Statistics include monthly and flow interval percent biases, overall percent biases, and overall DRMS values. DRMS is calculated using the previously defined Equation 2, while percent bias is defined as follows:

$$\%Bias = \left(\sum_{t=1}^{n} Q_{sim,t} - Q_{obs,t}) / \sum_{t=1}^{n} Q_{obs,t} \right) * 100 \qquad (3)$$

DRMS and percent bias statistics were computed for all model runs during this study, using a statistical package within NWSRFS (STAT-QME). Visual inspections of hydrographs included observing peak simulations, recession slopes, precipitation typing, and timing of spring snow melt. These criteria will be evaluated for all of the basins used in this study. All MACS simulations also are compared to the RFC manual calibration hydrographs and statistics, the baseline or reference for this study.

b. Methodology

In selecting the calibration data for this study, the historical record was evaluated for a period that consisted of high flood events along with years where drier conditions prevailed. In consultation with NCRFC, an 11-year period, WY 1971-1981, was selected for calibration of the study basins. After calibration of the basins, evaluation of the MACS procedure consisted of running simulations with the estimated parameters on the entire historical record of data, 1948-1993. All model runs were compared to RFC manual calibration statistics and hydrographs.

Parameter ranges for all calibrations were obtained from the NCRFC and were considered reasonable limits for parameters in the study region (Table 2).

1) Step 1 – Estimation of Baseflow Parameters

In the initial calibration phase of a basin, baseflow parameters of the SAC-SMA are estimated (Table 3). An optimization is run using the LOG objective function with all 16 parameters, 12 SAC-SMA, and four SNOW-17, using the 11-year calibration period (Table 3). Figure 3 illustrates one year, WY 1973, of the Step 1 model calibrations on basin AKWI4. Daily MAT and MAP time series are at the top of Figure 3a, with hydrographs of the RFC manual calibration vs. observed flows shown in 3b, and MACS Step 1 vs. observed flows displayed in 3d. Calibration residuals (the difference between observed and simulated flows) for each of the simulations are displayed in Figures 3c and 3e. The hydrographs depicted in Figures 3b and 3d present transformations of the flow values, which is done to expand the scale at the lower end of flow values for analysis of recessions, while still maintaining a visual perspective of the higher flows. The transform flow (Q) is calculated as follows:

$$Q_{tranformed} = \frac{(Q_t + 1)^{\lambda} - 1}{\lambda} \qquad (4)$$

where $\lambda = 0.3$ in this transformation. (Note: a value of $\lambda = 0$ equates to a log transformation, and $\lambda = 1$ equates to no transformation. A transformation of $\lambda = 0.3$ was chosen for transformation after an evaluation of hydrographs with a full range of λ values).

Both the MACS step 1 and RFC calibrations slightly underestimate peak flow values, yet the MACS step 1 simulation also does a better job of simulating recession flows than the RFC manual calibration. Figure 4 also shows another WY of the AKWI4 MACS step 1 simulation. The MACS method simulates recession and low-flow values comparable to the RFC simulation.

2) Step 2 – Calibration of Upper Zone SAC-SMA and SNOW-17 Parameters

The second step of the MACS process emphasizes the estimation of parameters that influence higher flow events. Lower zone parameters estimated in Step 1 are held constant, and a second optimization is run. Because of the emphasis on peak flows, the objective function chosen is the traditional DRMS, and only the SAC-SMA upper zone and percolation parameters, along with the four SNOW-17 parameters, are optimized (Table 3). Figure 5 shows that this second step significantly decreases the overall percent bias while slightly reducing the overall DRMS from Step 1 for basin AKWI4. Once the upper zone and snow parameters are estimated, they may be fine-tuned manually or held as estimated, but these parameters are not optimized further.

3) Step 3 – Refinement of Baseflow Parameters

Once parameters are obtained in Step 2, a third calibration is run to fine-tune the baseflow parameters with the new upper zone and snow parameters. This step may not show improved model performance for all basins. Only the six SAC-SMA lower zone parameters are optimized, again using the LOG objective function (Table 3). As illustrated in Figure 5, Step 3 does not improve percent bias or overall DRMS on basin AKWI4. However, both Step 2 and Step 3 show much improvement over the RFC statistics. Figure 6 shows monthly percent biases for Steps 1, 2, and 3 vs. RFC percent biases on basin AKWI4, for the 11-year calibration period. The plot shows that although Step 3 did not improve the overall percent bias and DRMS statistics, there is a significant improvement in monthly percent biases for this basin.

Figures 7 and 8 display resulting hydrographs from MACS Step 3, and the manual RFC simulations from basins BSSI4 and RPDM5. These plots are for a single water year and are the same as that described previously for Figure 3. These plots illustrate the different hydrologic regimes in the Minnesota and Iowa river basins. MACS shows comparable model simulations to the manual calibration simulations for basin BSSI4 (Figure 7), with slightly better fitting of recession flows. However, both model simulations tend to slightly underpredict on extreme or high flow events. The MACS simulation does a slightly better job than the RFC simulation in matching the observed flows for basin RPDM5 (Figure 8).

RFC and MACS statistics for the 11-year calibration period and 46-year verification periods are displayed in Table 4. Overall DRMS and percent bias statistics are listed for each basin. For nearly all calibration periods, the MACS procedure results in better overall statistics. The percent bias is significantly reduced from the RFC value in five of the six basins and the DRMS is also slightly improved in five of the six basins. Statistics during the 46-year verification period also reflect general improvement, with percent bias reduced in five of the six basins and DMRS decreased in three of the six basins.

Figure 9 illustrates the flow duration curve for the final calibration (Step 3) of the AKWI4 basin as compared to the observed flows and the RFC manually calibrated model simulation. The MACS simulation of the 11-year calibration period tends to match the observed flows throughout the range of flows on this basin. Although this traditional flow duration curve shows a general trend of the simulations, it is difficult to visualize how well the simulation performs at the higher range of flow values. Figure 10 illustrates modified flow duration curves, with the x-axis expanded at the higher flow values by use of a logarithmic scale. Five of the basins are plotted with parameters from Step 3 of MACS, while RPDM5 is illustrated with parameters estimated after Step 4 (discussed below). On four of the six basins, AKWI4, BSSI4, NRWI4, and MMLM5, the MACS simulation tends to better match higher flow values. On basin IDNI4, both RFC and MACS tend to over-simulate flow values, and on basin RPDM5, both RFC and MACS undersimulate observed flow values at the high end.

4) Step 4 – Adjustment of ET Values

As a final, but optional step, a final check of monthly percent biases may reveal trends that call for an adjustment of previously estimated ET parameters. The current version of OPT3 does not allow for automatic optimization of the ET demand curve. A manual fine-tuning or adjustment of these parameters, using monthly percent biases as a guide, may help in producing more accurate streamflows during all seasons. After the first three calibration steps with MACS, basins RPDM5 and INDI4 still had monthly biases that were unreasonably high and showed seasonal trends. Using monthly percent biases and ET values from nearby basin as a guide, monthly ET parameters for both basins were adjusted manually to bring the percent biases into a more reasonable range (ideally <10%). Figure 11 illustrates final monthly percent biases for the MACS method for basins IDNI4 and RPDM5 after ET adjustment. Monthly percent biases are plotted for Steps 1, 2, 3, and 4 (ETadj). Because there was no change in baseflow parameters when running Step 3 on RPDM5, Steps 2 and 3 are plotted together. The plot for Basin IDNI4 displays all four steps of the MACS method. The adjustment of the ET parameters significantly reduced the monthly biases for both basins, as evidenced in the decrease in percent biases from Step 3 to Step 4 (ETadj) for most of the months. This step was only necessary on basins IDNI4 and MMLM5 and was not performed for other basins.

c. Evaluation Period

Final parameter values obtained during the calibration are listed in Table 5 for all of the six study basins. As is evident, multi-step and RFC manual calibrations converged to slightly different values on the majority of basins. Parameter bounds used in the calibration were considered representative for the study area; therefore, the values obtained for both methods are considered conceptually realistic and yield satisfactory model performance.

After initial calibration of all the basins, evaluation of the calibrated parameters on each basin was performed by running the model for the entire 46-year data period, 1948-1993. Monthly percent biases and flow interval percent biases were calculated for each calibrated basin, and results for all six basins are displayed in Figures 12 and 13, respectively. A bar plot for each basin displays final statistics for the MACS vs. RFC simulations. The performance of the MACS methodology is evident in the evaluation statistics. Monthly percent biases vary from basin to basin, but generally the MACS final simulations are comparable to or better than the RFC simulations. Flow interval percent biases plotted in Figure 13 reveal that the MACS simulation performs comparably on all basins and generally achieves lower biases across the range of observed flows.

5. DISCUSSION AND CONCLUSIONS

A Multi-step Automatic Calibration Scheme (MACS) for calibration of NWS basins has been developed and tested. The MACS method generally yields improved DRMS and percent bias statistics over the RFC manual calibration on the selected study basins. Visual inspection of hydrographs (Figures 3, 4, 7, and 8) and flow duration curves (Figures 9 and 10) also indicates that MACS is adequately simulating observed flows for the basins. The multi-step process does a good job of matching recession flows, while still reasonably estimating high flow events. Monthly percent biases, along with flow interval biases, demonstrate that the multi-step process yields reliable model simulations across the range of seasons and flow events.

The development of this methodology was confined to the options available within the NWSRFS. Improvements to the OPT3 algorithm could enhance the automatic calibration methods available to the NWS RFCs. A major factor in the development of the multi-step scheme was the 16-parameter optimization limit in OPT3. The ability of the program to simultaneously estimate more parameters would enable different approaches to be utilized. The capability for user-defined objective functions, rather than pre-set options, also would be of great utility in using the OPT3 algorithm.

The MACS methodology is simple, straightforward, and produces model calibrations that demonstrate improved simulations over traditional manual estimation procedures. With the modernization of the NWS, RFCs are under pressure to provide improved flood and river forecasting for the nation. As demands on RFC hydrologists increase, the time-saving benefit of using an automated/semi-automated procedure is evident. The number of hours spent using

MACS was estimated to be around 3-4 hours per basin, with computer time per calibration estimated to be from 6-8 hours per run (IBM-RS6000, Model 591, single processor). During model calibration runs, the hydrologists are free to perform other forecast duties. With traditional manual calibration techniques taking an average of 15-20 hours per basin, the method developed here can drastically reduce the time spent by the NWS hydrologists performing calibration studies. MACS demonstrates the ability to provide prompt, quality model simulations for NWS forecasters.

Currently, the single-objective optimization algorithm within the NWSRFS, OPT3, is the only automatic calibration option available to NWS modelers. Although the Multi-step Automatic Calibration Scheme (MACS) developed here allows for quality calibration of NWS basins, there are obvious limitations with the single-objective optimization approach. With the choice of a specific objective function, it may not be possible to find a "true" parameter set for a particular watershed, as observed in this study. Application of a multi-objective approach would allow hydrologists to observe trade-offs associated with using different objective functions and may ensure better decision-making in the calibration of river forecast points. With the progress in development of multi-objective calibration methods, further improvements in automatic optimization procedures for NWS models can be expected.

Advances in technology have allowed significant improvements in automatic calibration techniques over the last few decades. Some of these technologies are now available to the NWS hydrologists responsible for producing timely and accurate forecasts. Interactions with RFC hydrologists indicate that there is decreasing resistance and more interest in using automatic calibration procedures. The time has come for NWS River Forecast Centers, with support from the NWS Office of Hydrology, to take advantage of these advanced, time-saving technologies that can produce prompt, quality model forecasts.

REFERENCES

Anderson, E. A., 1973: National Weather Service River Forecast System – Snow Accumulation and Ablation Model, NOAA Technical Memorandum: NWS Hydro-17, U.S. National Weather Service.

Anderson, E. A., 1978: Snow Cover Energy Exchange – NWSRFS Manual and Documentation II.2.1-1, NOAA Office of Hydrology, U.S. National Weather Service.

Brazil, L.D., 1988: Multilevel calibration strategy for complex hydrologic simulation models. Ph.D. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins.

Brazil, L.E. and Hudlow M.D., 1981: Calibration procedures used with the National Weather Service river forecast system. In: Water and Related Land Resource Systems, Y. Y. Haimes and J. Kindler (Editors), Pergamon Press, New York, pp. 457-566.

Brazil, L.E. and Krajewski, W.F., 1987: Optimization of complex hydrologic models using random search methods. Paper presented at Conference on Engineering Hydrology, Hydraulics Division, American Society of Civil Engineering, Williamsburg, VA, 3-7 August.

Cooper, V.A., Nguyen, V.T.V., and Nicell, J.A., 1997: Evaluation of global optimization methods for conceptual rainfall-runoff model calibration. *Water Science and Technology*, 36(5), 53-60.

Dawdy, D.R. and O'Donnell, T., 1965: Mathematical models of catchment behavior. *Journal of Hydraulics Division*, American Society of Civil Engineering, 91, 113-137.

Duan, Q., Gupta, V.K., and Sorooshian, S., 1992: Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resources Research*, 28, 1015-1031.

Duan, Q., Gupta, V.K., and Sorooshian, S., 1993: A shuffled complex evolution approach for effective and efficient global minimization. *Journal of Optimization Theory Application*, 76, 501-521.

Franchini, M., Galeati, G., and Berra., S., 1998: Global optimization techniques for the calibration of conceptual rainfall-runoff models. *Hydrological Sciences Journal*, 43(3), 443-458.

Fread, D.L., 1995: A pathway toward improving hydrologic predictions, presented at Iowa Hydraulics Colloquium: Issues and Directions in Hydraulics, *IAHR's Journal of Hydraulic Research*, 6.

Freedman, V.L., Lopes, V.L., and Hernandez, M., 1998: Parameter identifiability for catchment-sale erosion modeling: a comparison of optimization algorithms. *Journal of Hydrology*, 207(1-2), 83-97.

Gan, T.Y. and Biftu, G.F., 1996: Automatic calibration of conceptual rainfall-runoff models: Optimization algorithms, catchment conditions, and model structure. *Water Resources Research*, 32(12), 3513-3524.

Gupta, V.K. and Sorooshian, S., 1994: A new optimization strategy for global inverse solution of hydrologic models, In: Numerical Methods in Water Resources, A. Peters et al. (Editors), Kluwer Academy Press, Norwell, MA.

Gupta, V.K., Sorooshian, S., and Yapo, P.O., 1998: Towards improved calibration of hydrologic models: multiple and non-commensurable measures of information. *Water Resources Research*, 34, 751-763.

Harlin, J., 1991: Development of a process oriented calibration scheme for the HBV hydrologic model. *Nordic Hydrology,* 22, 15-36.

Hogue, T.S., 1998: Analysis of the National Weather Service Soil Moisture Accounting models for flood prediction in the Northeast Floods of January 1996. M.S. Thesis, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ.

Hooke, R. and Jeeves, T.A., 1961: Direct search solutions of numerical and statistical problems, *Journal Assoc. Computer Mach.*, 8(2), 212-229.

Ibbitt, R.P., 1970: Systematic parameter fitting for conceptual models of catchment hydrology. Ph.D. Dissertation, Imperial College of Science and Technology, University of London, London, England.

Ibbitt, R.P. and O'Donnell, T., 1971: Fitting methods for conceptual catchment models. *Journal of Hydraulics Division*, American Society of Civil Engineering, 97(9), 1331-1342.

Ingram J., 1996: Lesson taught by floods in the United States of America. Presented at ICSU SS/IDMDR Workshop on River Flood Disasters, Koblenz, Germany, November, 26-28, 1996.

Johnston, P.R. and Pilgrim, D., 1976: Parameter optimization for watershed models. *Water Resources Research*, 12(3), 477-486.

Karnopp, D.C., 1963: Random search techniques for optimization problems, *Automatica*, 1, 111-121.

Kuczera, G., 1997: Efficient subspace probabilistic parameter optimization for catchment models. *Water Resources Research*, 33(1), 177-185.

Monroe, J.C., 1971: Direct search optimization in mathematical modeling and a watershed model Application. Technical Memorandum–NWS Hydro-12, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD.

Masri, S.F., Bekey, G.A., and Safford, F.B., 1978: An adaptive random search method for identification of large-scale nonlinear systems. Identif. System Parameter Estim. Proceedings, IFAC Symposium 4th 1976, 246-255.

Nash, J.E. and Sutcliffe, J.V., 1970: River flow forecasting through conceptual models, 1, A discussion of principles. *Journal of Hydrology*, 10(3), 282-290.

Nelder, J.A. and Mead, R., 1965: A simplex method for function minimization. *Computer Journal,* 7(4), 308-313.

Page, D., 1996: The implementation of an Interactive River Forecast System for the National Weather Service. Presented at 12th International Conference on Interactive Information and Processing System (IIPS) for Meteorology, Oceanography, and Hydrology, Atlanta, GA, Jan. 28-Feb. 2, 1996.

Pronzato, L., Walter, E., Vernot, A., and Lebruchec, J.F., 1984: A general-purpose global optimizer: implementation and applications. *Mathematical Computer Simulation*, 26, 412-422.

Rosenbrock, H.H., 1960: An automatic method of finding the greatest or least value of a function. *Computer Journal*, 3, 175-184.

Sorooshian, S., Duan, Q., and Gupta, V.K., 1993: Calibration of rainfall-runoff models: application of global optimization to the Sacramento soil moisture accounting model. *Water Resources Research,* 29, 1185-1194.

Sorooshian, S. and Gupta, V.K., 1995: Model Calibration. In: Computer Models of Watershed Hydrology, V. P. Singh (Editor), Water Resources Publications, Highlands Ranch, CO, pp. 23-63.

Thyer, M., Kuczera, G., and Bates, B.C., 1999: Probabilistic optimization for conceptual rainfall-runoff models: a comparison of the shuffled complex evolution and simulated annealing algorithms. *Water Resources Research*, 35(3), 767-773.

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

Yapo, P.O., Gupta, H.V., and Sorooshian, S., 1998: Multi-objective global optimization for hydrologic models. *Journal of Hydrology*, 203, 83-97.

APPENDIX A

FIGURES

Table 1. Basins used in calibration study (average values based on 1948-1993 data).

Des Moines River	**Size**	**Mean Daily Ppt.**	**Mean Daily Flow**
AKWI4	1192 km^2	2.385 mm/day	7.275 cms/day
BSSI4	969 "	2.479 "	6.559 "
IDNI4	1302 "	2.353 "	7.520 "
NRWI4	904 "	2.328 "	5.243 "
Minnesota River			
MMLM5	671 "	1.6987 "	2.838 "
RPDM5	784 "	2.1102 "	1.795 "

Table 2. SAC-SMA and SNOW-17 parameter descriptions and ranges used for calibration.

SAC-SMA	Description	Parameter
Ranges for Calibration		
UZTWM	Upper zone tension water maximum storage (mm)	20 –120 mm
UZFWM	Upper zone free water maximum storage (mm)	10 – 100 mm
LZTWM	Lower zone tension water maximum storage (mm)	100 – 150 mm
LZFPM	Lower zone free water primary maximum storage (mm)	5 – 100 mm
LZFSM	Lower zone free water supplementary maximum storage(mm)	5 – 200 mm
UZK	Lower zone free water lateral depletion rate (day^{-1})	.100 - .800 day^{-1}
LZPK	Lower zone primary free water depletion rate (day^{-1})	.01 - .20 day^{-1}
LZSK	Lower zone supplementary free water depletion rate (day^{-1})	.01 - .50 day^{-1}
ADIMP	Additional Impervious area (decimal fraction)	.01 - .10 %
PCTIM	Impervious fraction of the watershed (decimal fraction)	--
ZPERC	Maximum percolation rate (dimensionless)	10 - 200
REXP	Exponent of the percolation equation (dimensionless)	1.5 – 3.5
PFREE	Fraction of water percolating from upper zone directly to lower zone free water storage (decimal fraction)	.01 - .40 % --
RIVA	Riparian vegetation (decimal fraction)	--
SIDE	Ratio of deep recharge to channel base flow (decimal fraction)	--
RESERV	Fraction of lower zone free water not transferable to lower zone tension water (decimal fraction)	--

SNOW-17	Description	
SCF	Snow correction factor (dimensionless)	.90 – 1.20
MFMAX	Maximum melt factor (mm/°C/6hr)	1.0– 2.0 mm/°C/6
MFMIN	Minimum melt factor (mm/°C/6hr)	10-.90 mm/°C/6 hr
UADJ	Wind function factor (mm/mb/6hr)	preset to.100 mm/mb/6 hr
SI	Water equivalent maximum (mm)	30 – 100 mm
Areal Depletion Curve		
MBASE	Melt base temperature (°C)	--
NMF	Maximum negative melt factor (mm/mb/6hr)	--
TELEV	Elevation of temperature series (m)	--
DAYGM	Average daily ground melt (mm)	--
PLWHC	Percent Liquid water holding capacity (decimal fraction)	--
PXTEMP	Rain/Snow temperature index (°C)	--

Additional Parameters (usually not optimized)		
EFC	Effective forest cover (decimal fraction)	--
PXADJ	Precipitation adjustment factor (dimensionless)	--

Table 3. Parameters optimized during MACS process.

Model	Step1	Step 2	Step 3
SAC-SMA	UZTWM	UZTWM	--
	UZFWM	UZFWM	--
	UZK	UZK	--
	ADIMP	ADIMP	--
	ZPERC	ZPERC	--
	REXP	REXP	--
	LZTWM	--	LZTWM
	LZFSM	--	LZFSM
	LZFPM	--	LZFPM
	LZSK	--	LZSK
	LZPK	--	LZPK
	PFREE	--	PFREE
SNOW-17	SCF	SCF	--
	MFMAX	MFMAX	--
	MFMIN	MFMIN	--
	SI	SI	--
OBJ. FX.	LOG	DRMS	LOG

Table 4. Model performance of RFC and MACS methods.

Calibration Period (1970-1980)

Basin	**RFC**		**MACS**	
	DRMS	**%Bias**	**DRMS**	**%Bias**
AKWI4	22.48	26.24	14.33	7.79
BSSI4	13.49	23.74	11.79	11.95
IDNI4	15.27	17.73	13.63	10.12
NRWI4	10.48	10.40	9.58	11.88
MMLM5	2.40	47.26	3.35	16.38
RPDM5	13.93	15.42	12.30	6.03

Verification Period (1948-1993)

Basin	**RFC**		**MACS**	
	DRMS	**%Bias**	**DRMS**	**%Bias**
AKWI4	18.72	17.84	15.94	4.55
BSSI4	13.60	11.36	14.05	0.14
IDNI4	13.29	9.69	12.60	2.14
NRWI4	9.30	-2.14	9.90	1.10
MMLM5	3.51	-4.36	3.96	-25.84
RPDM5	17.19	6.67	15.12	-4.24

Table 5. Parameter values of RFC manual calibration and Multi-Step (M-S) scheme.

	AKWI4		BSSI4		IDNI4		NRWI4		MMLM5		RPDM5	
SAC-SMA	**RFC**	**MACS**	**RFC**	**MACS**	**RFC**	**MACS**	**RFC**	**MACS**	**RFC**	**MACS**	**RFC**	**MACS**
UZTWM	50	119	40	72	100	120	40	120	83	119	50	40
UZFWM	15	46	25	57	35	16	25	37	40	66	30	43
UZK	0.3	0.534	0.6	0.527	0.4	0.23	0.6	0.33	0.34	0.1	0.15	0.1
LZTWM	120	140	175	160	80	118	225	107	170	150	120	150
LZFSM	60	47	30	18	50	28	45	38	100	29	100	66
LZFPM	10	13	10	16	30	11	10	7.3	25	53	20	14
LZSK	0.1	0.047	0.1	0.248	0.07	0.044	0.1	0.044	0.07	0.068	0.035	0.027
LZPK	0.007	0.008	0.005	0.015	0.005	0.007	0.005	0.01	0.004	0.002	0.005	0.002
ADIMP	0	0.1	0	0.1	0	0.1	0	0.099	0.01	0	0.02	0.098
ZPERC	20	199	150	199	47	200	150	101	82	199	40	62
REXP	3	1.5	1.75	1.5	2.8	1.5	1.75	1.5	1.8	2.4	2	2
PFREE	0.03	0.171	0.05	0.068	0.3	0.139	0.1	0.12	0.3	0.156	0.2	0.047
SNOW-17												
SFC	1	0.90	1.1	0.90	0.85	0.8	1.1	0.9	1.1	0.92	1	0.90
MFMAX	1.8	1.13	1.6	1.35	1.8	1.86	1.6	2	1.5	2	1.8	1.99
MFMIN	0.2	0.43	0.6	0.51	0.9	0.23	0.6	0.36	0.6	0.1	0.8	0.55
SI	50	64	35	76	50	91	35	90	90	32	90	86

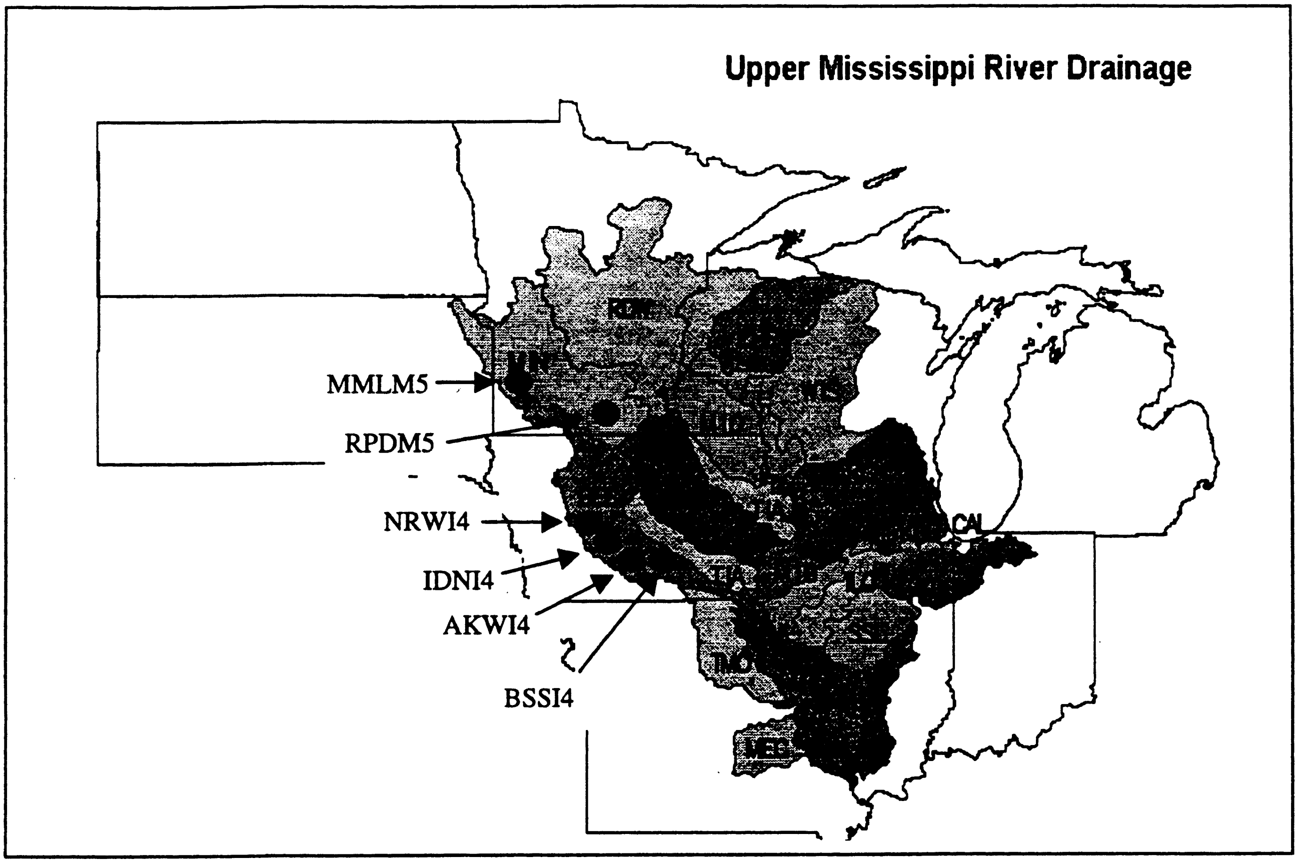


Figure 1. NCRFC Upper Mississippi River Drainage with approximate locations of study basins displayed as (•).

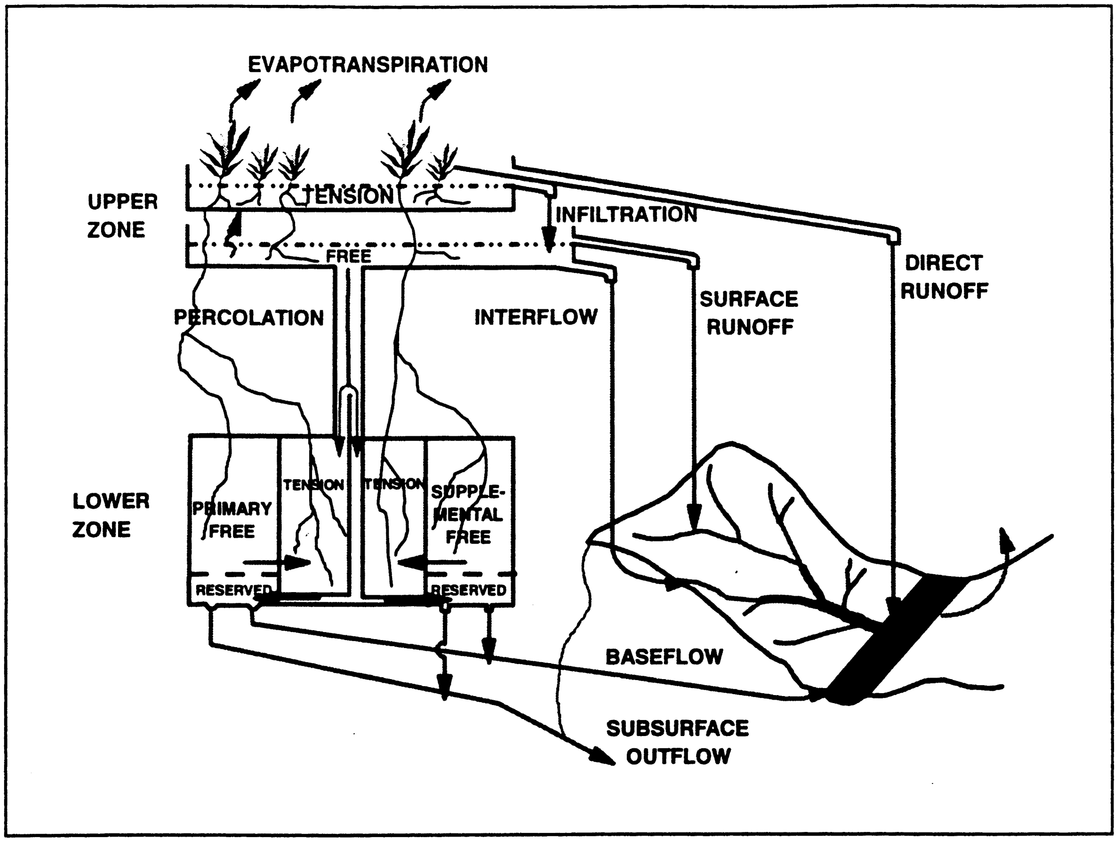


Figure 2. National Weather Service Sacramento Soil Moisture Accounting Model (SAC-SMA).

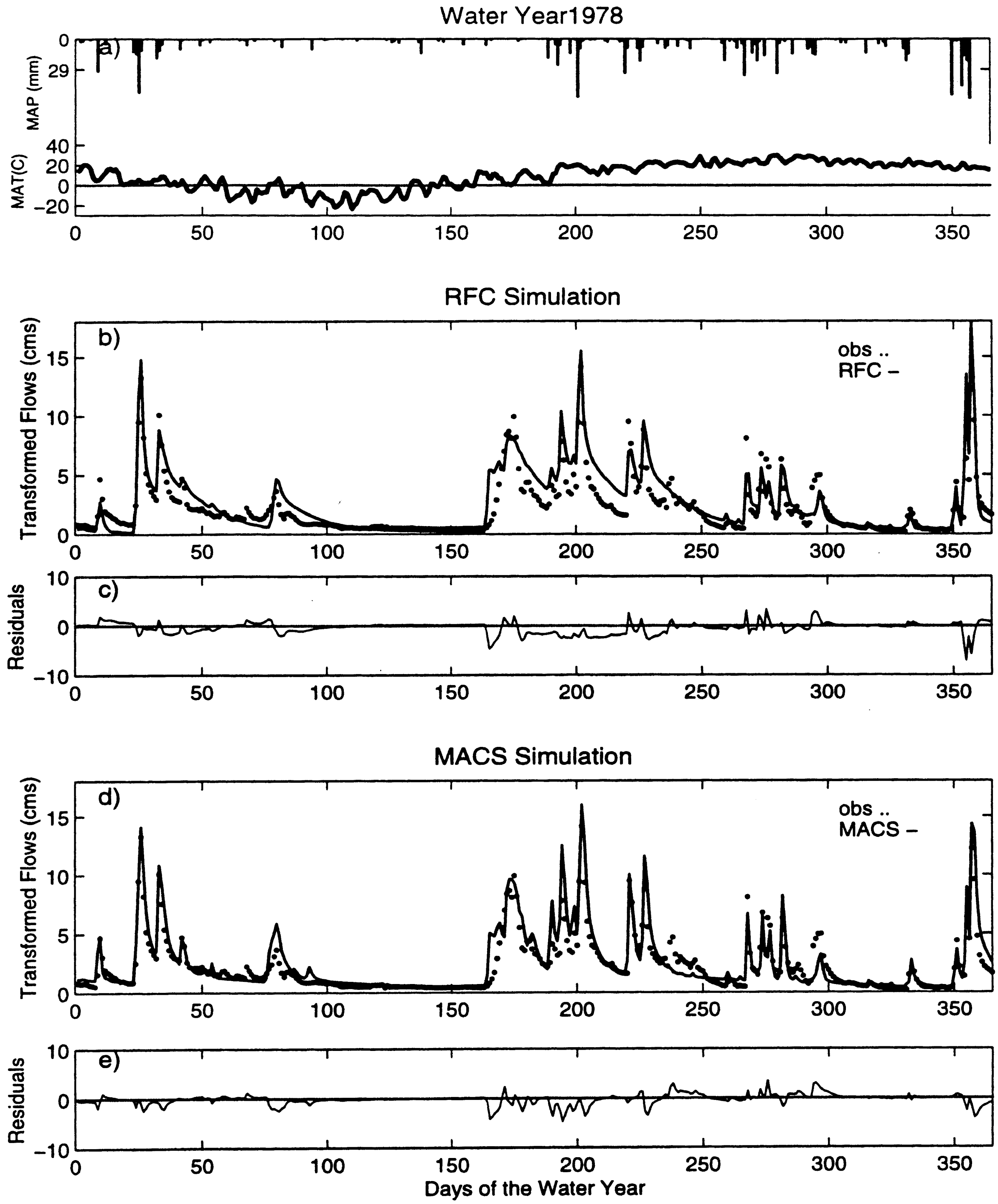


Figure 4. MACS Step 1 calibration for basin AKWI4, WY 1978. a) MAP and MAT time series, b) RFC simulation space, c) RFC residuals, d) MACS simulation, e) MACS residuals. Plots b) and d) are in the transformed space as described in Figure 3.

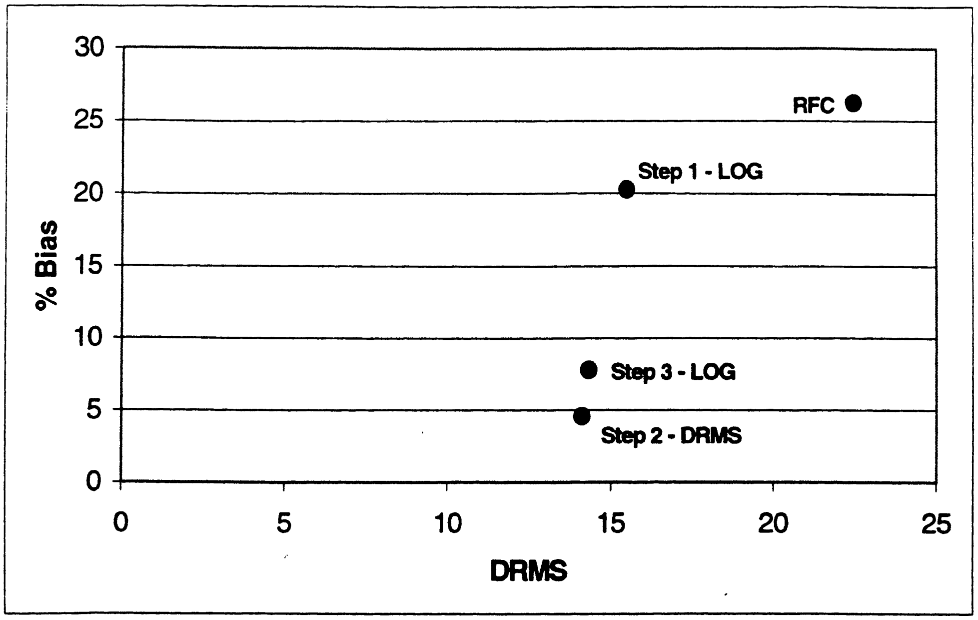


Figure 5. MACS steps 1, 2, and 3 statistics for basin AKWI4 (11 yr. Data period).

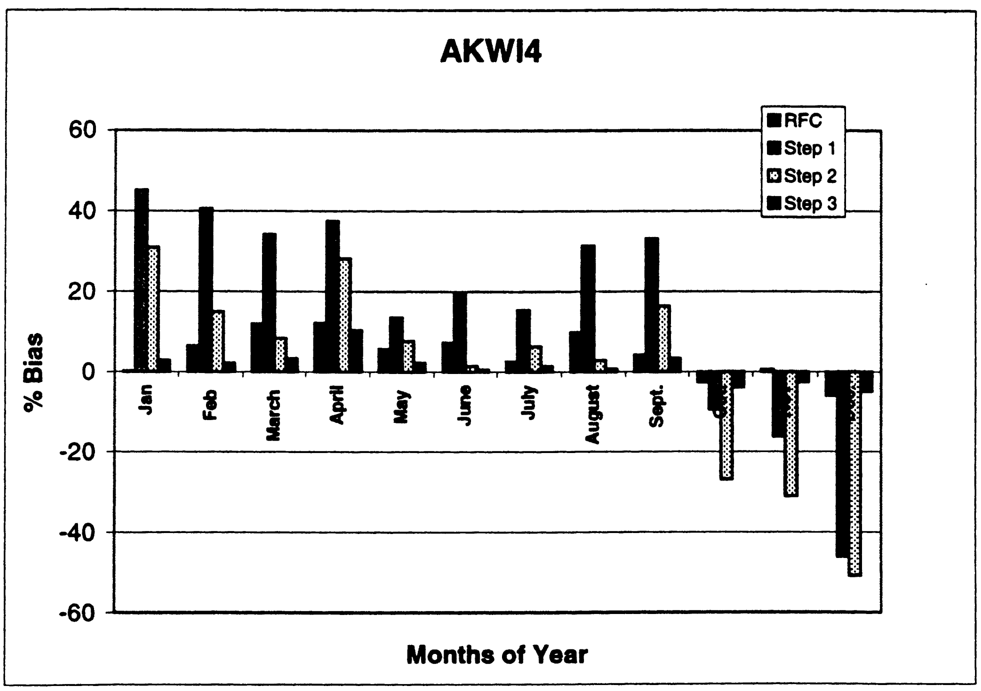


Figure 6. Monthly flow biases for MACS process on basin AKWI4 (11 yr. Data period).

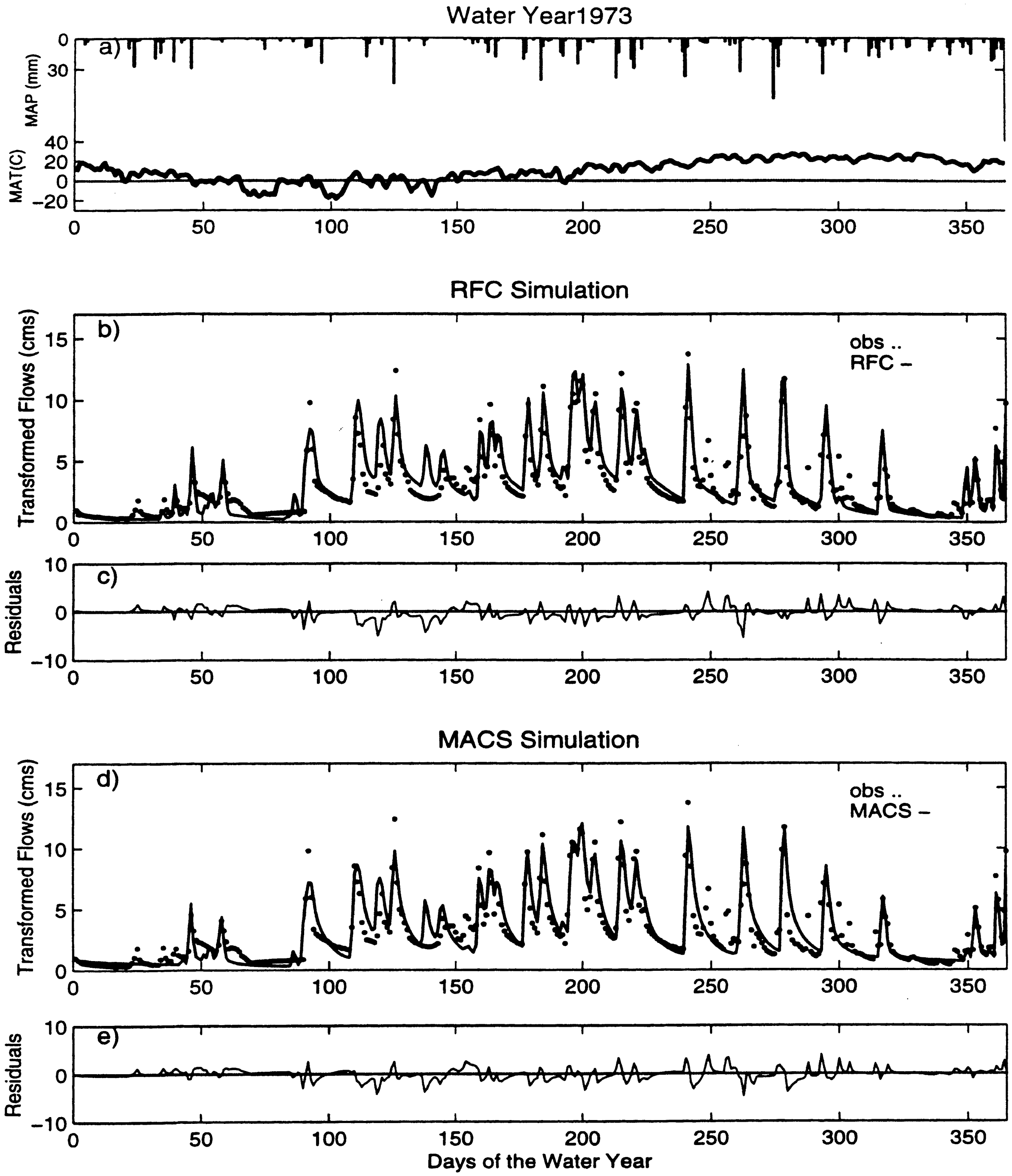


Figure 7. MACS Step 3 calibration for basin BSSI4, WY 1973. a) MAP and MAT time series, b) RFC simulation space, c) RFC residuals, d) MACS simulation, e) MACS residuals. Plots b) and d) are in the transformed space as described in Figure 3.

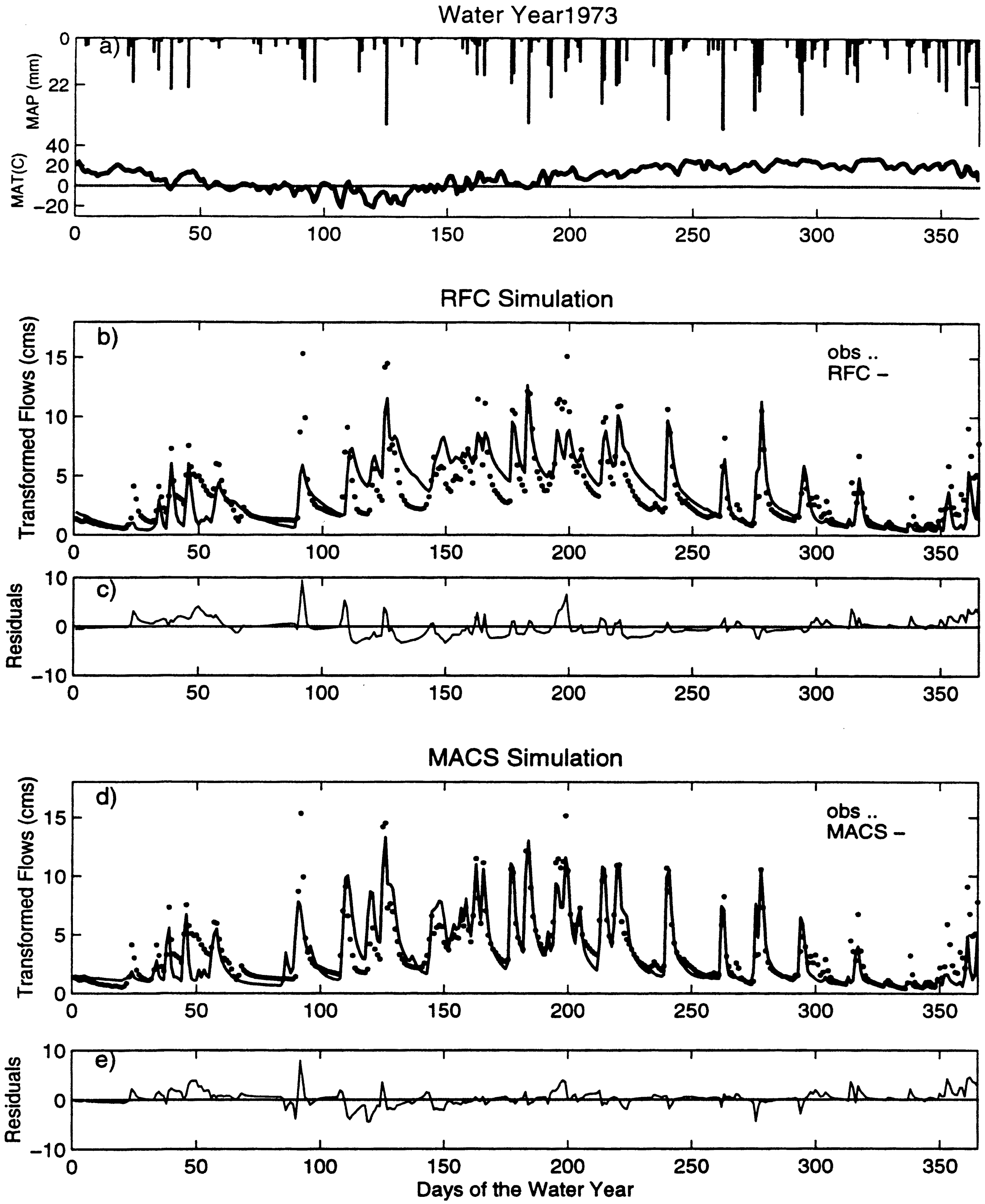


Figure 3. MACS Step 1 calibration for basin AKWI4, WY 1973. a) MAP and MAT time series, b) RFC simulation, c) RFC residuals, d) MACS simulation, e) MACS residuals. Plots b) and d) are transformed flows where:

$$Transformedflow = \frac{(flow+1)^{\lambda} - 1}{\lambda} \quad , \quad \text{and } \lambda = 0.3$$

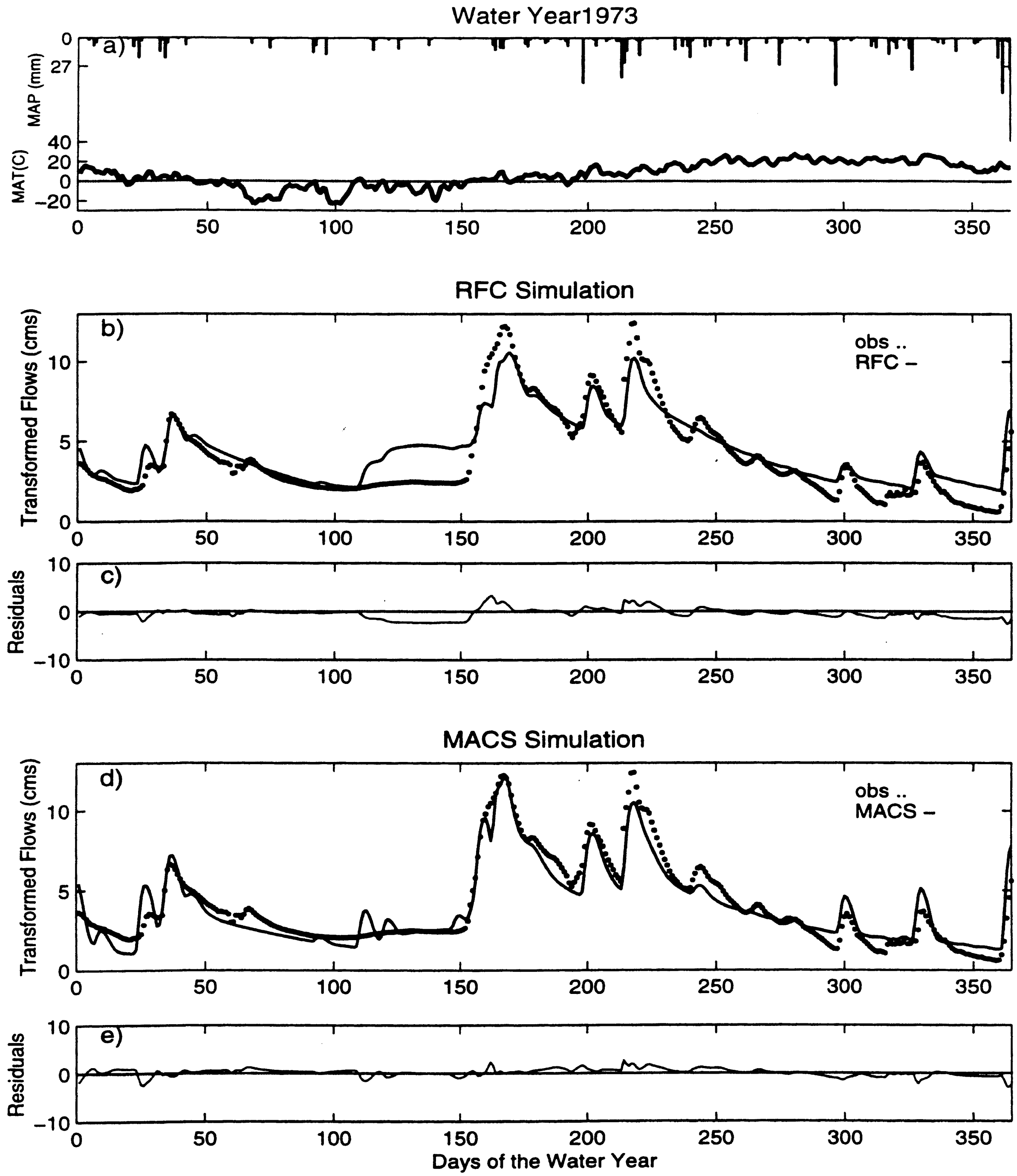


Figure 8. MACS Step 3 calibration for basin RPDM5, WY 1973. a) MAP and MAT time series, b) RFC simulation space, c) RFC residuals, d) MACS simulation, e) MACS residuals. Plots b) and d) are in the transformed space as described in Figure 3.

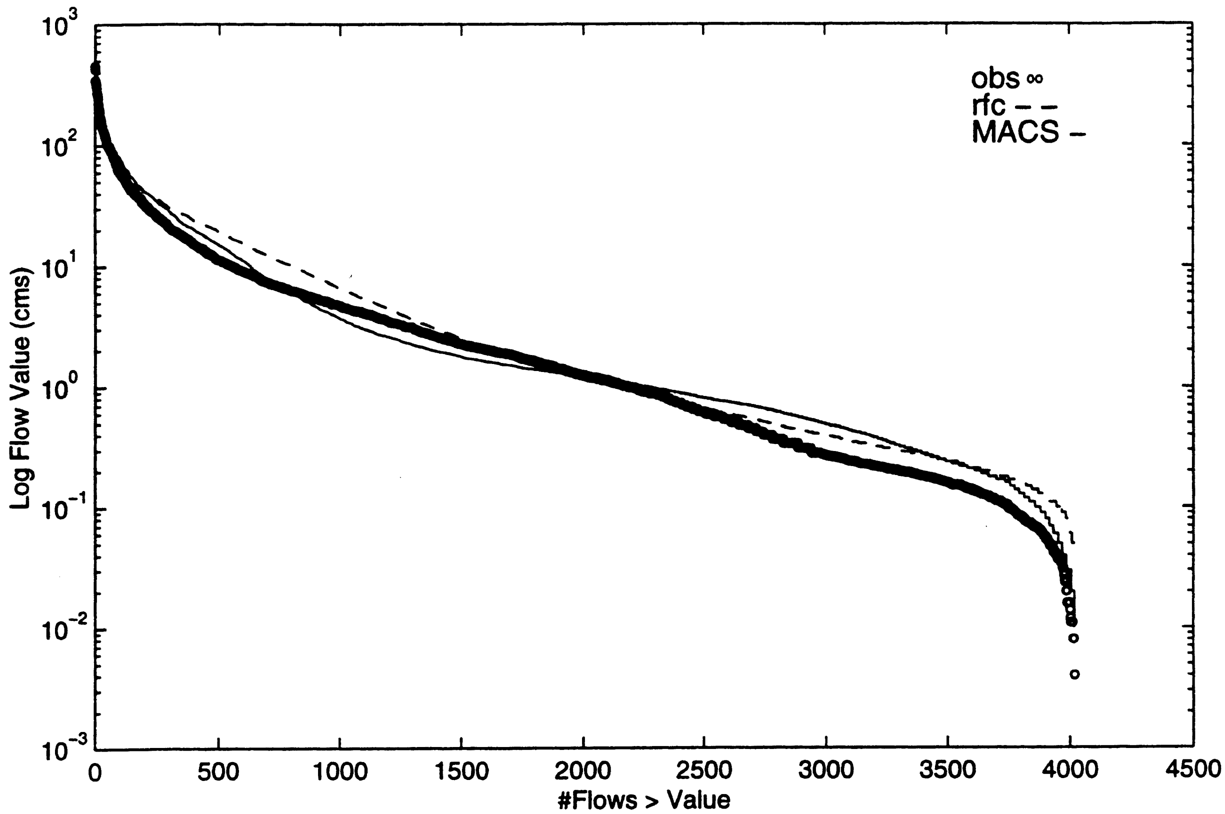


Figure 9. Flow duration curve for basin AKWI4 (calibration period). Observed (oo), MACS (-), and RFC (--).

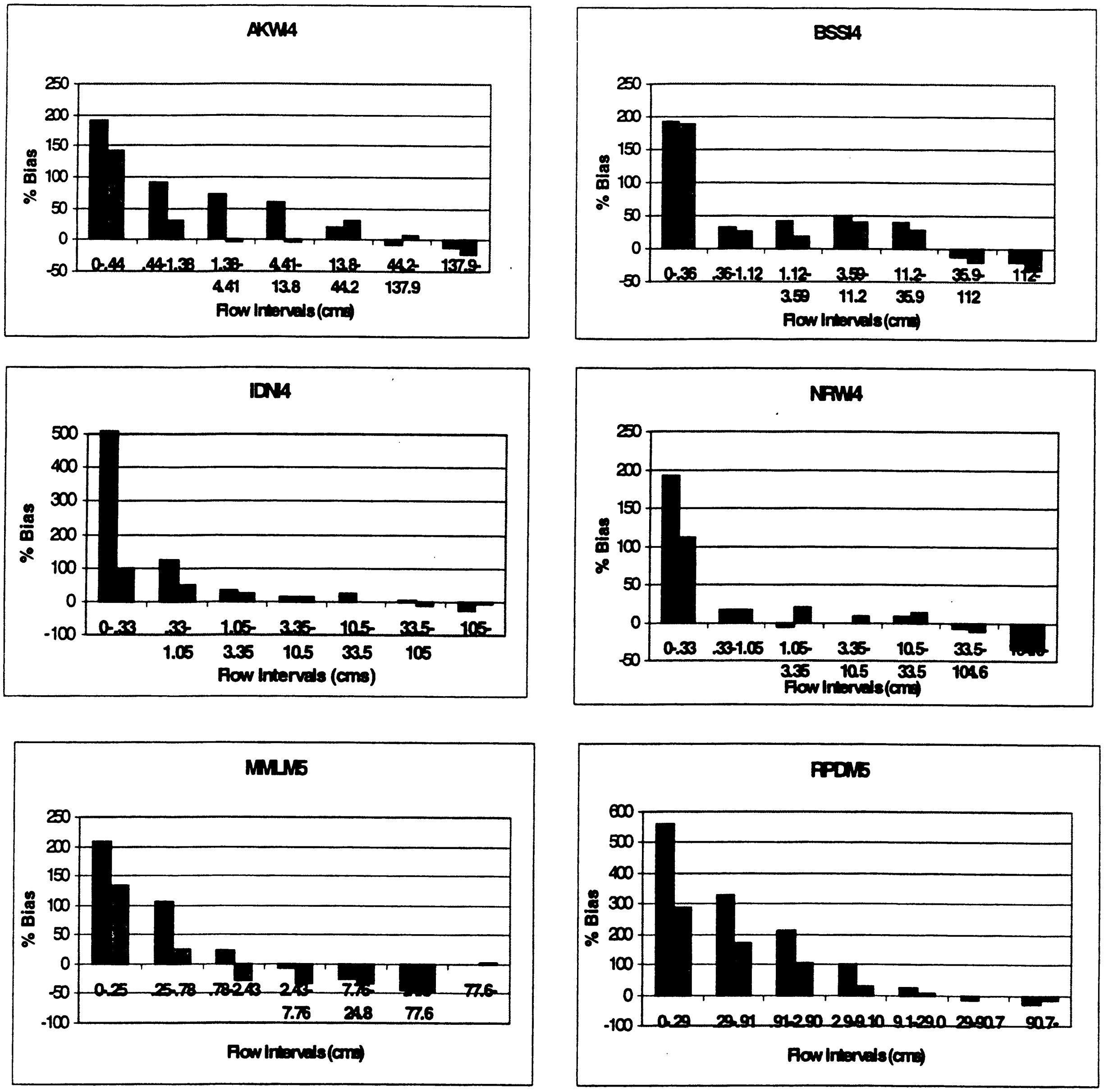


Figure 13. Flow Interval Biases for six study basins for evaluation period (1948-1993). RFC simulation is shown in black (■), MACS shown in grey (■).

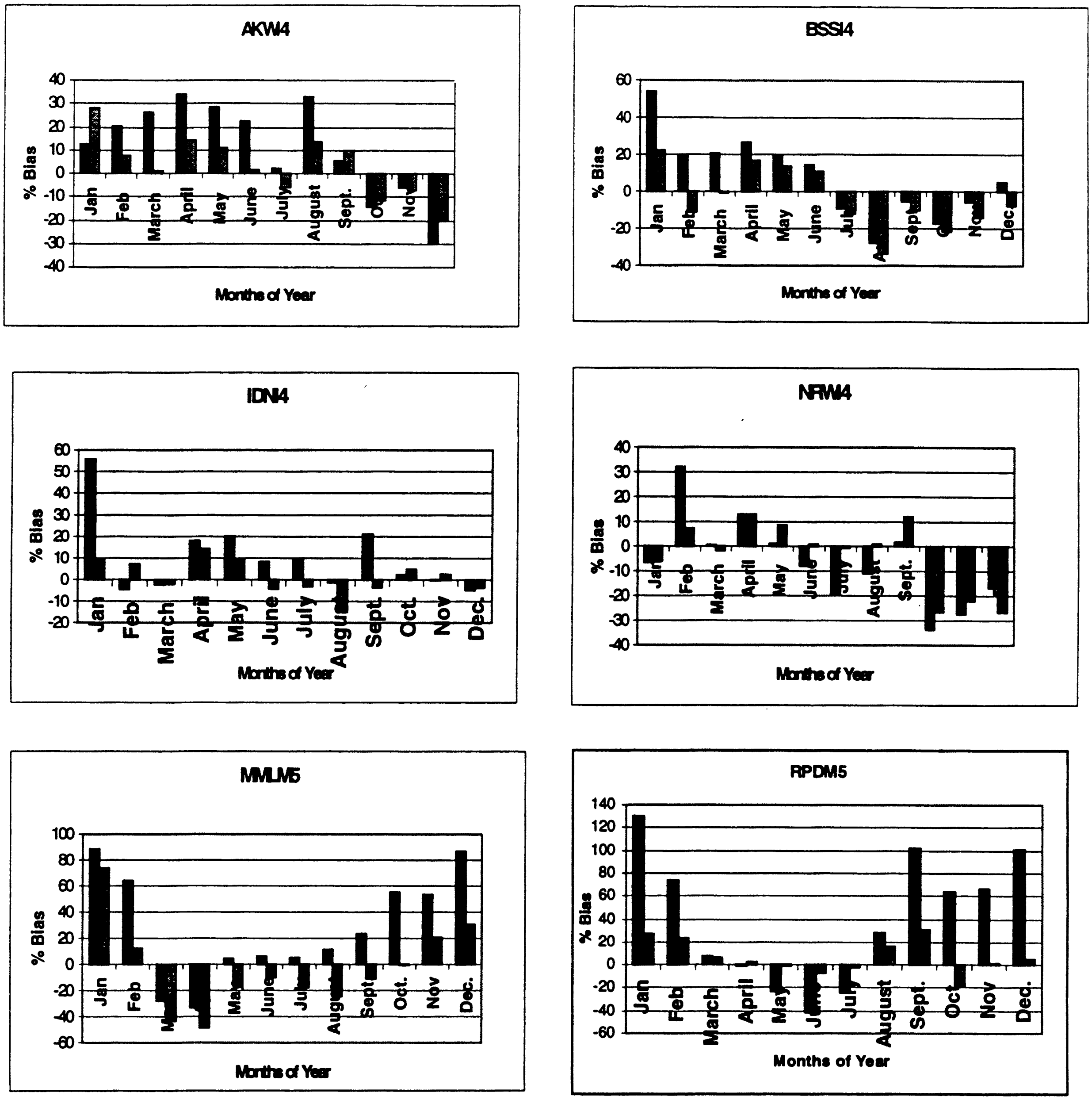
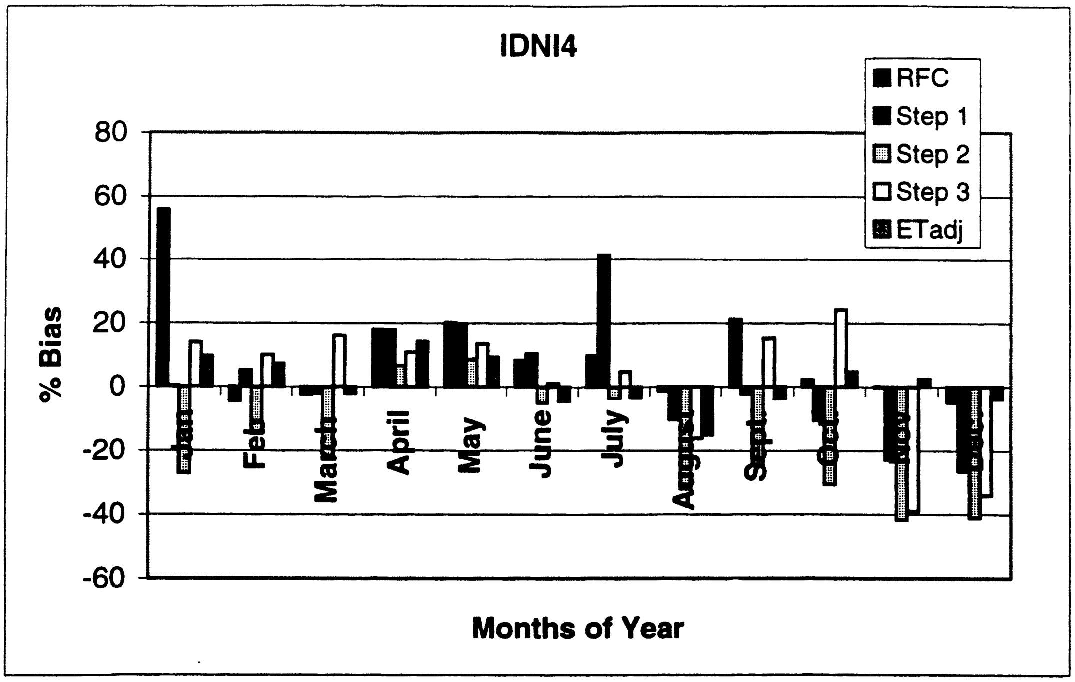


Figure 12. Monthly percent biases for six study basins for evaluation period (1948-1993). RFC simulation is shown in black (■), MACS shown in grey (■).

a)



b)

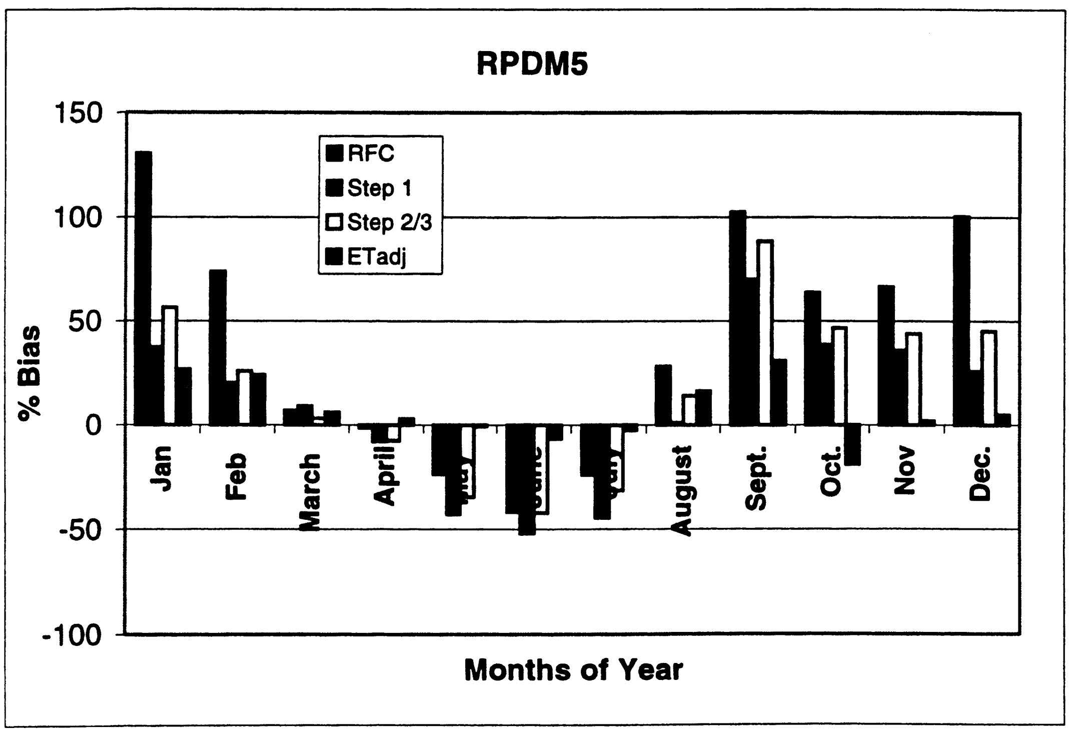


Figure 11. Monthly flow biases for all MACS steps on IDNI4 (a) and RPDM5 (b) for 11-year calibration period.

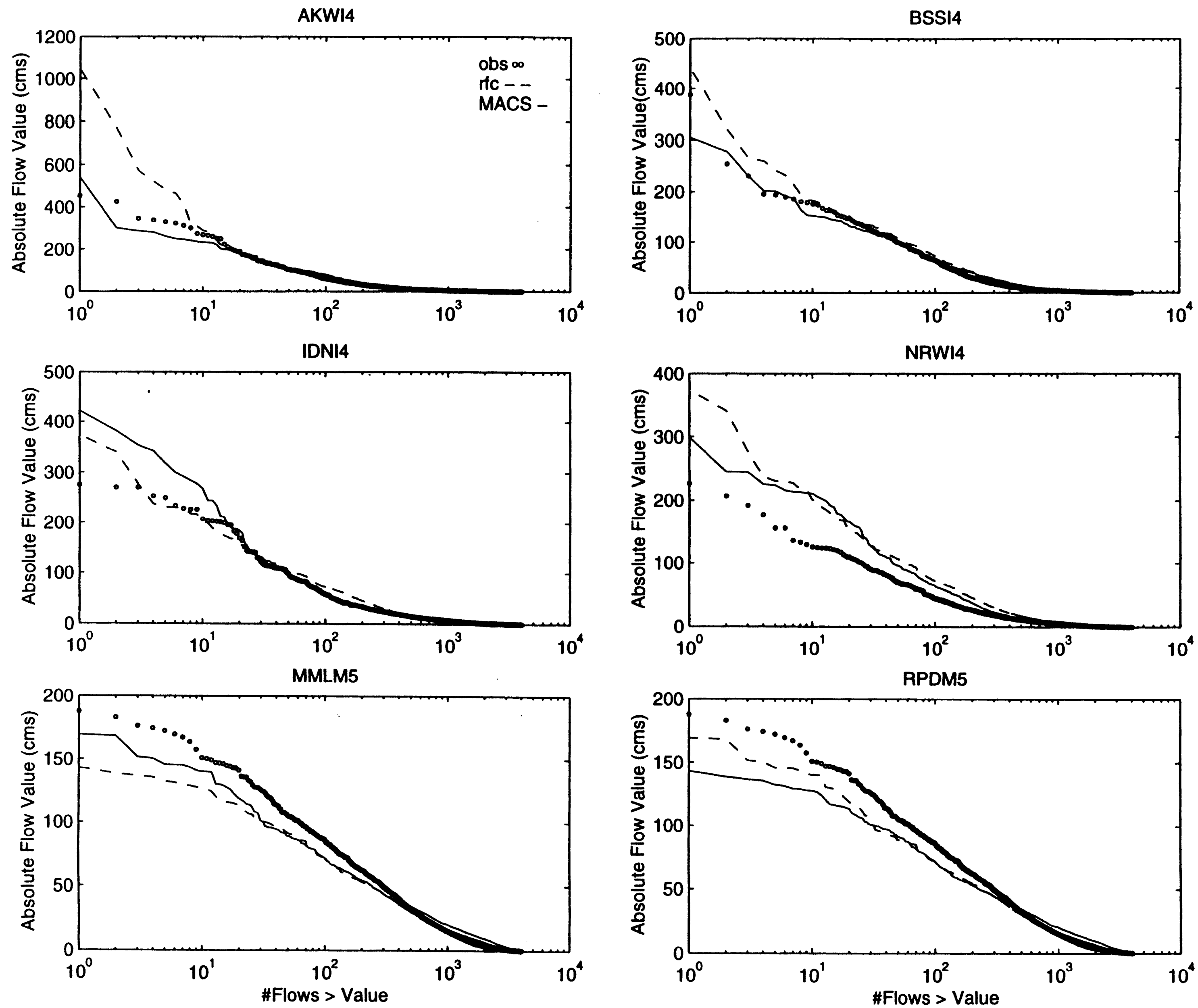


Figure 10. Modifed flow duration curve s for all six study basins (calibration period). Observed (∞), MACS (-), and RFC (--).