A CRITICAL APPROACH TO THE CALIBRATION OF A WATERSHED MODEL

V. M. F. Jacomino and D. E. Fields

ABSTRACT: A complex watershed-scale water quality simulation model, the Hydrological Simulation Program-FORTRAN (HSPF) model, was calibrated for a 16 km² catchment. The simulation step size was 0.33 hours with predicted and recorded hydrologic flows compared on an annual and monthly basis during a total calibration period of four years. Unguided numerical optimization when applied alone did not yield a model parameter set with acceptable predictive capability; instead, it was necessary to apply a critical process that included sensitivity analysis, numerical optimization, and testing of derived model parameter sets to evaluate their performance for periods other than those for which they were determined. Using this critical calibration process, the model was proven to have significant predictive capability. Numerical optimization is an aid for model calibration, but it must not be used blindly. (KEY TERMS: simulation; modeling/statistics; watershed management; hydrology; optimization; sensitivity analysis.)

INTRODUCTION

Models based on physical hydrology and ones which can incorporate the spatial inhomogeneities of catchments are becoming increasingly important to advances in computing facilities and experience in the capabilities of such models. These models are critical tools for estimating the peak discharge and runoff volume of floods.

Most of these models can be roughly classified on a scale between empirical and physically-based. If all the governing physical laws were well known and could be described by equations of mathematical physics, the model would be physically-based. However, all existing theoretical models simplify the physical system and often include obviously empirical components, so they are considered conceptual models. An empirical model omits the general laws and is in reality a representation of data. The conceptual runoff models only include the most significant physical processes for the simulation of runoff and use a combination of empirical and physically-based algorithms (Beven, 1989).

The calibration of conceptual models is not a straightforward task due to the large number of parameters involved and the computational requirements of making multiple runs. A set of calibrated parameters will generally represent one possible combination that, in conjunction with the particular model structure and solution scheme used, produces a response similar to that observed. It is unlikely that, for a particular model structure, this set of values is unique in this respect. Also, it should not be expected that this set of parameter values will give equally good results when used with a different model structure, even though the model may purport to solve the same equations and the parameters may have the same names (Binley et al., 1991). It is difficult to be entirely certain that one has avoided the drawback of obtaining “non-unique” parameter sets, but confidence may be placed in a particular calibrated parameter set if this set gives good predictions of rainfall events other than those constituting the basis of the calibration (Calver, 1988).

This paper explores the problem of calibrating a particular physically based model on a small catchment where there are few available parameter estimates. A sensitivity analysis was first used to reduce the dimensionality of the parameter space. Parameters were identified to which the model predictions were most sensitive. Following the sensitivity analysis, a numerical optimization was performed separately for each of four years of observed rainfall and

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streamflow data. This numerical optimization consisted of applying a pattern search technique, which started from a priori estimates of the parameter values and produced a set of "optimal values" for that particular year. The best-fit parameter sets yielded for each of these years was then evaluated by testing their ability to predict streamflow in years other than those used for a particular calibration.

This work documents a portion of a project that was started at the Oak Ridge National Laboratory in order to evaluate the magnitude of contaminated sediment transport during floods at the White Oak Creek (WOC) drainage system, and to develop strategies for controlling off-site transport. This project includes a data collection program to establish a conceptual model of contaminated sediment movement in WOC, calibration of a conceptual model, and generation of a database that will be used in the future to assess the effectiveness of completed site remediation (Fontaine, 1991).

DESCRIPTION OF THE HYDROLOGIC MODEL

In this study, the Hydrological Simulation Program – FORTRAN (HSPF) model (Johanson et al., 1984) was chosen to simulate hydrologic, sediment, and contaminant transport. The HSPF model was selected because it provides a comprehensive approach to simulating transport of contaminants in a hydrologic system on a continuous basis. The model has linked components for rainfall-runoff processes including overland, shallow subsurface, and groundwater pathways for hydrologic routing and contaminant transport. The model also has options for detailed reporting of storages, fluxes, and intermediate variables at each time step, and of the time series for a large number of output variables (Fontaine, 1989).

HSPF is a comprehensive, conceptual, continuous watershed simulation model designed to simulate the water quantity and water quality processes that occur in a watershed. It can reproduce spatial variability by dividing the basin into hydrologically homogeneous land segments and simulating runoff for each land segment independently, using different meteorological input data and watershed parameters. The model includes non-measurable and measured parameters.

HSPF has its origin in the Stanford Watershed Model (Linsley et al., 1982). The various hydrologic processes are represented mathematically as flows and storages. In general, each flow is an outflow from a storage, usually expressed as a function of the current storage amount and the physical characteristics of the subsystem. Thus the overall model is physically based, but many of the flows and storages are represented in a simplified or conceptual manner. Although this simplification requires the use of calibrated parameters, it has the advantage of avoiding the need for giving the physical dimensions and characteristics of inaccessible portions of the largely subsurface flow system.

The basin is represented in terms of land segments and reaches/reservoirs. A land segment is a subdivision of the simulated watershed, which is defined as an area with similar hydrologic characteristics. For modeling purposes, water sediment, and water quality constituents leaving the watershed move laterally to a downslope segment or to a reach/reservoir. A land segment that has the capacity to allow enough infiltration to influence the subsurface water budget is considered pervious. Otherwise it is considered impermeable. The two groups of land segments are simulated independently (Donigian et al., 1984).

The main modeling components of HSPF are the modules that simulate pervious land segments (PERLAND) and the modules that route runoff through reservoirs and reaches and simulate in-stream processes (RCHRES).

PERLAND simulates the water quality and quantity processes that occur on a pervious land segment and models the movement of water along three paths: overland flow, interflow and groundwater flow. A variety of storage zones are used to represent the storage processes that occur on the land surface and in the soil horizons. The model employs various surface and subsurface water storages, which in most cases are not defined explicitly and cannot be directly measured. The lower zone storage, for example, represents intermediate depth soil moisture storage, but neither the depth of the storage nor the maximum capacity of soil moisture storage are specified. Instead, a calibration parameter LZSN is utilized as an index value of water storage in the zone and the magnitude of current storage LZS varies over time. Similarly for the upper zone a parameter, UZSN, and a variable, UZS, are utilized.

Module RCHRES simulates the processes that occur in a single reach of an open channel or a completely mixed lake. The element consists of a single zone situated between two nodes and the flow through the element is assumed to be unidirectional. The module uses a modified version of the kinematic wave equation for routing. Figure 1 shows the interaction of storage and loss components which transform precipitation to streamflow.

These components work interactively, with continuous feedback, to represent the natural processes of interception, infiltration, surface and sub-surface storage and drainage, evapotranspiration, and channel routing.
A Critical Approach to the Calibration of a Watershed Model

The calibration of HSPF must be done in three stages, with the hydrologic mechanisms being calibrated before sediment and water quality processes. The first task in hydrologic calibration is to establish a water balance on an annual basis, following by the adjustment of monthly distribution of runoff and of hydrograph shape for selected storm events (Donigian et al., 1984). This paper will not consider the challenge of determining channel parameters, which strongly influence short-term (hourly) flow values.

**AREA OF STUDY**

White Oak Creek, the site used in this study, is a 16 km² catchment located at the Oak Ridge National Laboratory (ORNL) 32 km west of Knoxville, Tennessee. The catchment is 80 percent forest, 10 percent grass field, and 10 percent developed (i.e., similar to urban development). The terrain is 50 percent steep slopes and ridges and 50 percent valley bottoms and mild slopes. Soils have silt or very fine loam texture and are underlain by dolomite, limestone, sandstone or shale. Infiltration capacity is relatively high at the surface, and generally decreases enough in the top meter soil to create a shallow subsurface during moderate rainfalls. Overland flow is normally seen during very wet conditions and is located in flow convergence zones. A number of weirs and flumes used for discharge measurement are located on the tributaries and main stream channel (Clapp et al., 1994). A small, shallow lake is located near the outlet of the catchment. The seasonal climate generally involves cool winters with occasional heavy rainfalls from thunderstorms. Average annual precipitation is 137 cm (Fontaine, 1991). As will be shown later, the month with highest precipitation is usually December, and there is frequently a secondary peak in precipitation in March.

The catchment contains a short wide channel or embayment between White Oak Dam and the Clinch River, a small lake (White Oak Lake), and two main tributaries (Melton Branch and White Oak Tributary) which converge 1 km upstream of the lake. Hydrologic data used for this analysis includes hourly precipitation, hourly streamflow, and daily evaporation.

<table>
<thead>
<tr>
<th><strong>Figure 1. HSPF Flow Chart.</strong></th>
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**SENSITIVITY ANALYSIS**

Physically based models such as the HSPF require a large number of parameter values to be calibrated in applications to real catchments, even where simplifying assumptions are made to reduce the size of the parameter set. Sensitivity analysis, however, usually suggests that the simulation results are very much more sensitive to some parameters than others (Calver, 1988). In this study, a sensitivity analysis was performed for those parameters for which reliable estimates were not directly available. The parameters identified as being the most “sensitive”, were estimated using optimization, as described below.

For simple models a sensitivity coefficient for a particular parameter can be defined by the partial derivative of an output variable with respect to that parameter (Beven, 1979). For models such as the HSPF, which are too complex for analytical expressions for these derivatives to be obtained, values may be determined by numerical approximation (Rogers et al., 1985). The partial derivative with respect to a given parameter is estimated from the change in the model prediction which results when one parameter is changed by a relatively small amount, while the other parameters are maintained at a constant value.

In the sensitivity analysis reported here, the effect of changes in the hydrologic parameter values was investigated with reference to simulated annual and
monthly average discharges for 1991. This year was chosen because it was judged that the measured flow values had greater validity than other years. The monthly streamflow analysis was performed taking as baseline the simulated results from December of 1991, which was a month with normal antecedent conditions and the occurrence of two five-year floods.

An additional study was performed in order to investigate the effect of changes in the parameter values on individual storm runoff volumes, magnitude of peak discharge and time to peak discharge. These analyses together with the final data of hydrograph calibration for selected storms events are being concluded and will be submitted for publication later.

Thirteen parameters were considered. They are related to mechanisms occurring in the hillslope and describing such processes as interception, infiltration, soil moisture distribution, interflow, and ground water behavior. The list of parameters as well as their description (Donigian et al., 1984) are showed in Table 1. Preliminary values of the parameters involved in the discharge estimation for 1991 year were set using the database available from previous and ongoing studies at ORNL, which provided information on the streamflow and ground water system (Clapp et al., 1994).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>FOREST (%)</td>
<td>percent forest cover</td>
</tr>
<tr>
<td>LZSN (in)</td>
<td>lower zone nominal storage</td>
</tr>
<tr>
<td>INFILT (in/hr)</td>
<td>infiltration rate</td>
</tr>
<tr>
<td>AGWRC (1/day)</td>
<td>basic ground water recession rate</td>
</tr>
<tr>
<td>CEPSC (in)</td>
<td>interception storage capacity</td>
</tr>
<tr>
<td>UZSN (in)</td>
<td>upper zone nominal storage</td>
</tr>
<tr>
<td>NSUR</td>
<td>Manning’s n value for overland flow</td>
</tr>
<tr>
<td>INTFW (-)</td>
<td>interflow recession parameter</td>
</tr>
<tr>
<td>LZETP (-)</td>
<td>lower zone evapotranspiration parameter</td>
</tr>
<tr>
<td>UZS (in)</td>
<td>initial condition: upper zone storage</td>
</tr>
<tr>
<td>LZS (in)</td>
<td>initial condition: lower zone storage</td>
</tr>
<tr>
<td>AGWS (in)</td>
<td>initial condition: active ground water storage</td>
</tr>
</tbody>
</table>

The parameters having the most significant impact on the discharge at the outlet of the catchment were AGWRC (ground water recession coefficient) and AGWS (initial condition for ground water storage), both of which involve the baseflow processes as (Figure 2). The large impact on simulated streamflow of small changes in AGWRC does not normally cause problems to HSPF applications because this parameter is relatively easy to calibrate. Less significant were those parameters that involve the degree of saturation in the lower zone soil moisture (LZSN, LZS), the volume of the upper soil moisture zone (UZSN) and the rate of infiltration (INFILT). In general, for 50 percent changes in these parameters, the annual average discharge changes were less than 10 percent. For the parameters INTFW and IRC, the changes were less than 2 percent.

Approximately equal relative changes were found in the sensitivity study of monthly average discharge (Figure 3). In this case, within 50 percent changes in parameters LZSN, LZS, UZSN and INFILT, the monthly average discharge changes were less than 20 percent, and for the parameters INTFW and IRC less than 6 percent. Again, the most critical parameter was AGWRC (50 percent change in this parameters resulted in a 40 percent change in the streamflow).

All the others parameters investigated in the present study had no effect on the model results.

**PARAMETER CALIBRATION**

Calibration is an iterative procedure of parameter evaluation and refinement by comparing simulated and observed values. Calibration may be (for simple models) a process of measuring parameter values; of iteratively adjusting (manually) the values of the model parameter set until observed and simulated values are in acceptable agreement; or of using a mathematical process designed to minimize a function that expresses the difference between observed and simulated values. According to the Users Manual and the Application Guide for HSPF (Donigian et al., 1984), calibration of HSPF should be based on several years of simulation (three to five years is optimal) in order to evaluate the parameters under a variety of climatic, soil moisture, and water quality conditions.

In the present work a method was implemented for optimizing an input parameter set that governs the hydrologic processes. The HSPF code and the optimization subroutines were combined to form the HYDRO code. Three routines in the HYDRO code serve the purpose of directing the optimization. These routines are organized as follows:

(a) OPTOPT initializes HSPF parameter values and bounding values required for the execution of SEARCH, reads and transmits observed streamflow, and calls SEARCH to begin optimization.
(b) SEARCH is an optimization procedure that includes the nonlinear unconstrained optimization routine SEERCH (Westley and Watts, 1970). Given initial parameter estimates, SEARCH call for evaluation of the objective function, determines if the value is acceptably small, and, if not, determines the new trial parameter values for the next iteration. SEARCH calls HSPF to estimate the simulated streamflows and calls EVAL to obtain the value of the objective function. SEARCH is a gradient-based,
pattern-search technique, and determines parameter set values that identify local minima in a multi-dimensional parameter space. A local minima is assumed to be identified whenever one of several criteria has been established. These criteria may be based on the establishment of a zero-slope, an upwardly concave condition (within user-specified bounds), or upon completion of a fixed number of iterations. The user causes the procedure to seek a global minimum by initially specifying large step sizes,
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which are automatically reduced as the procedure progresses.

(c) EVAL evaluates the objective function (FB), which is expressed as the sum of the absolute differences between the observed and simulated flows divided by the observed flow values during that period of calibration.

PARAMETER OPTIMIZATION
(ANALYSIS AND DISCUSSION)

The optimization runs were performed to match monthly and annual average streamflows in cubic feet per second. The period covered was from 1990 to 1993. Each year was calibrated separately, resulting in four independent sets of optimized parameter values. Because of the choice of the functional form of the objective function, there was no overemphasis of high flows. No attempt was made to ignore days of low flow. All simulations were performed using a 0.33 hour time step.

Table 2 presents the optimization control values together with the final parameters obtained during each of three preliminary single-year optimization runs. In this process, a separate nine-parameter set was obtained by optimization of monthly hydrologic flows in each year for 1990, 1991, 1992 and 1993. Boundary conditions were adjusted on a year-by-year basis. Hydrologic parameter estimates were made after consideration of available topographic and soils data and extensive on-site inspection of the watershed and were in accordance with instructions and hints given in other published White Oak Creek documentation (Clapp et al., 1994). Parameter bounds were chosen on the basis of what range was reasonable, given the quasi-physical model framework. It should emphasized that the choice of upper and lower bounds must be made with (1) knowledge of the watershed being modeled and (2) insight into the nature of the model.

Figures 4 and 5 show the agreement between observed and simulated monthly streamflows, together with the corresponding monthly precipitation for each year. Each parameter set produces good agreement (average difference < 15 percent) between observed and predicted monthly flows for the year in which it was obtained, indicating the ability of the optimized parameter sets to reproduce observed flows.

Each of the four parameter sets was developed for the same watershed, yet they exhibit significant differences (Table 2). It has been reported that the HSPF model parameter sets may be different for years having significantly different precipitation patterns (Fontaine, 1989). However, this is not a desirable attribute of the model, since HSPF supposedly is based on physical watershed processes and the model parameters are ultimately derived from physical concepts. The years used in this study differed significantly in precipitation, with year 1991 being very wet. Obtaining different parameter sets for hydrologically dissimilar years might be called the “model deficiency” explanation. Other possible explanations for the different parameter sets include “data deficiencies,” “misrepresentation of watershed” and “model thresholds.” “Data deficiencies” refer to the use of erroneous watershed data or the use of data that are recorded at the watershed but that actually may apply to only a portion of it. For example, soil permeability varies considerably over the watershed, but may be assumed to be described by a single value. Also, measured precipitation values are assumed to be applicable to the entire watershed, but it is likely that rainfall events have considerable spatial inhomogeneity. “Misrepresentation of watershed” refers to errors in model application that result from incorrectly specifying the structure of the watershed to be simulated. "Model

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>LZSN</td>
<td>4.0-15.0</td>
<td>11.5</td>
<td>6.0</td>
<td>6.0</td>
<td>8.5</td>
<td>6.0</td>
</tr>
<tr>
<td>INFILT</td>
<td>0.04-1.5</td>
<td>0.30</td>
<td>0.132</td>
<td>0.076</td>
<td>0.098</td>
<td>0.343</td>
</tr>
<tr>
<td>AGWRC</td>
<td>0.899-0.999</td>
<td>0.978</td>
<td>0.966</td>
<td>0.995</td>
<td>0.978</td>
<td>0.990</td>
</tr>
<tr>
<td>UZSN</td>
<td>0.20-2.0</td>
<td>0.40</td>
<td>1.28</td>
<td>0.78</td>
<td>0.49</td>
<td>1.01</td>
</tr>
<tr>
<td>INTFW</td>
<td>1.0-2.0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>IRC</td>
<td>0.03-0.60</td>
<td>0.10</td>
<td>0.05</td>
<td>0.60</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>UZS</td>
<td>0.40-10.0</td>
<td>1.32</td>
<td>2.84</td>
<td>6.17</td>
<td>1.17</td>
<td>1.10</td>
</tr>
<tr>
<td>LZS</td>
<td>1.0-10.0</td>
<td>4.0</td>
<td>5.28</td>
<td>9.84</td>
<td>8.61</td>
<td>9.61</td>
</tr>
<tr>
<td>AGWS</td>
<td>1.0-6.0</td>
<td>3.7</td>
<td>4.65</td>
<td>3.83</td>
<td>3.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>
thresholds" refers to the use in HSPF of hidden parameters that are used to adjust model performance for different flow or storage regimes. The use of these parameters can cause the model to change its simulation behavior abruptly within a given simulation period, or to act as a different model for years having different hydrologic conditions.

It is desirable that a parameter set that is obtained by manual or computer-assisted optimization has predictive capability; i.e., that the data set may be used to produce simulation results in future years that are in good agreement with measured values. One reason that a data set may not have predictive capability is that although the parameter sets have met objective
Figure 5. Observed and Simulated Monthly Discharge with Corresponding Precipitation Data for Calibration Years 1992 and 1993.

criteria of reproducing an observable quantity (e.g., hydrologic flows) for a particular year, each parameter in itself does not have a value that corresponds to a reasonable physical value according to the conceptual model. A second reason may be that parameters are correlated (Fontaine 1989), which implies that several combinations of parameters may yield equally valid results within a given year. Thus a model calibration may only provide a parameter set that gives good agreement between observed and predicted values, while individual parameter values may not accurately describe watershed processes for which they
were intended. Each newly obtained parameter set should be tested for its predictive usefulness by using it to simulate processes in years other than the year for which it was developed. The parameter set is then retained or rejected, depending upon its success in simulating observed values.

**DEVELOPMENT OF A PARAMETER SET WITH PREDICTIVE CAPABILITY**

Because of the lack of initial success in determining a parameter set that had broad applicability for simulating streamflows in years other than the one for which it was developed, it was realized that an approach must be devised that would consider a greater span of time. Ideally, this process could be accomplished by optimizing the parameter set over a period of several years. However, this would necessitate writing a new model that would require significantly more computer time and storage capability than is available.

More encouraging results were obtained by examining the ability of optimized data sets developed for a given year to simulate observations in other years. The results of this approach are shown in Table 3, which shows the average of the absolute values of the monthly percent error ($X_{ave}$), for a given year. This value was calculated for N months using:

$$X_{ave} = \frac{1}{N} \sum_{i=1}^{N} \text{abs (monthly \% error)}$$

TABLE 3. Average of the Absolute Values of the Monthly Percent Error Results of Year Y2 Using Calibrated Data Set Derived for Year Y1.

<table>
<thead>
<tr>
<th>Y2 \ Y1</th>
<th>1990</th>
<th>1991</th>
<th>1992</th>
<th>1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>15.6</td>
<td>12.4</td>
<td>17.8</td>
<td>18.7</td>
</tr>
<tr>
<td>1991</td>
<td>31.2</td>
<td>12.7</td>
<td>21.6</td>
<td>21.2</td>
</tr>
<tr>
<td>1992</td>
<td>19.6</td>
<td>7.1</td>
<td>14.6</td>
<td>9.7</td>
</tr>
<tr>
<td>1993</td>
<td>29.8</td>
<td>12.1</td>
<td>24.2</td>
<td>15.3</td>
</tr>
<tr>
<td>Mean</td>
<td>24.1</td>
<td>11.1</td>
<td>19.6</td>
<td>16.2</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>7.6</td>
<td>2.7</td>
<td>4.2</td>
<td>5.0</td>
</tr>
</tbody>
</table>

In Table 3, the on-diagonal values represent the ability of a data set derived for a particular year to simulate observed values for that year, while off-diagonal values represent the applicability of the data set to simulate streamflows in other years. These results demonstrate that the optimized parameter set derived for 1991 has a much better predictive capability for other years than do the optimized parameter sets developed for other years. Indeed, the data set developed for 1991 appears to sometimes yield better for other years than that data set developed by optimizing for that year.

Two main conclusions came from these results. First, at least for the four years considered here, a set of model parameters exists that has reasonable predictive capability for years other than the one for which the set of parameters was developed, and this parameter set may be found by a process of numerical optimization. Second, numerical optimization may sometimes yield a set of parameters that is not an optimal set, even in terms of minimizing the objective function. For example, a higher value was obtained for the objective function for 1991. This may occur because the optimization process may converge on any of these. The user may benefit from starting the optimization process from several initial parameter sets, or from using large step sizes for parameter perturbations.

A final step in the generalization of the calibration procedure was to examine the effects of carrying final water storage values (UZS, LZS, and AGWS) for each year into the beginning of the succeeding year. The initial value for 1991 was the value obtained through optimization. Thus more realistic (simulated) initial conditions were specified. For each year, the other six significant parameters were those “best” values discussed in the preceding paragraph. Results for simulations performed in this final step are presented in Figure 6. The average percentage difference between monthly observed and simulated values is lower than obtained in the single-year runs presented in Figures 4 and 5 by as much as 50 percent.

**CONCLUSIONS**

This work demonstrates the value of an initial sensitivity study combined with a numerical optimization procedure to develop a set of hydrologic parameters with predictive capability. This procedure was applied to calibrate a complex hydrologic transport model that required a large number of parameters as inputs, many of which were not directly measurable.

The sensitivity of the HSPF model’s behavior to changes in the parameters that describe the main hydrologic processes in a watershed has been elucidated and should prove to be of value in reducing calibration time for future optimization studies under similar conditions. In general, the model performed well in the sensitivity analysis since the changes in model output were in all cases less than the changes
in input parameter (the partial derivatives were always less than unity).

It was demonstrated that numerical optimization may not be a sufficient tool for model calibration, since in some cases the resulting parameter sets may yield good agreement between observed and simulated values only for a limited time span. Numerical optimization is an aid for determining a parameter set that describes that watershed, but it must not be used blindly. Considerable interpretation and effort
usually must be employed to determine a set of values for nonmeasurable parameters that is applicable for simulating a large time span. The same caveat applies to manual calibration. Another concern is whether an optimal parameter set corresponds to a global, or only to a local, minimum value of the objective function calculated in the optimization procedure. It is for this reason that (a) each of several optimal parameter sets may be considered more-or-less equally valid results and (b) a considerable amount of judgment is required to guide the optimization procedure.

The temporal resolution of watershed calibration depends on the requirements of the modeler. If monthly simulated flow values are required, the level of analysis presented here is probably sufficient. When resolution of daily streamflow values is of interest, the analysis must be refined to include a comparison of daily simulated and measured flows. As part of the authors' need is to develop a capability for estimating sediment and radioisotope transport, the next step in watershed calibration will be to examine individual storms and to determine parameters that yield hydrologic and sediment transport values that agree with observations.

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LITERATURE CITED


