SACRAMENTO MODEL CALIBRATION USING DIFFERENT METHODOLOGIES – APPLICATION TO THE ITABAPOANA-MG RIVER BASIN

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ABSTRACT: Despite the considerable progresses in computational hydraulics the calibration of hydrological models still requires a meticulous and laborious effort. However, the development of model calibration supporting tools has facilitated that work and improved the obtained results. The objective of this paper, developed under a R&D project, is to evaluate the performance achieved by using different calibration techniques for the Sacramento rainfall-runoff model of the Itabapoana-MG river basin. Bom Jesus do Itabapoana, a flood prone city, is located about 35 km downstream of Rosal hydropower plant. The limited capacity of Rosal reservoir implies that it cannot be used to mitigate flooding at downstream cities. However, flood forecasting can be used to avoid potential downstream damages and support decision making to defend and mitigate the undesirable effects. There should be a balance between the models performance and their computational times. It is important consider sufficiently precise results for sound decision-making outcomes, as well as results fast enough to be used in an operational decision support system environment. SOBEK software was chosen for prediction of flood events and Sacramento hydrological model was selected as rainfall- runoff model. SOBEK does not offer a module for automatic calibration of their hydrological models. Thus, for the quantification of Sacramento parameters, it is possible to make use of external algorithms for automatic calibration based on global optimization techniques. This paper assesses the eficiency of using automatic calibration results using the Rainfall Runoff Library (RRL) within SOBEK hydrological module. In general, the results for RRL were better than the ones reached by SOBEK. Despite differences, the use of RRL as a tool to accelerate the parameters determination process for the Sacramento model has obtained satisfactory results within SOBEK.

Key Words: Flood Management, Sacramento Model, Calibration methodologies, SOBEK, RRL

1. INTRODUCTION

This paper was developed under the research project called "Deployment System for coupling models and telemetric information aimed at optimizing reservoir operation in real time, focusing on flood control", which was proposed by Companhia Energética de Minas Gerais S.A. (CEMIG) and supported by Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG).

This R&D project, lasting for three years, is being run by the LACTEC Institutes which has as consultant DELTARES Research Institute. In summary, the main objective is to build advanced tools for flood forecasting. Such tools will be applied to mitigate flood damage in river reaches downstream dams considering optimization of hydropower generation schemes.

One of the studied areas is the Itabapoana-MG river basin, with a drainage area of 2,303 km². Bom Jesus do Itabapoana, a flood prone city, is located about 35 km downstream of the Rosal hydropower plant. This reservoir has a draining area of 1,774 km². The limited capacity of Rosal reservoir implies that it cannot be used to mitigate flooding at downstream cities. However, the flood forecasting system will be used to avoid potential downstream damages and to support decision making to prevent and mitigate the undesirable effects (LACTEC, 2013a).

Developed by DELTARES, the software SOBEK (DELTARES, 2013) was chosen for the prediction of flood events since it can be applied both to one- and two-dimensional domains. This software consists of a set of integrated modules, that allows the simulation of hydrologic rainfall-runoff models in watersheds and performs the flood routing along river canals of the fluvial system (rivers and reservoirs). It can also be applied in urban areas (DELTARES, 2011).

The rainfall-runoff model selected for this project is Sacramento. It is implemented in SOBEK together other models. SOBEK does not offer a module for automatic calibration of hydrological models. This paper presents results of automatic calibration using the Rainfall Runoff Library (RRL) as an auxiliary tool to SOBEK hydrological module. RRL was developed by the CRC for Catchment Hydrology's Predicting Catchment Behavior Research Program in Australia and it allows the individual sub-basins calibration, assuming a single entry for precipitation, evaporation and discharges time series (CRC, 2004).

RRL considers just the lumped basin setup (hereafter called reduced model). In a near future, real-time operation of reservoirs will be based on detailed weather radar rainfall data. Hence, it is necessary to analyze if the calibrated parameters using large basins in a very simplified schematization can be used for semi-distributed and finer resolutions of SOBEK models. This paper presents results for the first phase of this assessment concerning the calibration of the reduced hydrological model using RRL.

2. SOBEK MODELLING PACKAGE

SOBEK (DELTARES, 2013) is a software package for river, urban or rural water management. It consists of an integrated framework which means that SOBEK can link river, canal and sewer systems for a total water management solution. It is designed to interface with existing software. It can use information from a variety of standard data formats and GIS systems.

SOBEK is based on high performance computer technology and integrates different modules to simulate particular aspects of the water systems. These modules can be operated separately or in combination. The data transfer between the modules is fully automatic and modules can be run in sequence or simultaneously to facilitate the physical interaction. The integrated approach makes SOBEK a valuable instrument for flood forecasting, navigation, optimizing drainage systems, controlling irrigation systems, reservoir operation, sewer overflow design, groundwater level control, river morphology regulation, and water quality control. The integrated approach also means that SOBEK can combine river systems, urban systems and rural systems for a total water management solution (DELTARES, 2013).

The software calculates the flow in simple or complex channel networks, consisting of thousands of reaches, cross sections and structures. It is possible to define all types of boundary conditions, as well as define lateral inflow and outflow using time series or standard formulas. For more detail, the rainfall run-off process of urban areas and various types of unpaved areas can be modelled, taking into account land use, the unsaturated zone, groundwater, capillary rise and the interaction with water levels in open channels. For water quality and environmental problems, the Water Quality module offers almost unlimited possibilities (DELTARES, 2013). This work was developed using model version SOBEK 2.13.002.

2.1 Sacramento Model in SOBEK

One of the available hydrological modules of SOBEK is based on the Sacramento model. This is a conceptual model that uses average precipitation and potential evapotranspiration data to estimate the flow rate in the basin. The generation of the flow is based on the subdivision of the soil into two main layers: the top and the bottom layers. At the top layer the fastest processes that occur along the surface (evaporation, seepage, runoff and subsurface flow) are represented and at the inferior layer the slower processes associated with the unsaturated soil zone (sweating, aquifer recharge and base runoff) are represented (DELTARES, 2013).

In both layers, regions where water is either under the effect of surface tension (capillarity) or hydrostatic pressure (water free) are considered, therefore it is possible to define at least four distinct storage reservoirs. The basic mechanism of the model considers that if the maximum storage capacity of the upper water reservoir under pressure is exceeded, the water becomes available for storage in the upper reservoir of free water. This region represents a temporary storage of water that infiltrates (percolation) in the lower system and contributes to the flow in the reach by sub-surface flow. Similarly, the filling of the lower water reservoirs that will give rise to the base flow is considered (DELTARES, 2013).

The calibration of the Sacramento model involves the quantification of sixteen parameters per sub-basin (Table 1), related to the soil and surface hydrological processes. Some of these parameters can be calibrated by analyzing hydrographs, others may be derived from the physiographic characteristics of the basin and the others must be estimated based on a trial and error analysis. It is still possible to make use of external algorithms for automatic calibration based on global optimization techniques, considering different error metrics. These parameters are obtained using RRL software, and inserted for each sub-basin of the SOBEK model.

Table 1: Parameters of Sacramento model

Parameter	**Unit**	**Description**
UZTWM	mm	Upper Zone Tension Water Maximum. The maximum volume of water held by the upper zone between field capacity and the wilting point which can be lost by direct evaporation and evapotranspiration from soil surface. This storage is filled before any water in the upper zone is transferred to other storages.
UZFWM	mm	Upper Zone Free Water Maximum, this storage is the source of water for interflow and the driving force for transferring water to deeper depths.
LZTWM	mm	Lower Zone Tension Water Maximum, the maximum capacity of lower zone tension water. Water from this store can only be removed through evapotranspiration.
LZFSM	m	Lower Zone Free Water Supplemental Maximum, the maximum volume from which supplemental baseflow can be drawn.
LZFPM	mm	Lower Zone Free Water Primary Maximum, the maximum capacity from which primary base flow can be drawn.
UZK	1/day	The ratio of water in UZFWM, which drains as interflow each day.
LZSK	1/day	The ratio of water in LZFSM which drains as baseflow each day.
LZPK	1/day	The ratio of water in LZFPM, which drains as baseflow each day.
PFREE	--	The minimum proportion of percolation from the upper zone to the lower zone directly available for recharging the lower zone free water stores.
REXP	--	An exponent determining the rate of change of the percolation rate with changing lower zone water storage.
ZPERC	--	The factor applied to PBASE to define maximum percolation rate.
SIDE	--	The decimal fraction of observed base flow, which leaves the basin, as groundwater flow.
SSOUT	$m^3/s/km^2$	The volume of the flow which can be conveyed by porous material in the bed of stream.
PCTIM	--	The impervious fraction of the basin, and contributes to direct runoff.
ADIMP	--	The additional fraction of pervious area, which develops impervious characteristics under soil saturation, conditions.
SARVA	--	A decimal fraction representing that portion of the basin normally covered by streams, lakes and vegetation that can deplete streamflow by evapotranspiration.

3. RAINFALL RUNOFF LIBRARY PACKAGE

RRL (Rainfall Runoff Library) was developed by the CRC for Catchment Hydrology's Predicting Catchment Behavior Research Program in Australia (CRC, 2004) as a tool to support the calibration of hydrological models. The software provides 5 commonly used rainfall runoff models, 8 calibration optimizers, a choice of 10 objective functions and visualization tools to facilitate model calibration. The rainfall-runoff models included in the library are:

- AWBM;
- Sacramento;
- Simhyd;
- SMAR; and,
- TANK.

The calibration optimisers included in the library are:

- Uniform random sampling;
- Pattern search;
- Multi start pattern search;
- Rosenbrock search;
- Rosenbrock multi-start search;
- Genetic algorithm
- Shuffled Complex Evolution (SCE-UA); and,
- AWBM custom optimiser.

After the model choice, the input data should be entered. Continuous daily time series of rainfall, runoff and evapotranspiration data are used as input. Some basic statistics are calculated by RRL and allow rapid analysis regarding the existence of inconsistency in the input data. The catchment area is also required, it is used to convert inputs and outputs between the flow and depth of runoff.

Calibration, verification and warm up periods can be specified. Some tools are also available to help the user find out the appropriate periods. The calibration takes place automatically or manually. In the first case, different optimization methods can be chosen in order to find the best combination of parameters. In the second case, the simultaneous analysis of the variation of the adjustment quality parameter can be done every time the hydrological model parameters values are changed (CRC, 2004).

4. CALIBRATION OF ITABAPOANA-ROSAL MODEL

This section presents the calibration of the rainfall-runoff model, based on data available at ANA (Brazilian National Water Agency). It was used discharge and precipitation gauge stations data for the calibration of the Sacramento rainfall-runoff model. This task was performed using available data for the period of January/2005 to March/2011. This six years period reveals an almost constant annual hydrological regime with a wet season followed by a dry season presenting some inter-annual variations. Results evaluation was performed using different metrics (LACTEC, 2013b).

4.1 Data

Precipitation are monitored in thirteen precipitation gauge stations. Data was processed using a Thiessen polygons approach to derive precipitation time series for each one of the 169 sub-catchments of the model. River discharges are monitored in five gauge stations that are presented in Table 2 and Figure 1.

Table 2: Itabapoana-Rosal model – River discharges gauge stations

Name	River	Latitude	Longitude	Area (km²)
Ponte do Itabapoana	Itabapoana	-21.029	-41.652	2,720
São Jose do Calçado	Calçado	-21.029	-41.652	153
Guacui	Veado	-20.772	-41.681	408
Caiana	São João	-20.695	-41.921	406
Dores do Rio Preto	Preto	-20.686	-41.847	222

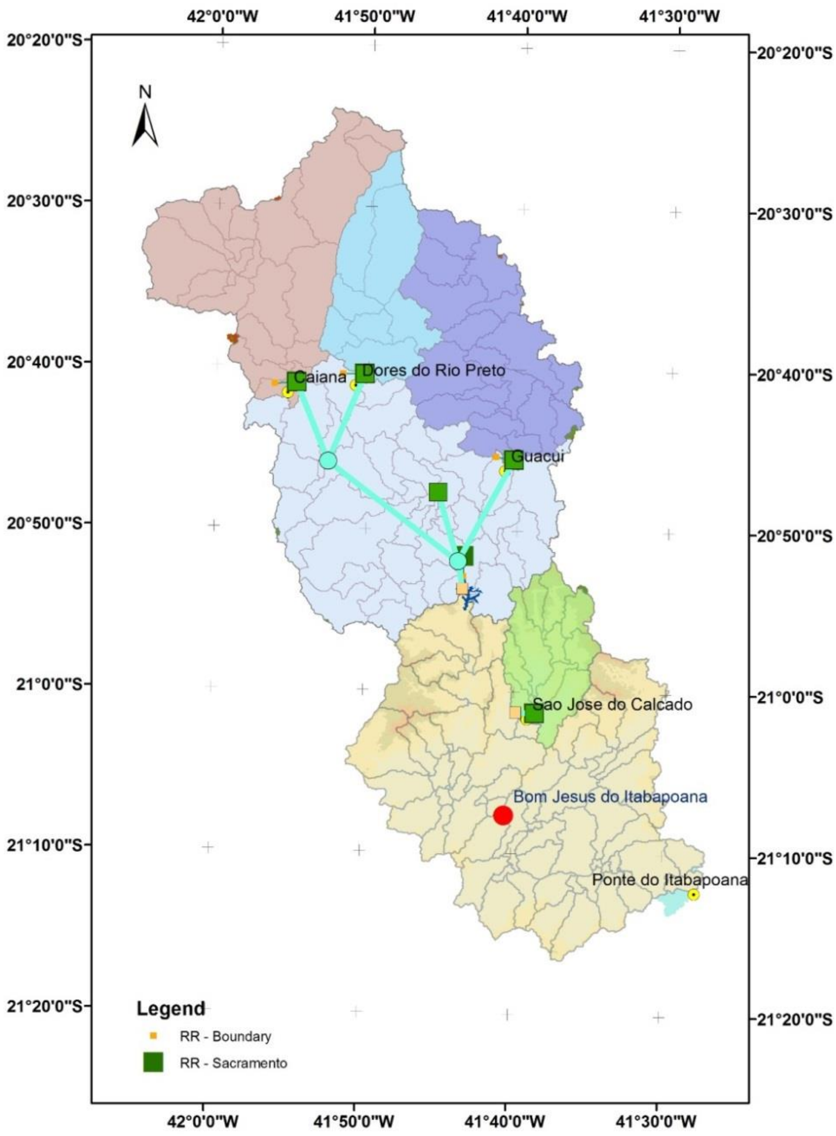

Figure 1: Setup of reduced model for Itabapoana-MG river basin

The evaporation was defined using long term monthly data that was disaggregated to define the necessary daily evaporation time series. The long term monthly averages were obtained from two ANA meteorological stations in the Itabapoana river basin.

4.2 Methodology

Hydrological model calibration strategy includes the calibration of five different sets of catchments located upstream discharge stations: Caiana, Dores do Rio Preto, Guaçui, São José do Calçado, and the basin located between the Rosal reservoir and the upstream discharge gauge stations (Figure 1). This paper presents the results for the four upstream discharge stations.

Initial values of model parameters were defined recurring either to hydrograph analysis, from their usual range obtained from literature (Anderson et al.; 2006) and also from soil characteristics (Koren et al., 2000). These initial values are very dependent on the selected events and either on the analyzed basin. Moreover, it was not possible to collect confident values for soil characteristics for each basin. In this way the final calibration was developed using the automatic features available at RRL, being that the algorithm of optimization of parameters that presented more satisfactory results was the genetic algorithm.

Model performance was evaluated recurring to different metrics: Nash Sutcliffe Model Efficiency (NSE), a bias parameter computation based on the difference between the sum of simulated discharges and the sum of observed ones ($BIAS$), Root Mean Squared Error ($RMSE$) and Mean Average Error (MAE), computed according Equations 1 to 4, respectively.

$$NSE = 1 - \frac{\sum(\hat{Q} - Q)^2}{\sum(Q - \overline{\overline{Q}})^2} \quad [1]$$

$$BIAS = \frac{1}{N}\left(\sum \hat{Q} - \sum Q\right) \quad [2]$$

$$RMSE = \sqrt{\frac{1}{N}\sum(\hat{Q} - Q)^2} \quad [3]$$

$$MAE = \frac{1}{N}\sum\left|\hat{Q} - Q\right| \quad [4]$$

where N is the number of measured discharges in the analyzed period, Q are measured discharges and $\hat{Q}$ are simulated discharges. The correlation coefficient (R^2) was also computed between measured and simulated results.

The calibrated parameters were applied for simulation on reduced model in RRL and reduced model setup for SOBEK.

4.3 Results

From the calibration exercise in RRL, the values depicted in Table 3 were obtained. Figures 2 and 3 show the reduced model performance considering the following measurements period: March/2008 to March/2011.

Table 3: Estimated Sacramento model parameters values obtained in RRL and used in SOBEK

Parameter	Faixa de variação	Caiana	Dores do Rio Preto	Guacui	São José do Calçado
ADIMP	0 - 0.2	0,068	0,118	0,004	0,062
LZFPM	0 - 1000	380,392	478,431	325,490	650,980
LZFSM	15 - 300	60,824	178,765	67,314	148,000
LZPK	0.001 - 0.015	0,006	0,009	0,008	0,007
LZSK	0.03 - 0.2	0,186	0,114	0,043	0,190
LZTWM	0 - 500	133,333	60,784	15,686	41,176
PCTIM	0 - 0.5	0,000	0,008	0,002	0,065
PFREE	0 - 0.4	0,365	0,395	0,370	0,391
REXP	1 - 3	2,678	2,137	2,129	1,220
RSERV	0 - 0.4	0,104	0,063	0,257	0,052
SARVA	0 - 0.5	0,000	0,027	0,000	0,000
SIDE	0 - 5	0,412	0,157	0,000	0,451
SSOUT	0 - 1	0,004	0,000	0,000	0,000
UZFWM	10 - 100	62,235	13,529	56,588	41,765
UZK	0 - 0.5	0,106	0,225	0,282	0,331
UZTWM	0 - 125	0,001	0,001	0,001	0,001
ZPERC	20 - 300	226,431	289,020	55,137	134,196

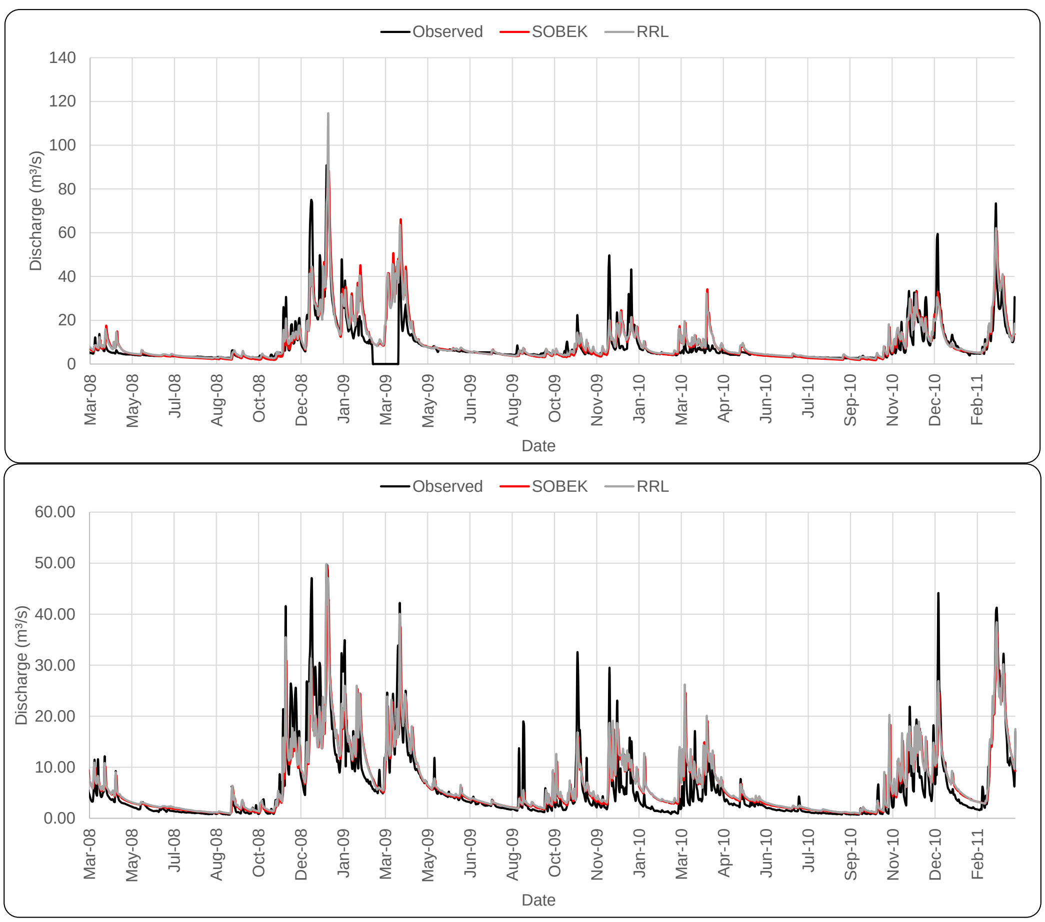

Figure 2: Observed, simulated in SOBEK and simulated in RRL discharges at Caiana (top graph) and Dores do Rio Preto (bottom graph)

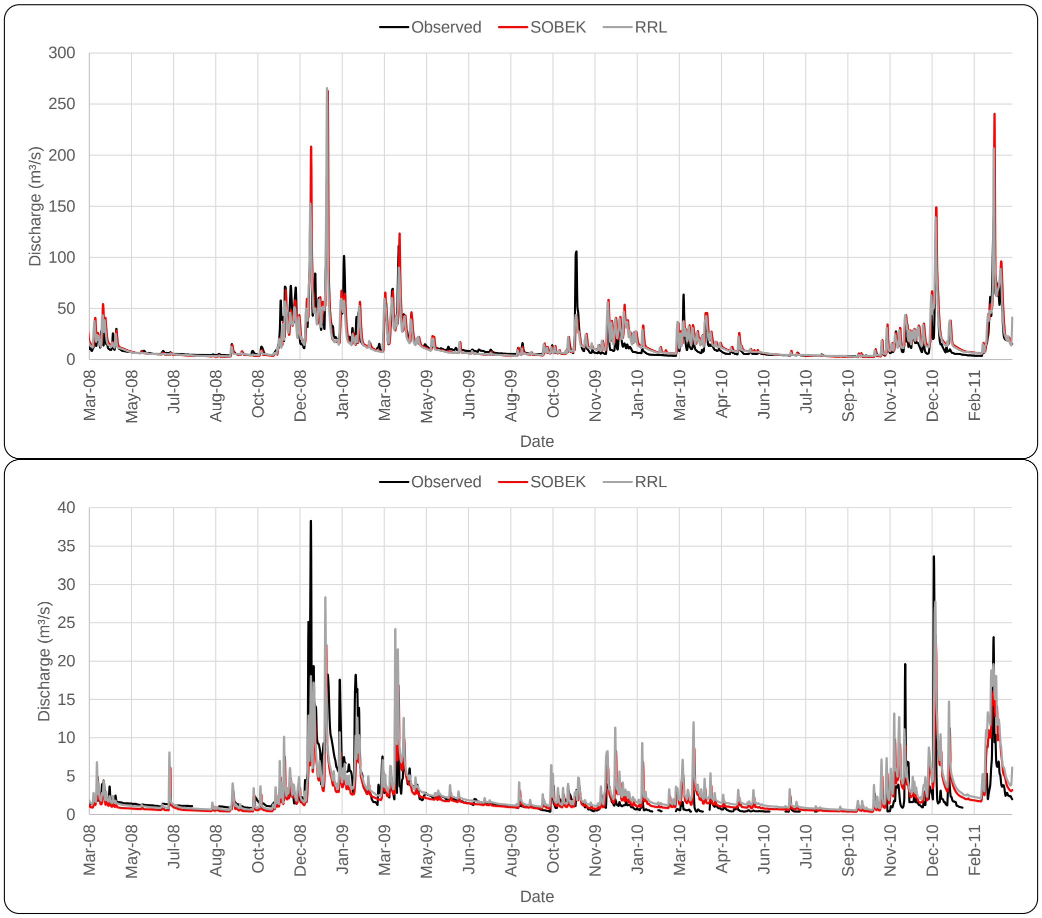

Figure 3: Observed, simulated in SOBEK and simulated in RRL discharges at Guacui (top graph) and São José do Calçado (bottom graph)

Using RRL it is possible to set different periods for calibration and verification, considering for each one specific warm up periods. In both cases a four months warm-up period was established, thus, calibration and verification periods were selected respectively from May/2005 to March/2008 and from August/2008 to March/2011.

In order to assess the models performance of the reduced model setup in SOBEK, using the previous presented parameters values obtained from simulations in RRL, for the entire simulation period, the results of performance parameters computed are presented in Tables 4 and 5. It might be observed that, in general, the best results depend on the chosen performance parameter, as depicted in Tables 4 and 5. Table 4 presents Nash-Sutcliffe coefficient values for calibration and verification periods. Table 5 shows the results for the other metrics and considering the entire measured data period.

Table 4: Reduced model performance for calibration and validation periods obtained with SOBEK and RRL

Metrics\Basin		**Caiana**		**Dores do Rio Preto**		**Guacui**		**São José do Calçado**	
		SOBEK	**RRL**	**SOBEK**	**RRL**	**SOBEK**	**RRL**	**SOBEK**	**RRL**
NSE Calibration	(-)	0,65	0,74	0,67	0,74	0,61	0,76	0,42	0,55
NSE Validation	(-)	0,68	0,78	0,76	0,83	0,63	0,81	0,42	0,45

As can be seen in Table 4, Nash-Sutcliffe coefficient values preliminarily obtained in RRL are superiors to those ones obtained for the same simulation conditions in SOBEK. This difference may be associated with the simulation initial conditions or with the different allowable ranges for each parameter in each software. Good results were found out for Caiana, Dores do Rio Preto and Guacui catchments while the worst results were obtained in São José do Calçado basin.

Table 5: Reduced model performance for entire measured data period

Metrics\Basin		Caiana		Dores do Rio Preto		Guacui		São José do Calçado	
		SOBEK	RRL	SOBEK	RRL	SOBEK	RRL	SOBEK	RRL
BIAS	(m^3/s)	-0,29	0,21	-0,17	0,16	0,52	-0,18	-0,49	0,20
RMSE	(m^3/s)	5,81	5,04	3,89	3,37	11,52	8,94	2,83	2,55
MAE	(m^3/s)	3,02	2,63	2,09	1,89	5,75	4,75	1,38	1,31
R2	(-)	0,64	0,72	0,71	0,79	0,68	0,77	0,43	0,53
Average simulated	(m^3/s)	8,34	8,83	6,23	6,56	15,99	15,30	2,18	2,80
Average observed	(m^3/s)	8,86		6,42		15,53		2,88	

In Table 5 can be observed that the correlation coefficient (R^2) values followed the same trend of the Nash-Sutcliffe coefficient when comparing the results between the SOBEK and RRL. The simulated average shows the same pattern for the catchments Caiana, Dores do Rio Preto and São José do Calçado, i.e., RRL reached higher values. The basin Guacui differed by being the only one for which the SOBEK simulation overestimates while the RRL simulation underestimates flow data, based on $BIAS$ metric. However, as shown in the table, generally the obtained $BIAS$ values are relatively close to the optimal value (zero) indicating low biased results both for RRL and SOBEK simulations.

Both the mean square error ($RMSE$) and the absolute error (MAE) provide a measure of the dispersion between simulated and observed data, but MAE is less sensitive to extreme values. For all catchments, these scatter degrees are larger for simulation carried out in SOBEK.

5. CONCLUSIONS

The calibration of hydrological models still requires a meticulous and laborious effort. However, the development of model calibration supporting tools has facilitated that work and improved the obtained results. The objective of this work was to evaluate the performance achieved by using different calibration techniques for the rainfall-runoff Sacramento model of the Itabapoana-MG river basin.

This paper was developed under a R&D project whose the main objective is to build advanced tools for flood forecasting. Such tools will be applied to mitigate flood damage in river reaches downstream dams considering optimization of hydropower generation schemes. The software SOBEK was chosen for the flood events prediction since it can be applied both to one- and two-dimensional domains. It can also be applied in urban areas, but it does not offer module for automatic calibration. The calibration of Sacramento model involves the quantification of sixteen parameters per sub-basin, related to the soil and surface hydrological processes. Thus, this paper presents results of automatic calibration using the Rainfall Runoff Library (RRL) as an auxiliary tool to SOBEK hydrological module.

Estimated Sacramento model parameters values implemented in SOBEK were obtained from the calibration exercise in RRL and the simulation period considered coincided with the period of data observed. The best results depend on the chosen performance parameter. In terms of the Nash-Sutcliffe coefficient, for example, good results were found for Caiana, Dores do Rio Preto and Guacui catchments and the worst results were obtained in São José do Calçado basin.

In general, the Nash-Sutcliffe coefficient values preliminarily obtained in RRL are superior to those found for the same simulation conditions in SOBEK. This difference may be associated with the different allowable ranges for each parameter in each software. The values of the correlation coefficient (R^2) followed the same trend of Nash-Sutcliffe coefficient when comparing the results between the SOBEK and RRL. The use of RRL as a tool to accelerate the process of obtaining the parameters for the Sacramento model has obtained, in general, satisfactory results.

Furthermore, it is important to keep in mind that the calibration results quality is a direct function of the input data quality. In addition, the use of automatic calibration methods does not replace the knowledge of the characteristics of each hydrological model. Despite having a good mathematical result, the automatic calibration could lead to values not physically acceptable for the conceptual structure of the hydrologic model.

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