Objective calibration of the hydrological model SEROS for the Odra watershed

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Abstract

Hydrologic models commonly contain parameters that can only be inferred by a trial-and-error process that adjusts the parameter values to closely match the input-output behaviour of the model to the real system it represents. Traditional calibration procedures, which involve manual adjustment of the parameter values are labour-intensive, and their success is strongly dependent on the experience of the modeller. This paper describes the application of the objective calibration methodology SCE-UA (Shuffled Complex Evolution – University of Arizona) to the hydrological model SEROS for the Odra watershed. SEROS combines the rainfall-runoff model SEWAB (Surface Energy and Water Balance) and a routing scheme. Simulated and observed time periods of the discharge show reasonable agreement during the calibration period as well as for the verification period. The latter includes the 1997 major flooding event.

Keywords: objective calibration, rainfall-runoff model, routing scheme, Odra watershed.

1 Introduction

Hydrologic models commonly contain parameters that can only be inferred by a trial-and-error process that adjusts the parameter values to closely match the input-output behaviour of the model to the real system it represents. Traditional calibration procedures, which involve manual adjustment of the parameter values are labour-intensive, and their success is strongly dependent on the experience of the modeller. Automatic methods for model calibration are objective. However, many studies have shown that such methods have difficulties in finding unique parameter estimates. Most hydrological methods suffer from similar problems,
e.g. the existence of multiple local optima in the parameter space with both, small and large domains of attraction (i.e. a sub-region of the parameter space surrounding a local minimum) or discontinuous first derivatives. The consideration of these problems resulted in the development of a robust and efficient global optimisation algorithm called ‘shuffled complex evolution’ (SCE-UA) global optimisation algorithm developed at the University of Arizona (Duan et al. [1, 2, 3]). The SCE-UA approach is applied to calibrate the hydrological model SEROS for the Odra watershed.

SEROS is a grid based model system which solves the coupled surface energy and water balance equations in each grid. Runoff is transported into the river system by use of a unit hydrograph approach and then along the river channel system by a kinematic wave approximation.

The calibration period for the SEROS system is the four years from 1992 until 1994. Data for the period 1995 until 1999 are used for validation purposes. Each of 39 sub-catchments is calibrated separately. The model efficiency shows a large regional variability. The calibration procedure and the validation with observed streamflow data are discussed.

2 Parameter estimation

Objective calibration techniques have been traditionally applied in hydrology to specify parameters in conceptual models for streamflow forecast in watersheds (Sorooshian and Gupta, [4]). A widely used optimization method is the Shuffled Complex Evolution - University of Arizona (SCE-UA) algorithm. Full details are given in Duan et al. [1, 2, 3]. Basically, an objective function is optimized (maximized or minimized) by “shuffling” parameter settings in a prescribed feasible parameter space. The objective function is some measure of the correlation between an observed and simulated time series. In hydrology, streamflow measured at some gauging station is commonly the target variable to be compared to the output of a hydrological model.

For details of the calibration methodologies we refer to the references. Here, only a brief outline is given.

We start by identifying the parameters of the model to be calibrated. There are input variables which force the model (wind speed, air temperature, air humidity, radiation, surface pressure). The model then as a function of and produces output. Corresponding to the simulated output there is an observed time series of the streamflow. The calibration problem can then be formulated as to optimize the objective function by adjusting the parameter set. The objective function is some measure of the distance between model output variable and observations. Gupta et al. [5] state that it was not possible to demonstrate that a particular objective function is better suited than some other. Here we use a modified (optimizing at 0) Nash-Sutcliffe efficiency as the objective function.
where the overbar denotes the mean of the observations. The calibration algorithm will find exactly one parameter set which minimizes $E_k (\Theta)$.

3 The hydrological model SEROS

The hydrological model SEROS combines the one-dimensional vertical land surface scheme SEWAB (Surface Energy and Water Balance, Mengelkamp et al., [6]) and a horizontal routing scheme (Lohmann et al., [7]).

3.1 The land-surface scheme SEWAB

The one-dimensional (vertical) land surface model SEWAB is designed to be coupled to atmospheric models or be run offline with forcing data. It calculates the vertical water and energy fluxes between the land surface and the atmosphere and within the soil column for a land surface grid cell. A land surface grid cell typically has horizontal dimensions of 1 to 100 km.

In SEWAB, both water and energy balance equations are solved at the land surface interface. The surface energy balance equation describes the equilibrium of net irradiance, latent heat flux, sensible heat flux and soil heat flux (and in case of snow, the energy available for melting). Precipitation is partitioned into runoff, evapotranspiration and change of snow pack and soil moisture storage. The evapotranspiration is calculated separately for bare soil and vegetated parts of the land surface grid cell.

Warrach et al. [8] incorporated a single-layer snow model to allow for a partially snow covered land surface grid cell. This snow model solves the energy balance for a snow pack and accounts for changes in density and surface albedo due to snowpack ageing. Snowpack meltwater either infiltrates into the soil or leaves the land surface as runoff.

The soil column (Fig. 1) is divided into a variable number of model layers. Within the soil column, temperature diffusion (with a term for soil freezing) and the Richards equation are solved. The Richards equation is modified to allow for root water uptake and soil freezing. The temperature of the first model layer is solved from the surface energy balance. The lower boundary temperature is prescribed by a time series representing the annual cycle. Leaf drip, precipitation on bare soil, evaporation from bare soil and the soil moisture are accounted for.

As a one-dimensional model, SEWAB represents a land-surface grid cell of an atmospheric circulation model with dimensions ranging from 1 to more than 10000 km$^2$. Runoff from the grid cell soil column is subject to transformation and translation processes before the water reaches the river as streamflow. Runoff may occur from saturated patches inside the grid cell before saturation of
the whole soil column or even may be delayed through ponding at the surface. These processes are described by the variable infiltration capacity approach for surface runoff and the concept of linear reservoirs for subsurface runoff and groundwater flow (Mengelkamp et al., [9]).

Figure 1: Sketch of the hydrological processes in SEWAB. a, b and c represent surface runoff, subsurface runoff and baseflow, respectively.

The variable infiltration capacity (VIC) approach indirectly accounts for the impact that topography and soil distribution have on surface infiltration (Wood et al. [10]; Liang et al. [11]). This concept does not necessarily need topographic data, the parameters can be calibrated to the catchment. However, within hilly and mountainous catchments the topography determines the distribution of soil type, soil depth and water table. i.e. when calibrating the parameters for the VIC approach the indirect effect of topography on the hydrological behavior is represented.

Linear reservoirs are added to the soil column to describe subsurface runoff and baseflow (Fig. 1). Subsurface runoff generation follows the ARNO model conceptualization (Dümenil and Todini [12]). Between field capacity and saturation the outflow of any soil layer is proportional to the current soil water content in that layer and controlled by the respective time constant which is subject to calibration.

The outflow from two linear groundwater storages for the slow and fast component represents the runoff baseflow component. The storages are filled by Darcian flow from the lowest soil layer. Individual time constants for the fast and slow component are determined empirically. This concept of storages allows a subtle adjustment of surface runoff, subsurface runoff and baseflow. However,
the large number of calibration parameters (time constants and storage heights) makes the calibration procedure a tedious task.

3.2 The routing scheme

The routing scheme (Fig. 2) describes both, the time runoff takes to reach the outlet of a grid box and the transport in the river channel system (Lohmann et al., [7]). Inside each grid box runoff is generated by the land surface model through the concepts outlined in section 3.1 or as saturation excess runoff. This runoff is transformed through the impulse response function of the unit hydrograph into box outflow. There is also upstream inflow into the grid cell through the river channel. This part of the flow through the grid cell is transformed by the river impulse response function to box outflow. The sum of streamflow generated inside the grid box and throughflow is the total outflow from the grid box and represents the river inflow to the next downstream box.

![Figure 2: Sketch of the horizontal routing scheme.](image)

The impulse response function of the unit hydrograph is based on the theory of a cascade of linear reservoirs (Lettenmaier and Wood [13]):

$$IRF^{UH}(t) = \frac{1}{k\Gamma(n)} \left( \frac{t}{k} \right)^{n-1} e^{-\frac{t}{k}}$$

The storage constant $k$ is the same for all $n$ reservoirs. $t$ [s] is time and the parameters $k$ and $n$ are subject to calibration. $IRF^{UH}$ describes transformation and translation processes streamflow undergoes inside a grid cell on its way to the outlet of the cell. $IRF^{UH}$, however, does not interact with the evapotranspiration through soil moisture control and as such is not an integral part of SEWAB. Therefore the $IRF^{UH}$ is here described as part of the horizontal routing scheme. The river impulse response function $IRF^{RIV}$ at any location $x$ and time $t$ reads

$$IRF^{RIV}(x,t) = \frac{s}{2t\sqrt{\pi Dt}} \exp\left(-\frac{(s - ct)^2}{4Dt}\right)$$
with the natural river length $s \,[\text{m}]$ in the grid cell. The diffusion coefficient $D \,[\text{m}^2/\text{s}^2]$ is deduced from observed streamflow data. The streamflow in the river channel at any location $x$ and any time $t$ is

$$Q^{\text{RIV}}(x,t) = \int_0^\tau I(0,t-\tau)IRF^{\text{RIV}}(x,\tau) \, d\tau$$

(4)

with the time dependent inflow $I(0,t)$ at the inlet of the grid box.

4 Data, set up and calibration of SEROS

SEROS is applied to the whole Odra basin covering 120,000 km² with a horizontal grid size of 4.5x4.5 km². The routing network and sub-catchments of each gauging station are determined from a digital elevation model (Fig. 3). The land-use type is deduced from the CORINE data set and the soil type from a polish soil type map.

Forcing data from 50 synoptic stations (6 hourly data) and 666 precipitation stations (daily data) are interpolated onto the model grid and used as forcing data. Daily discharges of 29 gauging stations and of 11 reservoirs in the
mountainous region are used for calibration and verification. The calibration period was 1992 to 1994, the verification period 1995 to 1999.

The rainfall-runoff (SEWAB) and the horizontal routing scheme are based on conceptual representations of the physical processes. Conceptual representations are controlled by physical parameters that describe measurable properties of the watershed and non measurable process parameters. Despite the detailed information for vegetation cover and soil type the respective parameters cannot be exactly defined for a single grid or a subcatchment. These include parameters of the evapotranspiration parameterization, runoff generation, initial soil water content and the water transport in the channel system. Some parameters can be deduced from watershed properties (i.e. the length of the river inside a grid box, the partition of major vegetation types from the CORINE data set). The interception reservoir or the stomata resistance of the vegetation, the retention period of the water inside a grid box or the partition in surface and subsurface runoff can not be known a priori. These parameters are among the ones which are subject to calibration. The choice of parameters conforms to the necessity to include the significant processes but to minimize the number of parameters.

Table 1: Calibration parameter and their lower and upper limit.

<table>
<thead>
<tr>
<th>notation</th>
<th>units</th>
<th>description</th>
<th>lower</th>
<th>upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI</td>
<td>[-]</td>
<td>VIC-Parameter for surface runoff</td>
<td>0.001</td>
<td>1.00</td>
</tr>
<tr>
<td>CBAS-L3</td>
<td>[-]</td>
<td>exponent for subsurface runoff, 3\textsuperscript{rd} soil layer</td>
<td>1.00</td>
<td>3.00</td>
</tr>
<tr>
<td>T1/2-L3</td>
<td>[d]</td>
<td>time constant 3\textsuperscript{rd} soil layer</td>
<td>50</td>
<td>1000</td>
</tr>
<tr>
<td>WS-L3</td>
<td>[-]</td>
<td>fraction to baseflow from 3\textsuperscript{rd} soil layer</td>
<td>0.40</td>
<td>0.99</td>
</tr>
<tr>
<td>DM-L3</td>
<td>[mm/s]</td>
<td>maximum runoff from 3\textsuperscript{rd} soil layer</td>
<td>0.001</td>
<td>0.500</td>
</tr>
<tr>
<td>CBAS</td>
<td>[-]</td>
<td>exponent for baseflow 6\textsuperscript{th} soil layer</td>
<td>1.00</td>
<td>3.00</td>
</tr>
<tr>
<td>T1/2</td>
<td>[d]</td>
<td>time constant for baseflow 6\textsuperscript{th} soil layer</td>
<td>50</td>
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<td>WS</td>
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<td>DM</td>
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<td>0.500</td>
</tr>
<tr>
<td>rsFactor</td>
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<td>correction for minimum stomata res.</td>
<td>0.50</td>
<td>2.50</td>
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<td>iniGW</td>
<td>[m]</td>
<td>initial baseflow storage</td>
<td>1.50</td>
<td>4.0</td>
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<tr>
<td>n</td>
<td>[-]</td>
<td>number of storages for unit hydrograph</td>
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<td>4.0</td>
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<tr>
<td>k</td>
<td>[h]</td>
<td>retention period</td>
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<td>diff</td>
<td>[m\textsuperscript{2}/s]</td>
<td>Rate of diffusion x 1000</td>
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<tr>
<td>velo</td>
<td>[m/s]</td>
<td>velocity of kinematic wave</td>
<td>0.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>

During the calibration period 1992 to 1994 more than 80\% of the subcatchments show an efficiency over 65\%, more than 40\% of the subcatchments reach efficiencies over 90\%. The efficiencies for the validation period 1995 to 1999 are lower (as expected) in particular in the eastern part of the Odra watershed. An explanation might be that the spatial density of precipitation stations is lowest in the eastern part and that subsurface water transports in these flat areas and some smaller reservoirs are not adequately accounted for in the model. Additionally, the validation period includes the
5 Streamflow at the Otmuchow gauging station

Exemplary the discharge from the subcatchment Otmuchow is discussed here which contributed much to the 1997 extreme flooding event. The Otmuchow watershed covers an area of 2361 km² in the Sudete mountains. Fig 4 shows the simulated and measured discharge for 1993, a year out of the calibration period. The maximum discharge in March mainly caused by snow melt is slightly overestimated (172 instead of measured 134 m³/s) but exact in time. The total volume of discharge from March 12 to 31 is underestimated by 10 percent. Some snow melt events in January and April are underestimated as well. Probably precipitation fallen as snow was not corrected for adequately. Some discrepancies also occur during two heavier precipitation events end of October and early November. The efficiency is estimated as 76 percent.

Figure 4: Simulated and observed streamflow at the gauging station Otmuchow for the year 1993 (calibration period).

A similar picture is shown for the year 1997 out of the validation period (Fig. 5). Streamflow due to snow melt is underestimated (February) while during the rest of the year the total amount of discharge is adequately simulated. With 86% the efficiency is even higher than during the calibration phase. The extreme flooding event in July 1997, caused by two heavy precipitation events, with a maximum discharge of 800 m³/s on July 9 and a second maximum with 520 m³/s on July 21 is timely simulated with slightly over- and underestimating the peaks.
A small maximum on July 3 due to heavy precipitation is simulated but not seen in the observations. The efficiency for July exclusively is 79 percent.

![Figure 5: Simulated and observed streamflow at the gauging station Otmuchow for the year 1997 (validation period).](image)

6 Conclusions

The hydrological model SEROS is described which consists of a grid based rainfall-runoff scheme with advanced features for runoff generation and a horizontal routing scheme. The model is forced by observed synoptic data interpolated onto the spatial grid. The free parameters are found by objective calibration. This results are in reasonable agreement between observed and simulated streamflow during the validation and the calibration period, the latter including the 1997 extreme flooding event.

References


