Multiscale and Multicriterial Hydrological Validation of the Eco-hydrological Model SWIM

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Abstract: The hydrological validation described in this paper follows a bottom-up approach, when at first 12 mesoscale subbasins, covering the main subregions of the basin, are validated, and then the information gained from the mesoscale is used to validate the hydrological processes of the whole basin. Special attention was paid to the use of spatial information (maps of water table depth) in addition to usual point data (water discharge at gauge stations) to validate the model. While the primary purpose of distributed hydrological models is to reproduce both water fluxes in subbasins and hydrotopes along with river discharge, they are often validated using only observed river discharge. The paper describes a method to reproduce and validate also local hydrological processes such as water table dynamics inside subbasins, using contour maps of the water table and observed groundwater level data as additional input for the validation. The investigation was carried out with the ecohydrological model SWIM (**S**oil and **W**ater **I**ntegrated **M**odel), which integrates hydrology, vegetation, erosion and nutrient dynamics at the watershed scale. It was developed to investigate the impacts of climate and land use changes on the hydrological processes and water quality at the meso- to macroscale. The study area is the German part of the Elbe basin (80,256 km^2). It is representative of humid / semi-humid landscapes in Europe, where water availability during the summer season is the limiting factor for plant growth and crop yields.

Keywords: macroscale hydrological validation; ecohydrological model; groundwater dynamics; sensitivity; uncertainty

1.   INTRODUCTION

The paper focuses on validating the hydrological module of the ecohydrological model SWIM (**S**oil and **W**ater **I**ntegrated **M**odel, Krysanova *et al.*, 1998). The water cycle is of special importance, because all other ecological processes are related to or dependent on water, its flows and state. Model results for 12 subbasins of the Elbe with a size of 280 to 23,690 km^2, from different regions of the basin and for the whole basin (80,258 km^2) are presented and discussed. It is demonstrated how basin integrated information like water discharge in rivers can be used in combination with maps of the groundwater table as spatial information to calibrate and validate the model.

Hydrological modeling at the meso- to macroscale implies various uncertainties (Bergström & Graham, 1998). One reason is that the data are normally available at a rough resolution (maps of soils and land use data), or have to be interpolated (climate data, groundwater data). In addition, process-based models normally combine physically-based mathematical descriptions and conceptual formulations. Therefore, hydrological models at the macroscale have to be calibrated and need to be validated with historical time series.

Nested investigations in different subbasins from the main subareas (in our case the mountains, the loess area and the lowlands) help to understand the overall pattern of the hydrological processes. Multicriterial validation using a combination of point data like water discharge at the basin outlet (as an integrated characteristic for the whole basin), and spatially distributed data, like contour maps of the water table, will improve the reliability of results, e.g. of the simulated flow components (Arnold, 1993; Refsgaard & Knudsen, 1996; Andersen, 2001).

Another important issue is to determine model sensitivity to the input parameters and uncertainty of the simulated hydrological processes, so that the robustness of model results can be estimated.

2.   MATERIAL AND METHODS

2.1   The model

The watershed model SWIM integrates hydrology, vegetation, erosion and nutrient dynamics. A three level scheme of spatial disaggregation from basin to subbasin and to hydrotopes is used in SWIM. A

hydrotope is a set of elementary units in the subbasin, which have the same geographical features like land use, soil type, or average water table depth, and therefore it can be assumed that they behave hydrologically in a uniform way. Water, plant growth and nitrogen dynamics are calculated for every hydrotope, where vertically up to 10 soil layers can be considered. The outputs from the hydrotopes are aggregated at the subbasin scale and finally routed over the river network, taking into account transmission losses.

The Priestley-Taylor (1972) method is used to estimate the potential evapotranspiration. Soil evaporation and plant transpiration are calculated using the approach of Ritchie (1972), where they are functions of the leaf area index *LAI*. The snowmelt component of SWIM is a simple degree-day equation.

Surface runoff is calculated using a modification of the Soil Conservation Service (SCS) curve number technique. Water, which has infiltrated into the soil, percolates through the soil layers using a storage routing technique (Arnold *et al*., 1990). Lateral subsurface flow or interflow is calculated simultaneously with percolation using the cinematic storage model. Interflow occurs in a given soil layer, if the soil layer below is saturated. The flow routing from subbasin to subbasin is calculated using the Muskingum flow routing method (Maidment, 1993), where a continuity equation is assumed.

The equations to calculate groundwater flow and groundwater table depth at the subbasin or hydrotope scale were derived from Smedema & Rycroft (1983), assuming that the variation in return flow *GWQ* at time step *t* is linearly related to the rate of change in water table height *GWH*:

$$GWQ_t = GWT_{t-1} \exp(-rf * \Delta t)$$
$$+ RCH_{\Delta t} * (1 - \exp(-rf * \Delta t)) \quad (1),$$

$$GWH_t = GWH_{t-1} * \exp(-rf * \Delta t)$$
$$+ \frac{RCH_{\Delta t}}{0.8 * SY * rf} * (1 - \exp(-rf * \Delta t)) \quad (2),$$

with

$$\frac{dGWQ}{dt} = \frac{8KD}{L^2} * \frac{dGWH}{dt} \quad (3).$$

Here *RCH* is the groundwater recharge and *SY* is the specific yield. The retention factor *rf* is a function of the transmissivity *KD* and the slope length *L*:

$$rf = \frac{10 * KD}{SY * L^2} \quad (4).$$

The retention factor can be calibrated using observations of the groundwater table.

2.2   The Basin and data pre-processing

The German part of the Elbe, where the model was applied, covers 80.256 km² from the Czech border to Neu Darchau, the lowest gauge station not influenced by the North Sea tide (see Figure 1). The total length of the Elbe river is 1092 km, 728 km of that in Germany. As a result of river management like river regulation, flood protection and land drainage, the eastern tributaries mostly lost their natural flow regime (flooding in winter and early spring and low water levels in summer and autumn).
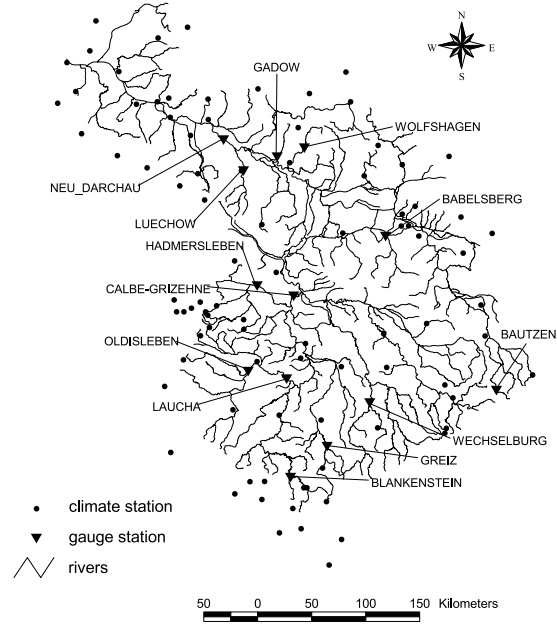

Figure 1: The river network of the Elbe basin and the location of the stations with climate and river discharge observations.

Climatically, the Elbe basin is one of the driest regions in Germany, with mean annual precipitation below 600 mm in the western parts of the basin. The long-term mean annual precipitation over the whole basin is 659 mm, and the long term mean discharge at the estuary is 877 m³/s with an average inflow from the Czech Republic of 315 m³/s. Hydrologically, the area can be subdivided into three main subregions: (1) the mountainous area in the south, approximately 20 % of the total area, (2) the hilly mountain foreland, predominantly covered by loess soils, and (3) the undulating sandy northern lowlands, approximately 52 % of the total area.

All spatial information, the digital elevation model (DEM), the soil map of the federal republic of Germany (scale 1:1.000.000), the land use (CORINE land cover map), and water table contour maps were stored on a grid format with 250 m

resolution. The whole Elbe basin was separated into 226 subbasins. In addition, 12 nested mesoscale basins were selected and modeled separately to get a better understanding of the hydrological pattern in the main subregions of the whole basin. They are disaggregated into 20 – 120 subbasins, depending on their total area.

About 90 climate and 400 rain gauge stations are located in and around the Elbe basin. Four methods were compared to interpolate the climate: Thyssen polygons (TP), inverse distance (ID), ordinary kriging (OK) and external drift kriging (EDK). A cross validation was then applied to select the method with the best results.

2.3 Modeling procedure

First, the hydrological processes for 12 subbasins of the Elbe from different subregions (drainage area from 280 to 23690 km^2) were calibrated on a daily time step using the observed river discharge for a six year period (see figure 1). Besides the initial storage values and the radiation (radiation is mostly not directly measured and has therefore often a bias), the following three parameters were used to calibrate the hydrological processes in the model: the routing factor roc, the factor to calibrate saturated soil conductivity $sccor$ (both global paramters) and the groundwater retention factor rf (subbasin parameter, see equation 4). Statistical evaluation of the results was made by analysing the long term difference between observed discharge in the river Q_{obs} against the simulated one Q_{sim} (the relative difference in discharge or discharge balance):

$$discharge\ balance = \frac{(Q_{sim} - Q_{obs})}{Q_{obs}} * 100 \quad (5)$$

and calculating the efficiency criteria using Nash & Sutcliffe (1970) for Q_{sim} against Q_{obs} on a daily time step (t):

$$efficiency = 1 - \frac{\sum_t (Q_{obs_t} - Q_{sim_t})^2}{\sum_t (Q_{obs_t} - \overline{Q}_{obs})^2} . \quad (6)$$

The contour map of the water table and observed time series of groundwater levels were taken to investigate the spatial behaviour of the hydrological processes. The long term mean water table in three lowland basins with shallow groundwater (Löcknitz, Stepenitz and Nuthe) was adjusted by calibrating the retention parameter.

The last step was to validate the hydrology of three selected subbasins, one basin in the lowlands (Löcknitz), one in the loess area (Mulde), and one in the mountains (Upper Saale), and the total basin. The same basins were used in parallel in the sensitivity and uncertainty study. When analysing the results, some general patterns were apparent. It was possible to divide the parameter sets into three main clusters: one set for the lowlands, one for the loess area and one for the mountains. Based on the information gained from the mesoscale catchments, the parameter sets were taken and used to validate the hydrological processes in the model over the whole Elbe basin.

In parallel, a sensitivity and uncertainty analysis was performed, so that the robustness of the simulated hydrological results could be estimated.

3. RESULTS AND DISCUSSION

3.1 Spatial validation using water table dynamics

The assumption, that changes of groundwater flow are linearly correlated with fluctuations of the groundwater table (see equation 4), allows to access the dynamics of the groundwater recharge (where normally no observations are available) through calibration of the groundwater table (where the data base is normally far better) at the subbasin scale.
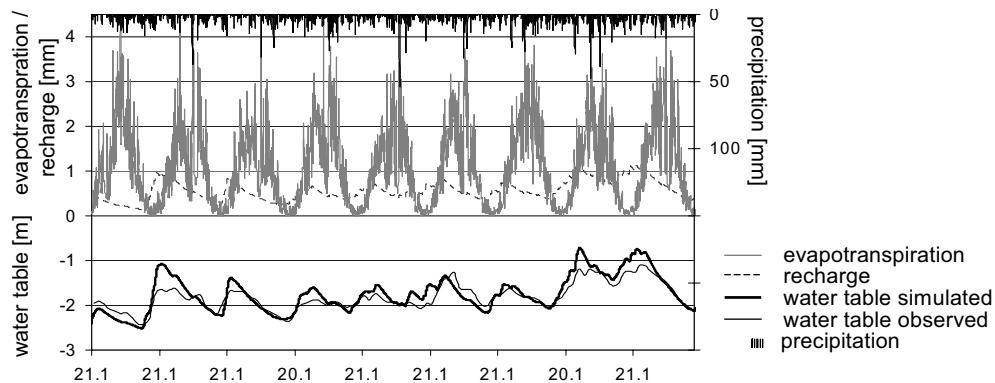

Figure 2: Comparison of the observed and simulated groundwater table (station Wendisch Priborn, Stepenitz).

First, the simulated mean annual water table depth of all subbasins in the Stepenitz, Nuthe and Löcknitz catchments were calibrated, separately for each subbasin of the catchments. The mean square error of the long term mean observed against the mean simulated water table depth in all subbasins was 0.08 m². The groundwater retention factors of the subbasins had values between 0.1 (loamy sediments) and 0.3 (sandy sediments) and were used as additional information to estimate the retention factors of the total basin.

Figure 2 shows the comparison of observed water table against simulated from a subbasin in the Stepenitz river. The simulated daily water table shows a good fit with the observed monthly values, when considering the amplitude and retention of the curves (the dynamic of the simulated fluctuations was not calibrated).

3.2 Calibration and validation of river discharge

The model performed rather well in all 12 case studies. The quality of the model results is comparable to recently published results from similar macroscale applications of other models (Abdulla *et al.*, 1997; Krysanova *et al.*, 1999; Kite *et al.*, 1999). The most sensitive model parameters in the investigation were the factors *sccor* and *roc* used to correct the saturated soil conductivity and river routing respectively (see also the sensitivity study in chapter 3.3).

The discharge balance (equation 5) was in a range from –2.0 to 2.0 %, the daily efficiency (equation 6) in a range from 0.7 to 0.89 and the monthly efficiency from 0.71 to 0.94 (one exception is the Nuthe basin with an daily efficiency of 0.61 and a monthly one of 0.66. The hydraulic regime of the Nuthe basin is strongly affected by land use management).

Some main features were obvious. First, the results (efficiency and relative difference in discharge) are scale independent, they are in the same range for smaller catchments as for larger ones. Secondly, the values of the main calibration factors are correlated with the landscape of the subbasins, this is best seen when comparing the two extremes, the basins from the mountains and the lowlands. The routing correction factor *roc* and the parameter to correct the soil conductivity *sccor* are clearly lower for lowland subbasins (Löcknitz, Stepenitz) than those for mountain catchments (upper Saale and Weiße Elster). The catchments with mainly loess soils (Bode and Unstrut) have high *roc* and very high *sccor* values. It is clear that the parameters from the soil database underestimate the saturated conductivity of loess sediments. The factor *rf* to correct the groundwater retention time, was rather insensitive to the river discharge and mostly has the same value. In lowland catchments, it was determined using the knowledge gained during the investigation of groundwater dynamics (see chapter 3.1).

The calibrated parameters of the entire Elbe basin are very similar with those from the lowland catchments. The lowlands cover the largest part of the Elbe basin, and apparently their processes dominate river discharge in the basin.

The validation was carried out in 3 subcatchments of the Elbe (upper Saale, Löcknitz, Mulde) and for the total basin with a daily time step, over a six year period from 1987 – 1992. Table 1 summarises the results. The results are between 0.72 and 0.92 for the daily efficiency and 0.81 and 0.94 for the monthly efficiency. Figure 3 presents the comparison of the observed and simulated river discharge of the total Elbe basin and for the period 1981 to 1986.
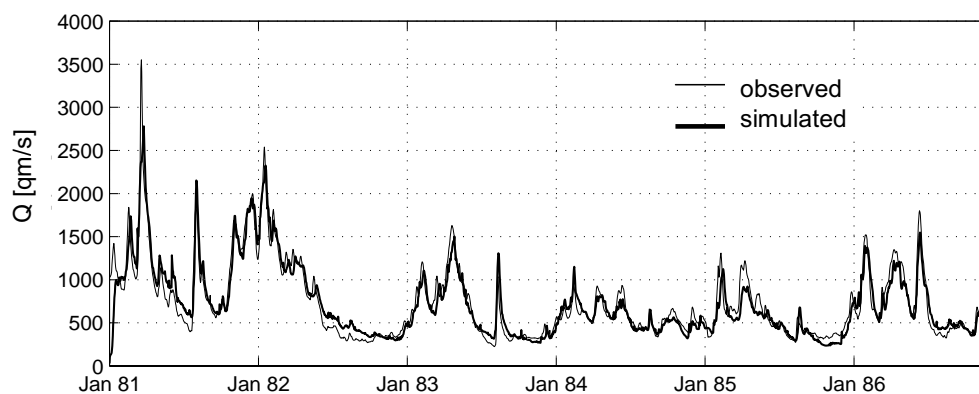

Figure 3: Comparison of the observed and simulated recharge of the total Elbe basin.

Table 1: The efficiency criteria of the observed and simulated river discharge of the calibration period (1981-86) and the validation period (1987-92).

river	gauge station	topography	efficiency daily cal.	val.	efficiency monthly cal.	val.	rel. diff. in discharge cal.	val.
Saale	Blankenstein	mountains	0.79	0.81	0.85	0.86	0	4.2
Mulde	Wechselburg	mountains / loess	0.75	0.76	0.87	0.83	2	-6.1
Löcknitz	Gadow	lowlands	0.74	0.72	0.82	0.81	-1	6.6
Elbe	Neu-Darchau	integrates all	0.89	0.92	0.94	0.94	-1	9.7

3.3 Sensitivity and uncertainty analyses

Three subbasins of the Elbe, the rivers upper Saale (mountains), Mulde (mountains / loess area), Löknitz (lowlands), and the total Elbe basin were selected to investigate the model sensitivity and uncertainty.

Some of the parameters that were tested in the analyses are calibrating factors (*sccor* for saturated soil conductivity, *roc* for the river routing, *rf* for groundwater return flow and table depth). The other parameters were chosen to understand the sensitivity of the model to input data, as provided by the local authorities (*slope* and *rad* to analyse the influence of the topography and the radiation), or as taken from tables (maximum and minimum *LAI* and *cnum* to analyse the influence of the leaf area index and the SCS curve number). The latin hypercube sample method was used in order to restrict the number of simulations. The limits, in which the calibration parameters were randomly sampled, were set based on information gained during the nested model validation. 300 parameter sets were generated for each basin. The model was applied with each new parameter set for a four year simulation. Two model results were taken into account: the relative difference in discharge and the efficiency criteria using Nash & Sutcliffe (1970) of daily simulated against daily observed discharge. The sensitivity of model results to these factors was estimated using the Partial Correlation Coefficients (PCC) of the rank transformed data (the simulation results).

In all cases, radiation has the highest correlation with the discharge balance, followed by the saturated soil conductivity, while the other parameters have nearly no influence.

In contrast, the sensitivity of the parameters to the model result 'efficiency' is not as uniform in the different subbasins. In the mountainous catchment, the routing correction factor has the highest influence, whereas in the loess area catchment, the saturated soil conductivity and radiation are more sensitive. The efficiency of the lowland catchment has by far the highest correlation with the saturated soil conductivity. Apparently, routing is the most important process in areas with high relief intensity, while in lowland basins the simulation of the soil processes is dominating the quality of the model results.

The uncertainty was investigated by calculating the mean and the standard deviation of the 300 simulations for every basin. The results are summarised in Table 2. The first result is, that except the lowland catchment, the model tends to overestimate the discharge (and, hence, underestimate the evapotranspiration) slightly. The efficiency values of nearly all simulations are above zero. The conclusion is, that also with randomly selected parameter sets as input, the model reproduces the dynamic flow pattern of the river discharge in the different basins. The overall result of the uncertainty analyses is, that in macroscale applications of SWIM, the greatest problems and uncertainties in simulating the hydrological processes occur in lowland subareas, while the results in mountainous parts of the basin show a robust performance and are not very sensitive to small changes in model parameters.

Table 2: Results of the uncertainty analysis: The means and standard deviations of 300 simulations for each basin.

	basin	rel. diff. in discharge mean	stand. dev.
mountains	upper Saale	7.7	3.3
loess area	Mulde	15.9	5.3
lowlands	Löknitz	3.9	8.4
total	Elbe	8.7	4.2

	basin	Efficiency mean	stand. dev.
mountains	upper Saale	0.68	0.07
loess area	Mulde	0.62	0.058
lowlands	Löknitz	0.41	0.47
total	Elbe	0.48	0.17

4. SUMMARY AND CONCLUSIONS

The SWIM model produces good simulation results on a daily time step in terms of river runoff for meso- to macroscale basins (200 – 80,000 km^2) after calibration modifying mainly three parameters, where the investigation is focused on. It was possible to divide the parameter sets into three main clusters, one for the lowlands, one for the loess area and one for the mountains. The validation results were better in mountainous catchments (efficiency of daily results 0.75 – 0.79, of monthly ones 0.82 – 0.84) than in lowland basins (0.61 – 0.72 daily efficiency, 0.66 – 0.86 monthly efficiency). It was also possible to reproduce local hydrological processes like water table dynamics inside subbasins, using contour maps of the water table depth and observed groundwater level data. The additional use of water table maps and observed groundwater levels has a high potential to enhance the simulation of spatially distributed hydrological processes. This is crucial, because the primary idea of ecohydrological models like SWIM is to simulate processes in subbasins and hydrotopes in addition to river discharge, but they are often validated using exclusively the observed river discharge. The correct representation of river discharge by the model does not guarantee adequacy in spatial and temporal dynamics of all water components in the basin.

It was found that the best reproduction of the hydrological processes in the total Elbe basin was possible with a parameter set very similar to the one of the lowland subbasins. It is apparent that the hydrological processes of the lowlands dominate the dynamics of the river discharge in the Elbe basin.

The sensitivity and uncertainty analysis show that the model results were robust but more stable in mountainous catchments than in lowland parts of the model area. The most sensitive calibration parameter in the lowland was the saturated conductivity correction factor, the most sensitive one in the mountainous catchments was the routing correction factor, indicating that river routing is the crucial process in mountainous areas with high elevation intensity. In lowlands with low elevation intensity, the percolation of water through the soil is the most important process.

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