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Using a simple model as a tool to parameterise the SWAT model of the Xiangxi river in China

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ABSTRACT

The parameterisation and calibration of complex hydrological models like SWAT [Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams, J.R. 1998. Large-area hydrologic modeling and assessment: part I. Model development. J. American Water Resour. Assoc. 34, 73–89.] is a time consuming process. The use of simple models can shorten this effort substantially because they enable us to identify the important processes in the catchment very fast and thus facilitate the parameterisation of the complex model.

We used the models SWAT and SIMPEL [Hörmann, G., 1997. SIMPEL – Ein einfaches, benutzerfreundliches Bodenwassermodell zum Einsatz in der Ausbildung. Dt. Gewässerkundliche Mitteilungen 41, 67–72.]. SWAT is a complex, meso-scale eco-hydrologic model, SIMPEL is a set of spreadsheets with a one-dimensional soil water model where runoff is calculated with a unit hydrograph. The parameterisation of the SWAT model was very time consuming because many parameters had to be estimated due to the scarce data situation (e.g. of land use data). To avoid long test runs, we first implemented and tested possible solutions in SIMPEL and finally transferred it to SWAT.

The models were applied to the Xiangxi catchment in China which is a tributary of the Yangtse, situated near the Three Gorges dam. Elevation ranges from 150 to 3000 m. The database consists of 8 climate stations, one station with pan evaporation and one gauging station at the basin level. Land use in the valleys is mainly agriculture, the hill slopes are terraced and planted with tea or citrus plants, the remaining area is covered by forest. The water of the river is also used by ca. 39 small hydropower stations.

As an example, we present the estimation of the effect of the power stations in the river valley. After the basic calibration, the modelled low flow of both models in winter was too low compared to the measured values. Possible causes were the terraces and the power stations. By implementing different storage strategies in SIMPEL we finally found out, that the best approximation could be achieved by a storage of about 300 mm with a constant release in the low discharge season. Finally, this strategy was implemented in SWAT and led to an increase of the Nash–Sutcliffe index from 0.27 to 0.75.

Compared to the normal calibration process, the use of SIMPEL as a test bed has shortened the time consuming calibration process of the SWAT model considerably.

1. Introduction

Hydrologic models have grown more complex with time, the high number of parameters of modern models makes it difficult to find the correct combination of parameters for a catchment, especially if some parameters have to be estimated (Bardossy, 2007). A different combination of parameters can lead to the same output and the interpretation of the results is often difficult (equifinality, see Beven, 2006).

The parameterisation, calibration and validation of hydrologic models are time consuming processes (for a summary see Beven (2000), Singh and Frevert (2002) and Singh (2006)). Normally, calibration of a meso-scale catchment can take up to 6 months, depending highly on the experience of the modeller and the complexity of the catchment. Even the new autocalibration tools do

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not always produce better results than manual calibration, especially if many parameters are used, as e.g. Van Liew et al. (2005) have shown in their case study.

The production of databases has not kept pace with the complexity of the models. In many regions of the world, only the most important parameters are available as input. In extreme situations, a complex model is driven by roughly estimated parameters.

A possible alternative to the estimation of the database is to reduce the complexity of the model, i.e. to adapt the model to the database. The SIMPEL model is an example of such a simple system which can be changed and adapted quite easily. We have already shown in another paper (Hörmann et al., 2007) how we expanded the model to simulate the water budget of a small catchment dominated by wetlands. Here we want to show how we used the fast and easy to use SIMPEL model as a tool for the system analysis to find a better parameterisation for the SWAT model of the large Xiangxi catchment. The aim is not to replace the autocalibration of the SWAT model but to show how simple models can be used to check hypotheses and parameter sets very fast to speed up the calibration process of more complex models.

2. Database and models

2.1. Database

The Xiangxi (see Fig. 1) is located in Hubei province, Xingshang and Zigui county between 110.47 and 111.13°E and 30.96 and 31.67°N, with a maximum width of 7867 km in north/south direction and 6290 km in east/west direction which amounts to a catchment area of 2939 km^2. The river is 94 km long. The elevation ranges from 154 m to nearly 3000 m.

Originated from Shennongjia forest region, Xiangxi River is a tributary to the Yangtse. The land use of Xiangxi river catchment is typical for China: the headwater of the river is almost kept in pristine state and population density remains low due to the location in Shennongjia National Natural Reserve. In the middle and lower reach, anthropogenic activities are more intense. At present, 39 hydropower stations are located at the Xiangxi River (Wang, 2006). Information about operation guidelines, the position of the stations and the date of their construction were not available for us.

The soils are mainly limestone soils in the upper regions and brown and yellow-brown soils in the lowlands.

Land use is mainly a function of elevation and topography. Slopes are covered by forests. The main agricultural crops are rice and wheat in the valleys. Terraced fields are often used for corn and potatoes and a considerable area of tea.

For both parameters, soils and land use, there was no official map, only some rough descriptions of the general structure of the landscape. Scholten et al. (2001) reported the distribution of soils and He et al. (2003) the traditional land use. We used these information and the DEM to create a soil and land use map. The single steps are too complex to be described here, please see Köplin (2008) for detailed explanation.

The climate is subtropical with mean temperatures between 12 °C and 20 °C. Rainfall distribution is characterized by a dry winter and a summer monsoon from May to September. The absolute amount depends strongly on elevation and covers a range from 1200 mm/a in the lower until up to 2400 mm/a in the high regions.

The database from the years 1970–1986 consists of 8 climate stations, one station with pan evaporation and one gauging station located at the outflow of the catchment.

2.2. SIMPEL

The philosophy of the SIMPEL model family (Hörmann 1997, 2007) is not to create the best possible model, but the most simple model, we called it a “low end hydrologic model”. The system itself and the complete documentation are available in a German and an English version at www.hydrology.uni-kiel.de/simpel. It is licensed

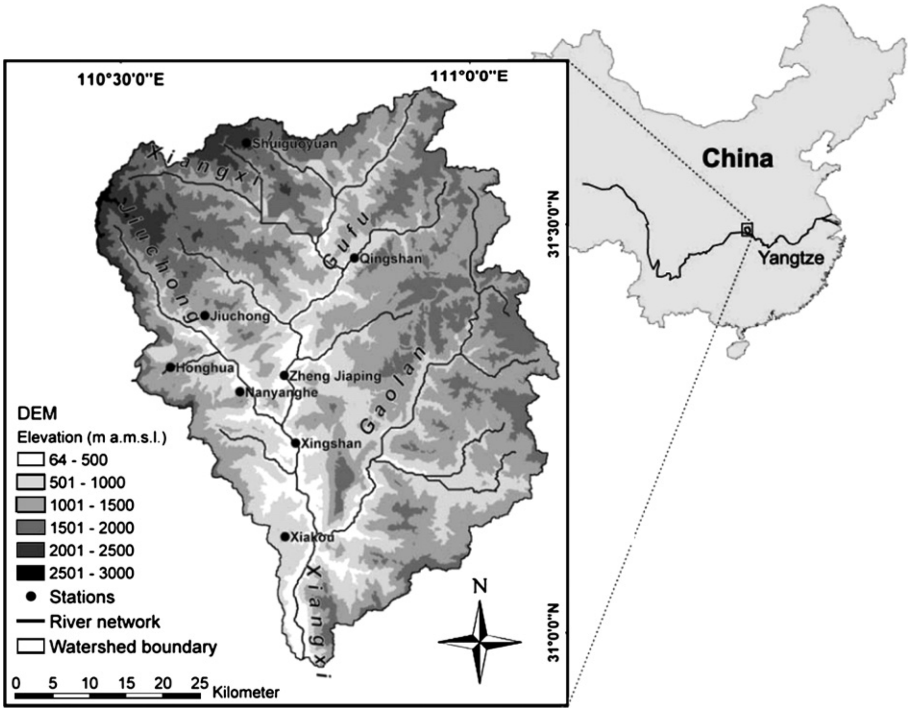

Fig. 1. Location of the Xiangxi catchment.

under the Creative Commons Licence and is free for educational and commercial use. As a first modelling step a one-dimensional bucket model was used with an optional surface runoff module using the unit hydrograph method. The model is intentionally kept at the most basic level of hydrologic modelling which is needed to simulate a soil column or a catchment. The structure is very similar to hydrologic models like the HBV (for an overview of these first models see Beven (2000) or Singh (1995)). Due to the simple structure and the implementation in a spreadsheet program (MS Excel), the model is used in many introductory courses at universities as a first practical example. In practice, it often serves as a first plausibility test for data sets, because it takes only a few minutes to set up a model run. For examples see Gaiser et al. (2002) and Hörmann and Meesenburg (2000). Because the model does not contain a routing module, it is theoretically only suited for small catchments with a runoff concentration time smaller than the time step. To facilitate the use of the model for larger catchments, we added the Unit Hydrograph method, a well known, empirical method to estimate the transformation of surface runoff to discharge in a river.

The model estimates evaporation with commonly used methods in Germany (Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (DVWK), 1996), but for this project we used the measured pan evaporation data. The model has four compartments where water is stored: canopy, litter layer, soil and groundwater. Input data are precipitation (*P*) and potential evaporation (ETp). The model calculates interception from canopy and litter, combines transpiration and evaporation and the fluxes to the groundwater. Canopy and litter storage are implemented as simple bucket models with overflow. Soil water flux is calculated with a nonlinear bucket model according to Glugla (1969). For wet soils, ETa is equal to ETp, in dry soils, ETa is calculated as a linear function of plant available soil water. Groundwater is a single, linear storage with unlimited content.

Runoff has two components: the first, fast component is created by separating infiltration from runoff at the soil surface as a linear function of soil water deficit and a constant factor (range between 1 and 0); the second component is flow from the linear groundwater storage, which is roughly equivalent to the base flow. As for surface runoff, there is no explicit routing for the base flow, the temporal distribution has to be modelled by changing the outflow factor of the groundwater storage.

It is possible to calculate a unit hydrograph function based on surface runoff.

The calibration can be carried out with the built-in solver function of Excel which makes it possible to use freely defined parameter ranges but only one goal variable. For practical purposes, the Nash–Sutcliffe (NS, Nash and Sutcliffe, 1970) index is a suitable goal variable. In addition we also use the correlation coefficient (r^2) and the root mean square error (RMSE) to compare measured and simulated discharge values.

2.3. SWAT

SWAT (Soil and Water Assessment Tool, Arnold et al., 1998) is a semi-distributed, process-oriented model for simulating water, nutrient and pesticide transport. It is used mainly for meso-scale catchments, the basic units are so called Hydrological Response Units (HRU; hydrotopes) based on different soil, land use and slope. SWAT is used for spatially differentiated analyses of seasonal dynamics, land use changes, different management options, etc. The model is applied worldwide for most climate zones, a summary of a wide range of applications is provided by Gassman et al. (2007).

The SWAT simulations were carried out with the SWAT 2005 version and the corresponding user interface AVSWAT-X.

2.4. Parameterisation

Both models were parameterised as similar as possible. For the parameterisation of spatially distributed SWAT we used the full spatial data set with soil, land use and climate data. The one-dimensional SIMPEL model works with only one land use and soil type. We used the parameters of the most frequent soil in the catchment: brown limestone soil. The root depth was set to 30 cm. Both models were calibrated with their respective autocalibration tools. To avoid problems with initial values, the first year (warm up period) was not included in the analysis.

3. Results and discussion

3.1. Base simulation

Figs. 2 and 3 show the results of the calibrated basic simulation. i.e. the unmodified SIMPEL version and the SWAT run without reservoirs.

In SWAT 27 parameters are tested within the automatic sensitivity analysis by default. The six most sensitive parameters according to the objective function (sum of the squares of the residuals) will be calibrated in the automatic calibration and are in order of descending sensitivity: CH_K2 (channel effective hydraulic conductivity, mm/hr), CN2 (initial SCS CN II value), surlag (surface runoff lag time, days), ALPHA_BF (baseflow alpha factor), sol_z (soil depth, mm) and Esco (soil evaporation compensation factor). The use of the surlag parameter did not improve the results.

In SIMPEL, only soil physical properties (soil water capacity, infiltration factor) were used for calibration.

The discharge during the dry winter period is underestimated by both models. Apparently there is a continuous baseflow during winter (marked with ellipses in Fig. 2) which can only be explained by an unknown storage component in the catchment. The sources of this water fluxes could not be described in the standard data set.

A comparison of Figs. 2 and 3 also shows, that the Nash–Sutcliffe index (NS) of the SIMPEL model (0.53) is better than for the complex SWAT model (0.27). Given the size of the catchment and the simplicity of model, the one-dimensional data set and the missing routing module, this high NS-index is quite surprising. It shows that the potential of simple, statistical models may be underestimated. However, we must admit that the steep, mountainous topography of the catchment makes it easy to apply statistical methods. Due to the shallow soils lying on impervious rock and the steep slopes, surface runoff is the most dominant

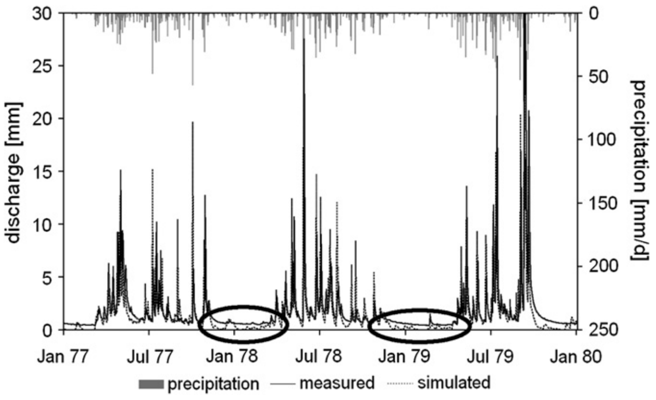

Fig. 2. Results of the basic SWAT run (NS-index: 0.27, r^2: 0.34, RMSE: 2.6).

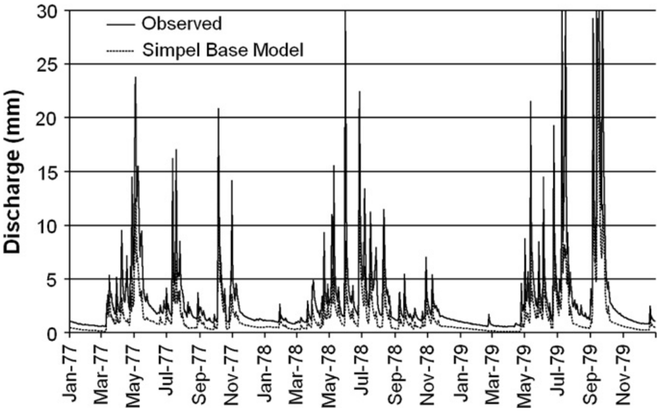

Fig. 3. Results of the basic SIMPEL run (NS: 0.53, r^2: 0.55, RMSE: 2.1).

hydrologic process. The river beds have also high slopes, thus reducing travel time.

3.2. Adjustments

The simulated SWAT hydrograph (Fig. 2) shows that the measured runoff in winter is much higher than calculated. From several excursions in the catchment we knew that the soil map and the rooting depth are relatively correct. The existence of a huge groundwater body which could explain this behaviour is not very probable in this mountain region with shallow soils. We concluded that there must be an unknown storage in the catchment where water is stored during the flood season in summer and released in the low water period in winter.

There were however two components of the water storage which were not included in the initial parameter set: terraced fields and the small dams used for power generators. Both components would add additional storage capacity in the catchment and would release their content slowly.

To identify the amount and the possible effects of these storages, we implemented and tested different algorithms with SIMPEL. The following algorithm proved to be the best method to generate the required flow in summer:

- in summer: a part of the surface runoff is added to the storage

$$Q_{\text{in}} = R \times \left(1 - \frac{SC}{S_{\max}}\right) \times 0,8 \qquad (1)$$

- in winter: a *constant* amount of water is released from the storage

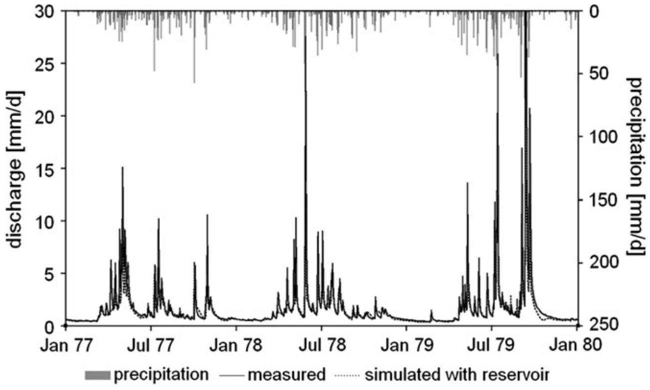

Fig. 4. Optimized SWAT run (NS: 0.75, r^2: 0.85, RMSE: 1.5).

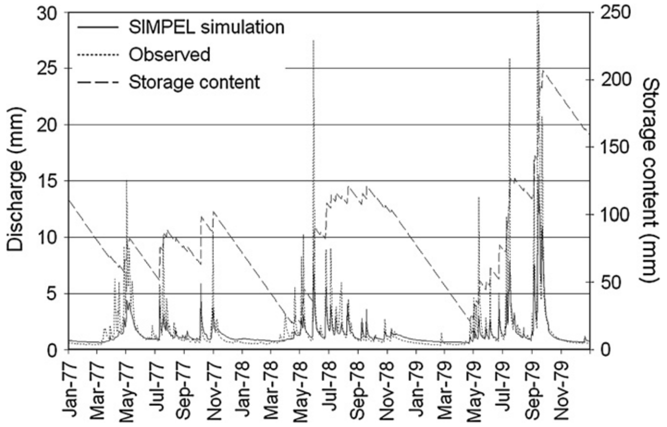

Fig. 5. Results of the SIMPEL simulations with an additional storage (NS: 0.55, r^2: 0.74, RMSE: 2.02).

$$Q_{\text{out}} = 0.5 \qquad (2)$$

with (all variables in mm)

Q_{in}: Inflow to the storage
Q_{out}: Outflow from the storage
SC: Actual storage content
$S_{\max}$: Maximum storage content
R: Surface runoff

The inflow in summer is a function of water content and surface runoff. If the storage is low, more water flows in and if the storage is filled up, no water is added to the store. The additional constant 0.8 avoids that all surface runoff is transferred to the storage if the water content of the soil and the additional storage is low.

3.3. Final comparison

Figs. 4 and 5 show the calibrated final runs with an additional storage component, called "managed reservoir" in SWAT. The NS-index for the SWAT model achieves 0.75 and is now much higher than the 0.55 for the SIMPEL.

Fig. 5 also shows the water content of the reservoir: during the dry winter season, the discharge is nearly completely fed by the constant outflow of the reservoir. The annual variation of the additional reservoir is ca. 100 mm/a (see Fig. 4). If we assume a porosity of 0.33 this would mean a 30 cm soil layer filled with water. The absolute quantity is ca. 3 millons m^3. Distributed equally among the 39 power generators we get 81,081 m^3 for each station which is equivalent to a cube with 43 m or a basin with 100 × 100 area and 8.1 m height. If we attribute a small fraction of this amount to the terraced fields, the values are quite close to the size of the reservoirs we have observed in the field.

4. Conclusions

The calibration of the meso-scale model SWAT is always a time consuming task, especially if the input and parameter database is not perfect and some information is missing. In our case, the calibration of the SWAT model was difficult initially because there was an unknown source of water in winter. The normal procedure to solve this kind of problems would be to try out many possible alternative parameter combinations in SWAT. To avoid this time consuming process we used the SIMPEL model, implemented different algorithms and strategies to generate higher discharge in winter. We found out that the discharge can be maintained during winter if we assume a big storage of water in the catchment which releases water at a nearly constant rate. Of the many SWAT options, this behaviour could be best matched with the reservoir functions where filling and outflow can be defined freely. This approach shows that simpel models can be valuable tools to analyse unknown behaviour of hydrologic systems. However, it should be clear that tools like SIMPEL cannot (and were never intended to) replace complex eco-hydrological models like SWAT. We like to regard them as a kind of Swiss army knife: it cannot replace a well filled toolbox, but it is very handy for small fixes and quick solutions.

However, both tools cannot solve the final question of the natural causes of this behaviour. The additional water storage could possibly be located in the large areas of terraced fields and/or reservoirs of the 39 small hydropower generators. Even we did not have information about the date of construction of dams, it is clear that at least some of them were not existing during the calibration period – therefore the terraces may be a major source of water for the base flow. In the next step of the project we will try to investigate the influence of both factors in more detail.

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