Addressing input data uncertainties in the hydrological simulation of a small forested catchment in north-central Portugal

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Datenunsicherheiten bei der hydrologischen Simulation eines kleinen bewaldeten Einzugsgebiets in Nord-Zentral-Portugal

Introduction

During the last two decades, hydrological modelling has seen major advances with the appearance of increasingly process-based and spatially-distributed models as well as sophisticated model-assessment methods involving uncertainty and sensitivity analysis. Process-based models are now widely accepted, especially due to their higher potential for testing the current understanding of hydrological processes as well as for projecting hydrological impacts of possible climate and land-use change scenarios (BEVEN, 2000). A major drawback of process-based models is nonetheless their significant data input requirements. Exploratory modelling work in forested catchments of north-central Portugal revealed that little to no information was available for almost half of the selected model input variables (TUINENBERG et al., 2006). For example, there was and is a lack of detailed information on soil properties for the entire study area and basic soil characteristic (e.g. saturated hydraulic conductivity) was measured at no more than a handful of impreciselocations. There also continues to be a lack of baseline information on key hydrological processes. The poor knowledge of water balance components like evapotranspiration or spatially-distributed hydrological variables (e.g. soil moisture) strongly hampers model calibration as well as validation. This work concerns initial modelling of the hydrological behaviour of a small forested catchment in north-central Portugal. The main aim is improving the understanding of the predominant processes of runoff generation in catchments unaffected by fire over the longterm.

Zusammenfassung

Für eine Überprüfung und Sensitivitätsanalyse der Abflussverhältnisse wurde das Wasserhaushaltsmodell SWAT an einem kleinen, bewaldeten Einzugsgebiet in Nordportugal angewendet. Anhand regionaler Daten erzielt das Modell gute Ergebnisse bei Monatswerten, Tageswerte wurden jedoch nur mäßig gut simuliert. Dies verdeutlichen die erzielten Gütekennwerte bezogen auf die Abflüsse (nach Nash-Sutcliffe) mit 0.82 bzw. 0.49. Für 20 Modellparameter wurden Sensitivitätsanalysen durchgeführt. Dabei zeigte sich die Wichtigkeit der Berücksichtigung von Grundwasser und lateralen Abflusskomponenten.

Schlagwörter: SWAT-Modell, Parameterunsicherheit, Sensitivitätsanalyse, automatische Kalibrierung.

Summary

The Soil and Water Assessment Tool (SWAT) was employed to carry out a calibration and sensitivity analysis for a small forested catchment in North-Central Portugal. A regional data set allowed obtaining good results with SWAT at the monthly scale but only acceptable model results for daily time steps. The Nash-Sutcliffe model efficiency (E_{NS}) for the validation runoff data was 0.82 and 0.49, respectively. Sensitivity analysis was carried for a total of 20 SWAT parameters. It highlighted the possible importance of groundwater and/or lateral flow in the SWAT results obtained by manual and auto-calibration.

Key words: SWAT, parameter uncertainties, sensitivity analysis, autocalibration.

Study area

The study catchment (Serra de Cima) belongs to a set of four experimental catchments (COELHO et al., 2001) that are located in the foothills of the Caramulo mountain range, north-central Portugal (Figure 1). These catchments have been monitored by the University of Aveiro, in collaboration with the University of Swansea, since the late 1980s. The Serra de Cima catchment has an area of 0.52 km^2 and consists predominantly of commercial eucalypt plantations (*Eucalyptus globulus* Ait.). The catchment's elevation varies from 405 to 487 m, with a mean catchment slope of 30%, and a mean river slope of 15%.

In September 2009, the existing hydrometric station at the outlet of the Serra de Cima catchment was supplemented with a new station comprising a cut-throat flume equipped with an ultra-sound level recorder. The streamflow data from the two stations was combined to assess SWAT performance over the measurement period

Material and methods

The SWAT model (Soil and Water Assessment Tool), as developed by the USDA Agricultural Research Service (ARNOLD et al., 1998), was selected for the present study. SWAT was programmed to predict the impact of land management practices on water, sediment and agricultural chemical yields, particularly in large complex watersheds with varying soils, land-use and management conditions over long time periods. SWAT is a physical-based model, uses readily available inputs, is computationally efficient and enables users to study long-term impacts. The input data for SWAT is grouped into five categories: climate, terrain, land cover and use, and soil. Hydrologic response units (HRU) are defined that consist of a unique combination of land cover, management, and soil type. Runoff is predicted separately for each HRU, and routed to obtain the total runoff for the watershed. SWAT allows detailed insight into the water balance of the distinct HRUs and in the simulated processes of evaporation, infiltration, overland flow, interflow, baseflow and deep aquifer recharge.

The SWAT model was set up using the ArcGIS interface ArcSWAT 2005 (WINCHELL et al., 2008). In the present work, SWAT was applied using a regional input data set, based on readily available information from European and national sources. The climate information was obtained from the water resources information system in Portugal (SNIRH), selecting the nearest meteorological stations. The input data on land cover were obtained from the CORINE Land Cover project (CLC 2006; 1:100,000) of the European Environment Agency, topography from the DTMs (25 x 25m) of the Geographical of the Portuguese Army, and soil type from the Portuguese Atlas of the Environment (1:1,000,000).

The HRUs were obtained after substituting land-cover types that occupied less than 2% of the catchment area). In total, three land cover types were identified: coniferous fo-

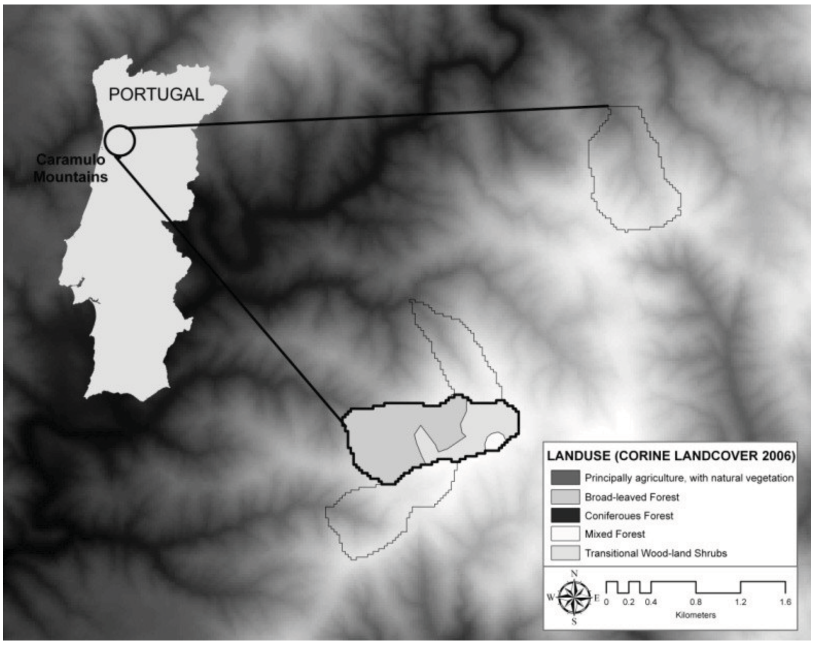

Figure 1: Location and land cover of the Serra de Cima experimental catchment
Abbildung 1: Lage und Landnutzung des Testgebiets Serra de Cima

rest, broad-leaved forest and transitional woodland-shrub (Figure 1). There is only one soil type in the watershed, Cambisols. The terrain was divided in two slope classes, i.e. smaller vs. greater than 3%. The resulting HRU map of the catchment comprised 5 elements.

ArcSWAT2005 includes procedures for auto-calibration and uncertainty analysis as well as for sensitivity analysis. The auto-calibration procedure is based on a multi-objective calibration and a single, global optimization criterion that can evaluate multiple output parameters and employs the Nash-Sutcliffe model efficiency (E_{NS}; NASH and SUTCLIFFE, 1970). Amongst the different calibration methodologies available in ArcSWAT2005, the so-called PARASOL method was applied here. Uncertainty analysis is based on the distinction of good vs. not-good model runs, with the former providing the uncertainty bounds on the model outputs (VAN GRIENSVEN and MEIXNER, 2007). The uncertainty analysis divides the simulation runs carried out in the optimization procedure into 'good' simulations and 'not good' simulations. The good simulations then provide the uncertainty bounds for the model outputs (VAN GRIENSVEN and MEIXNER, 2007).

Results and Discussion

Manual calibration

Based on the SWAT user's manual (NEITSCH et al., 2002) and prior studies by ECKHARDT and ARNOLD (2001) and VAN LIEW et al. (2005), 11 parameters were selected for the manual calibration. Of these parameters, 9 are related to groundwater flow and 2 related to surface flow. The same range of values was the same for all 5 HRUs, except in the case of curve numbers (CN2). The lag between the time that water exits the soil profile and enters the shallow aquifer (GWDELAY) was fixed at its maximum value, whilst the surface runoff lag coefficient (SURLAG) was fixed as its minimum value.

Manual calibration was done at the monthly scale for the period from January 2009 to December 2009, during

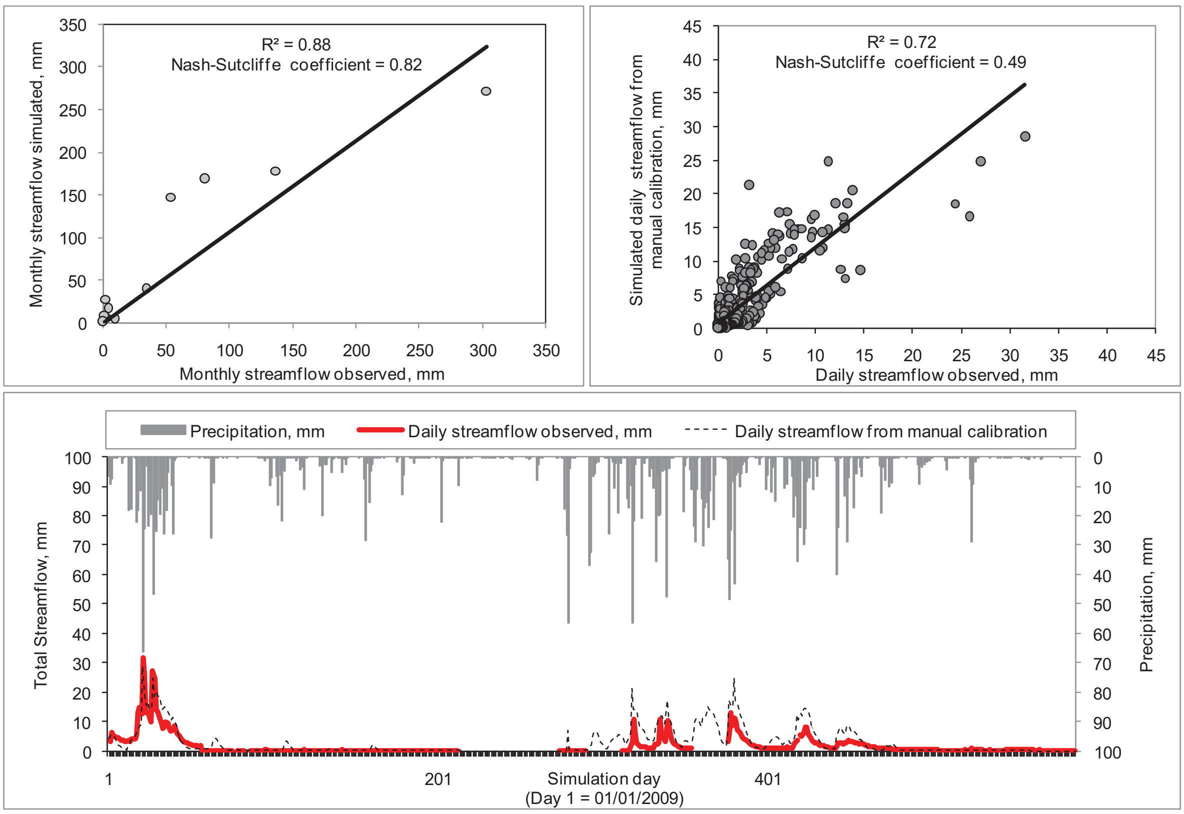

Figure 2: Results from the manual calibration: observed and simulated daily streamflow from January 2009 to June 2010 for the Serra de Cima catchment

Abbildung 2: Ergebnisse der manuellen Kalibrierung. Vergleich des Abflusses der Periode Jänner 2009 bis Juni 2010 which total precipitation was 1584 mm and total streamflow amounted to 551 mm. Manual calibration allowed a good fit for the monthly values (Figure 2), with the Nash-Sutcliffe model efficiency (E_{NS}) being 0.82. The parameter values resulting from manual calibration are shown in Table 1. Using these same parameter values, model performance for the daily stream values was considerably lower (E_{NS} = 0.49) but can still be regarded as acceptable.

Sensitivity analysis

Sensitivity analysis was carried out using a total of 20 parameters, and included with and without consideration of the observed flow data. Using SWAT's parameter the two sensitivity analyses produced similar results in terms of the six most influential parameters, i.e. curve number (CN2), soil depth (Sol_Z), hydraulic conductivity (Sol_K), soil evaporation compensation factor (ESCO), threshold water depth in the shallow aquifer for evaporation to occur (REVAPMN), and threshold water depth in the shallow aquifer required for return flow to occur (GWQMIN). However, SWAT's sensitivity to hydraulic conductivity (Sol_K) and, in particular, curve number (CN2) becomes much greater when the observed data are taken into account (Figure 3).

Autocalibration and uncertainty analysis

Auto-calibration and uncertainty analysis resulted in 1,953 sets with "good" parameters, one of which provided the best fit. Table 2 shows the parameters values of the best model run as well as the parameter bounds employed in auto-calibration.

The auto-calibration procedure produced basically the same model performance (E_{NS} = 0.50) as the manual calibration. The two calibrations, however, resulted in rather distinct hydrographs, especially in terms of the recession curves (Figures 3 and 4). The observed recession curves were simulated clearly better by the manual than auto-calibration. Figure 5 shows that the two calibrations differ markedly in the contributions of lateral and groundwater flows.

Table 1: Parameters values obtained in manual calibration
Tabelle 1: Optimierte Parameter bei manueller Kalibrierung

Parameter	Description	Best value
SHALLST	Initial depth of water in the shallow aquifer (mmH2O)	0.5
DEEPST	Initial depth of water in the deep aquifer (mmH2O)	1000
GWDELAY	Ground-water delay time (days)	1
ALPHA_BF	Base-flow alpha factor (days)	0.99
GWQMIN	Threshold water depth in the shallow aquifer required for return flow to occur (mm)	50
GWREVAP	Ground-water "revap" coefficient	0.2
RCHRG_DP	Deep aquifer percolation fraction (fraction)	0.05
GW_SPYLD	Specific yield of the shallow aquifer (m3/m3)	0.003
SURLAG	Surface runoff lag coefficient (days)	1
N	Manning's roughness coefficient	0.04
CN2	SCS runoff curve number	55-90

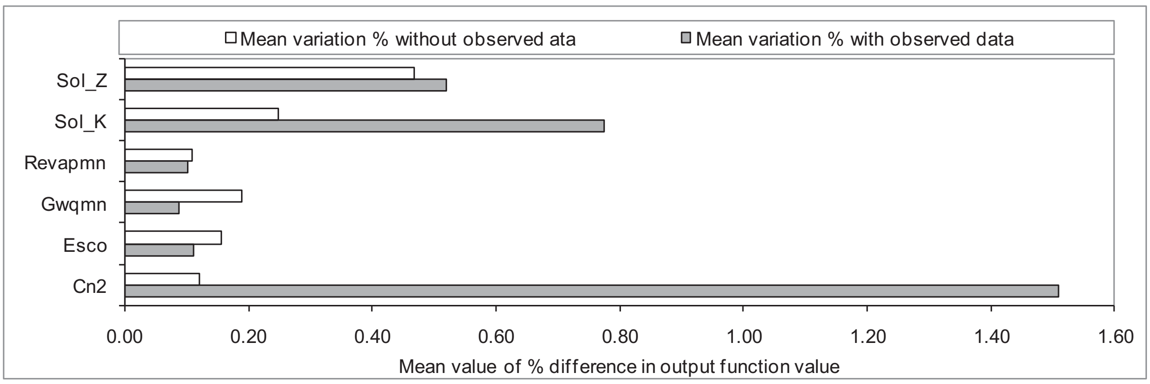

Figure 3: Mean value of percentage difference in output function value with and without observed flow data
Abbildung 3: Mittelwerte des Prozentfehlers mit und ohne Berücksichtigung der beobachteten Abflüsse

Table 2: Parameter bounds and best values obtained by auto-calibration
Tabelle 2: Parametergrenzen und optimierte Werte bei automatischer Kalibrierung

Parameter	**Alpha_Bf**	**Biomix**	**Blai**	**Canmx**	**Ch_K2**	**Ch_N2**	**Cn2**	**Epco**	**Esco**	**Gw_Revap**
Lower bound	0.9	0	3	0	0	0	55	0.75	0.5	0.02
Upper bound	1	1	7	10	1	1	90	1	1	0.5
Best value	0.93	0.18	5.12	0.22	1	0.73	55	0.75	0.5	0.49
Parameter	**Gwqmn**	**Revapmn**	**Sftmp**	**Slope**	**Slsubbsn**	**Sol_Alb**	**Sol_Awc**	**Sol_K**	**Sol_Z**	**Timp**
Lower bound	0	0	0	-25	-25	-25	-25	0.5	-33	0
Upper bound	100	100	5	25	25	25	25	20	400	1
Best value	100	0	4.62	23.5	23.72	-21.08	8.7	11.68	204.74	0

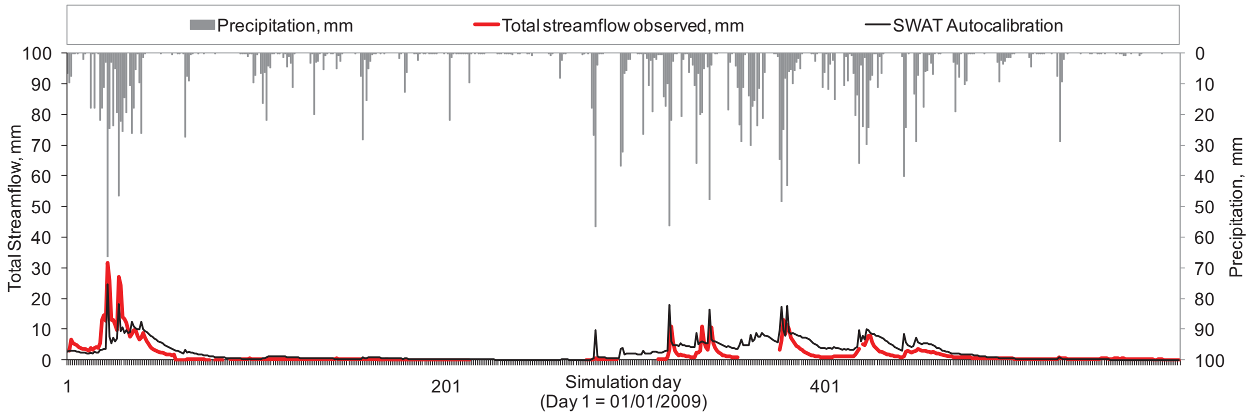

Figure 4: Results from the auto-calibration with the best parameter set. Observed and simulated daily streamflow from January 2009 to June 2010 for the Serra de Cima catchment
Abbildung 4: Modellergebnisse mit optimierten Parametern. Vergleich des Abflusses der Periode Jänner 2009 bis Juni 2010 für das Gebiet Serra de Cima

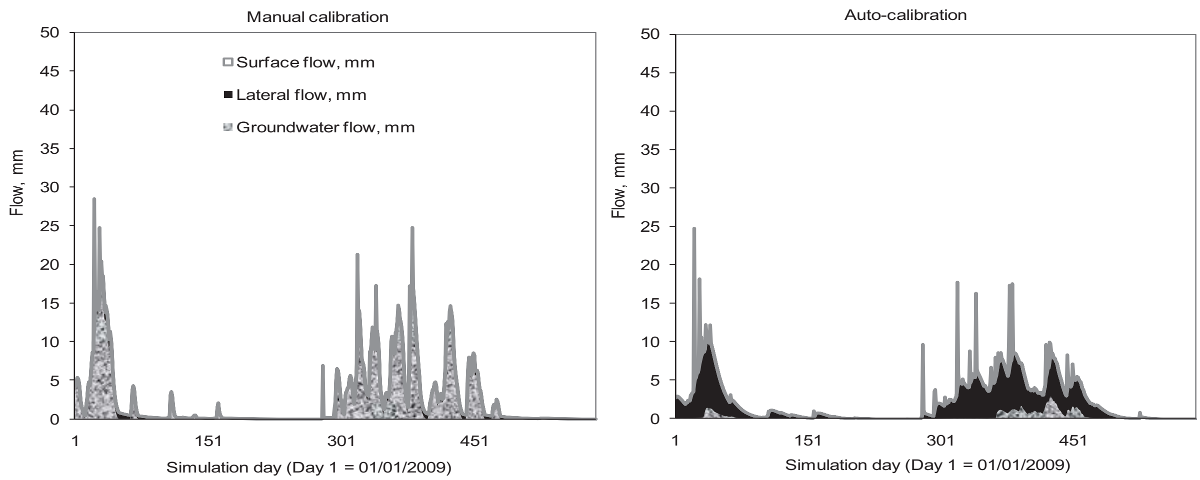

Figure 5: Hydrograph separation for the manual and auto-calibration n
Abbildung 5: Aufteilung der Abflusskomponenten für manuelle und automatische Kalibrierungsergebnisse

Conclusions

The SWAT results presented here are very encouraging as they are based on widely-available information and could possibly be improved substantially by using data that were collected in the study catchment or its immediate surroundings.

Automatic calibration did not markedly improve model performance compared to manual calibration. However, it brought to light an alternative hypothesis for the observed streamflow patterns at the catchment outlet that deserves further attention.

Sensitivity analysis showed that soil and groundwater characteristics are the main parameters to be targeted by additional data collection.

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