Soil moisture simulations using two different modelling approaches

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Simulation der Bodenfeuchte mit zwei verschiedenen Modellansätzen

1 Introduction

Soil moisture plays a key role in the hydrological cycle and also in the entire ecosystem, as it controls the fluxes of water between soil, vegetation and atmosphere. Thus, the understanding of soil moisture variability participates in the modelling of the climate system, improves the skills of eco-hydrological simulation, and also provides the background for the hydrological forecasting systems as the antecedent moisture conditions and its pattern represent the crucial parameters (ENTIN et al., 2000; PAUWELS et al., 2001; BROCCA et al., 2009; SHEIKH et al., 2010).

The soil moisture content might be simulated with different approaches. The techniques range from solving the physically-based Richards' equation (RICHARDS, 1931) to box modelling approaches which deal with the soil moisture content in a simpler way, e.g. LAIO et al. (2001) or BROCCA et al. (2008). Each approach has its advantages and limitations, therefore various approaches must be compared in order to get the information about model efficiencies.

On this basis, the aim of this study is to assess the ability of two different types of models to simulate the total soil moisture content in the micro-scale area where detailed measurements are available. The study is primarily focused on the soil moisture regime in the forested mountainous catchment. The first type of the model is represented by Soil and Water Integrated Model (SWIM) by KRYSANOVA et al. (2005), which is a meso-scale hydrological model, and the second is the conceptual box model proposed by LAIO et al. (2001).

Zusammenfassung

Ziel der Studie war die Überprüfung zweier Modelltypen zur Schätzung der Bodenwasserdynamik in einem kleinen, bewaldeten Einzugsgebiet. Das erste Modell war das mesoskalige, ökohydrologische Bodenwassermodell (SWIM), das zweite ein konzeptuelles Boxmodell. Die Bodenfeuchte wurde im experimentellen Einzugsgebiet Liz (0,99 km^2) in der Tschechischen Republik für die Jahre 2009 und 2010 gemessen. Beide Modelle zeigen zufriedenstellende Ergebnisse für die warme Jahreszeit. Das SWIM-Modell zeigte geringfügig bessere Ergebnisse als das einfache Laio-Boxmodell.

Schlagworte: Bodenfeuchte-Simulation, SWIM-Modell, konzeptuelles Boxmodell.

Summary

The aim of this study is to examine the appropriateness of two types of models to estimate the soil water dynamics in a small scale forested watershed. The first type is represented by the mesoscale ecohydrological Soil and Water Integrated Model (SWIM), the second by a conceptual box model. The soil moisture has been measured in the Liz experimental basin (0.99 km^2), in the Czech Republic, in two subsequent years 2009 and 2010. Both models exhibit satisfactory results within the warmer part of the year. Generally, the SWIM model performs slightly better than the simpler Laio box model.

Key words: Soil moisture modelling, SWIM model, box modelling approach.

2 Data and methods

The study area is located in the mountainous and forested part of the Bohemian Forest Protected Landscape Area, in South Bohemia, Czech Republic (13°41´E, 49°04´N). The total catchment area attains 99.7 ha. The soil type is determined by the geologic base and can be classified as sandy loam moderately deep acidic podzols with a good water permeability (saturated conductivity ranges from 200 to 350 mm/hr). Climate and vegetation are characteristic for the mild climate zone with the mean monthly temperature varying from –3.4 °C in January to 13.6 °C in July. The average annual temperature is 6.3 °C. The average annual precipitation attains 825 mm with summer being the most humid period. The entire catchment is covered by mixed forest, with prevailing coniferous trees of various ages (up to 140 years). The overview of the catchment and locations of measurements sites are displayed in Figure 1.

The suction pressure of the soil water was measured by the UMS T8 tensiometer in 40 cm depth with a resolution of 15 minutes. The average daily values were obtained as the mean value for every particular day, which might cause smoothing of peak values in days of the soil moisture content rise. As these data are available from July of 2008, our study deals with two subsequent years (2009 and 2010), in which only two days of measurement are missing. The soil moisture content was derived from the suction pressure using a retention curve proposed by van Genuchten (1980). The specific site of the soil moisture content measurement was chosen based on the vegetation and topographical characteristics, representing the average tree age and also the average slope angle of the entire catchment.

2.1 SWIM

The ecohydrological model SWIM is a continuous-time semi-distributed model that integrates hydrological processes, vegetation and crop growth, erosion, and nutrient dynamics at the river basin scale. It is based on two previously developed tools – SWAT (Arnold et al., 1993) and MATSALU (Krysanova et al., 1989). The spatial disaggregation of the SWIM model is a three-level scheme: basin – subbasin – hydrotope. The hydrotope is a spatial unit of the same geographical properties and therefore it may be assumed as a unit of uniform hydrological response to a rainfall. The Liz catchment is considered to be a single hydrotope as it has uniform land use, soil type, and topographical characteristics. This physically based model includes calculations of the individual hydrological processes following specific techniques: water percolation – storage routing technique based on the Simulator for Water Re-

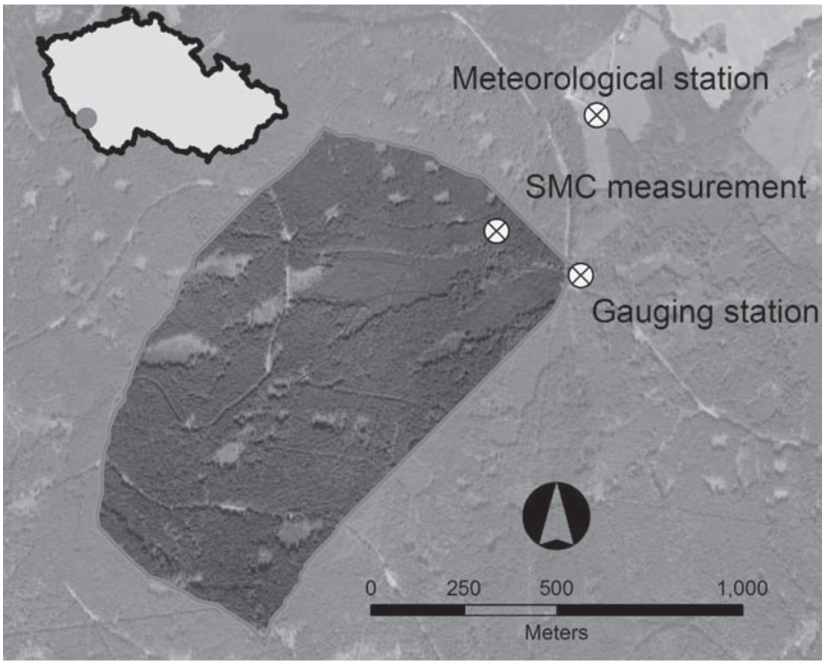

Figure 1: Study site location and overview map of the Liz catchment with depicted measurements sites (SMC denotes soil moisture content)
Abbildung 1: Untersuchungsbereich und Übersichtdarstellung des Liz-Einzugsgebiets mit ausgewiesenen Messstellen (SMC … Bodenfeuchtemessung)

sources in Rural Basins (ARNOLD, 1993); direct runoff – Soil Conservation Service-Curve Number technique; interflow – kinematic storage model (SLOAN & MOORE, 1984); groundwater recharge (SANGREY et al., 1984), and Muskingum routing. The method of PRISTLEY-TAYLOR (1972), which is used in the model for the estimation of potential evapotranspiration, requires only solar radiation, air temperature, and elevation as input. Further, the model calculates actual evaporation from soils and transpiration by plants separately using an approach similar to that of RITCHIE (1972). Transpiration is simulated as a linear function of potential evapotranspiration and the leaf area index (area of plant leaves relative to the area of the HRU). Potential soil water evaporation is estimated as a multiple of potential evapotranspiration and an exponential function of the leaf area index according to the equation of RICHARDSON & RITCHIE (1973). Actual soil evaporation is then calculated in two stages. In the first stage, soil evaporation is limited only by the energy available at the surface, and is equal to the potential soil evaporation. When the accumulated soil evaporation exceeds the first stage threshold (equal to 6 mm), the second stage begins. In the second stage, the actual evaporation is quickly decreasing. The routing component is not used in this particular case as no channels are considered to be within this particular hydrotope. Thus, leaving out routing coefficients there are 12 parameters involved in the calibration process for the SWIM model.

2.2 Laio Box Model

The conceptual box model introduced by LAIO et al. (2001) assumes that the soil column is one conceptual reservoir from which the water is depleted using two distinct mechanisms. First, evapotranspiration, which is assumed to vary with the soil water content, is ranging from zero, when the soil moisture content is below wilting point, to maximum daily value when the plant stomata are fully open. Concerning the soil water content, four important breaking points determine the behaviour of this model: the residual water content, the wilting point, the point where evapotranspiration is no longer limited by the water supply and reaches its potential value, and the field capacity of soil. These parameters might be either measured or determined by the calibration procedure. Second, when the field capacity is reached, the remaining water is lost from the system through leakage losses growing exponentially from zero (at the field capacity) to the hydraulic conductivity (at saturation). The leakage loss has two additional parameters to be determined: the coefficient for exponential and the saturated conductivity. According to the model, the infiltration is equal to the rainfall rate and interception is taken to attain first 2 mm deducted from each individual rainfall. As the model, in its original version, does not have any snowmelt routine, it might be applied only for the warm part of the year. Altogether, the Laio model has six parameters to be defined. The rate of potential daily evapotranspiration is estimated by the similar approach as in the SWIM model.

3 Results

The hydrological model SWIM, applied for the Liz River basin, was calibrated with respect to the discharge in the daily time step using the period of two consequent years 2009 and 2010. The automatic parameter estimation algorithm (PEST) (DOHERTY, 2004) was chosen as a calibration tool. The Laio model was calibrated using the same period, but with respect to the soil moisture content, as it is not designed to estimate the runoff response. Hence, various calibration variables are the most important difference, considering the calibration procedure. If the SWIM model was calibrated with respect to the soil moisture content the results would be probably better. Nevertheless, this model is designated to be calibrated using discharge series because, in the case of larger scales, the detailed measurements of soil moisture are usually not available. The period of interest is defined by the soil moisture data availability and thus two calibration periods are compared in this study. The parameters of the Laio model were gained from the manual calibration. The model efficiency considering the calibration was, in the case of the Laio model, assessed based on the correlation coefficient and overall balance. The simulation using the SWIM model was run continuously from the 1st January 2009. The Laio model was used separately for two warmer parts of the year, but using the same set of calibrated parameters. Only the starting value of the soil moisture content was set separately for each year, corresponding to the value of the day before the simulation started. The warmer period was set to extend from 1st of April to 31st of August, nearly corresponding to the vegetation period defined by TESAŘ et al. (2001).

The results for two warm periods of the years 2009 and 2010 are depicted in Figure 2. It might be stated that both modelling approaches demonstrated the ability to simulate the course of the soil moisture content in the Liz catchment

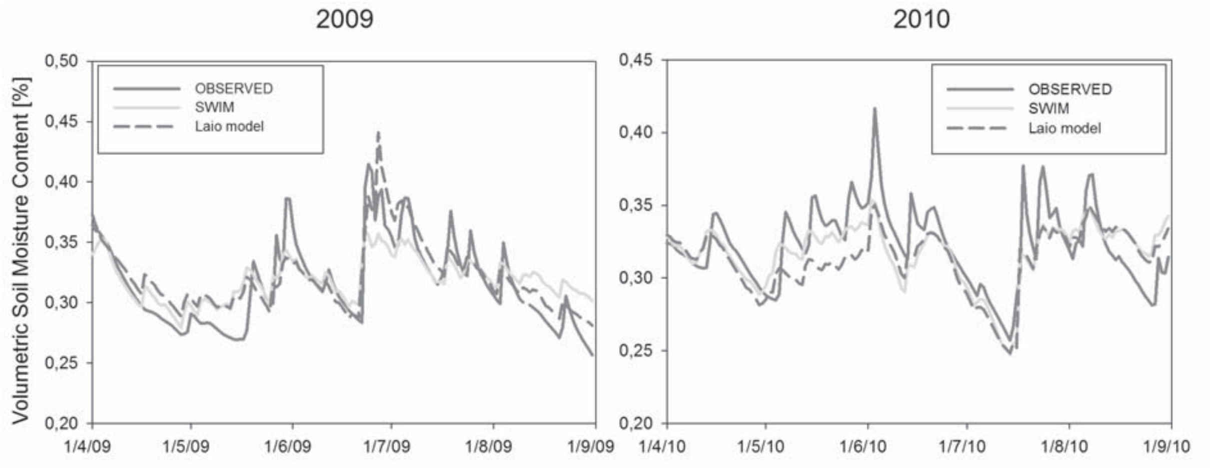

Figure 2: Simulations of the total soil moisture content in warm seasons of 2009 and 2010
Abbildung 2: Simulation des Gesamtwassergehalts der Warmperioden von 2009 und 2010

satisfactorily. Rises and declines of the soil moisture content are represented sufficiently by both model types especially in the year 2009. The year 2010 is simulated slightly more efficiently by the SWIM model compared to the Laio approach. The statistical comparison of both modelling approaches is shown in Table 1. The results from both years are very similar. Only according to the correlation coefficient, both models efficiencies are higher in the year 2009. One possible explanation is that the year 2010 was significantly drier (precipitation attained 528 mm in the warm part of the year) than the year 2009 (638 mm). The peak values of the soil moisture content are slightly underestimated by both modelling techniques, which might be attributed to the daily time-step of both models. The Laio model is subtly more liable to underestimate or overestimate the absolute values of the soil moisture content, which correspond to the overall balance differences in Table 1. The performance of the SWIM model is more balanced.

Table 1: The error statistics of the soil moisture simulations (Correl – correlation coeff., NS – Nash-Sutcliffe coeff., RMSE – root mean square error)
Tabelle 1: Fehlerstatistik der Bodenfeuchtesimulation. (Correl – Korrelationskoeffizient, NS – Nash-Sutcliffe Koeff., RMSE – Quadratwurzelfehler)

sesaon	model	Coreel	Balance	NS	RMSE
2009	SWIM	0.856	2.00%	0.37	0.03
	Laio model	0.861	2.73%	0.47	0.03
2010	SWIM	0.707	-167%	0.46	0.02
	Laio model	0.682	-2.96%	0.34	0.02

4 Conclusion and Discussion

In the warm part of the year (April to August), the dynamics of the soil moisture content is simulated sufficiently, using both mesoscale hydrological model SWIM and also simple Laio box model. The minimum values are predicted well and only a few peak values of the moisture content are slightly underestimated. The results are comparable to those obtained by DELIBERTY & LEGATES (2003) using the SWAT model, which is very similar to the SWIM model considering the hydrological component. In both years the physically based SWIM model gives similar or slightly better results than the Laio model. The Laio model performance is worse than showed by BAUDENA et al. (2012) using the same model or by BROCCA et al. (2008) using a different box model. The possible improvement of the Laio model performance might be reached by better estimation of potential evapotranspiration. Focusing on the SWIM model, uncertainties may also be assigned to the rate of evapotranspiration and percolation, which might lead to discrepancies in the representation of soil moisture declines present at the end of period under study.

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References

ARNOLD, J.G., P.M. ALLEN and A. BERNHARDT (1993): A comprehensive surface-groundwater flow model. Journal of Hydrology, 142, 47–69.

BAUDENA, M., I. BEVILACQUA, D. CANONE, S. Ferraris, M. Previati and A. Provenzale (2012): Soil water dynamics at a midlatitude test site: Field measurements and box modelling approaches. Journal of Hydrology, 414-415, 329–340.

BROCCA, L., F. MELONE and T. MORAMARCO (2008): On the estimation of antecedent wetness conditions in rainfall-runoff modelling. Hydrological Processes, 22, 629–642.

BROCCA, L., F. MELONE, T. MORAMARCO and R. MORBIDELLI (2009): Antecedent wetness conditions based on ERS scatterometer data. Journal of Hydrology, 364, 73–87.

DELIBERTY, T.L. & D.R. LEGATES (2003): Interannual and seasonal variability of modelled soil moisture in Oklahoma. International Journal of Climatology, 23, 1057–1086.

DOHERTY, J. (2004): PEST Model-Independent Parameter Estimation. User Manual: 5th Edition. Watermark Numerical Computing: Brisbane.

ENTIN, J.K., A. ROBOCK, K.Y. VINNIKOV, S.E. HOLLINGER, S. LIU and A. NAMKHAI (2000): Temporal and spatial scales of observed soil moisture variations in the extratropics. J. Geophys. Res., 105, 865–877.

LAIO, F., A. PORPORATO, C. FERNANDEZ-ILLESCAS and I. RODRIGUEZ-ITURBE (2001): Plants in water controlled ecosystems: active role in hydrological processes and response to water stress II. Probabilistic soil moisture dynamics. Advances in Water Research, 24, 707–723.

KRYSANOVA, V., A. MEINER, J. ROOSAARE and A. VASILYEV (1989): Simulation modeling of the coastal waters pollution from agricultural watershed. Ecological Modelling, 49, 7–29.

KRYSANOVA, V., F. HATTERMANN and F. WECHSUNG (2005): Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. Hydrological Processes, 19, 763–783.

PAUWELS, V.R.N., R. HOEBEN, N.E.C. VERHOEST and F. DE TROCH (2001): The importance of the spatial patterns of remotely sensed soil moisture in the improvement of discharge predictions for small-scale basins through data assimilation. Journal of Hydrology, 251, 88–102.

PRISTLEY, C.H.B. & R.J. TAYLOR (1972): On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review, 100, 81–92.

Richards, L.A. (1931): Capillary conduction of liquids through porous mediums. Physics, 1, 318–333.

RICHARDSON, C.W. & J.T. RITCHIE (1973): Soil water balance for small watersheds. Transactions of American Society of Agricultural Engineers, 16, 72–77.

Ritchie, J.T. (1972): A model for predicting evaporation from a row crop with incomplete cover. Water Resources Research, 8, 1204–1213.

SANGREY, D.A., K.O. HARROP-WILLIAMS and J.A. KALIBER (1984): Predicting ground-water response to precipitation. ASCE Journal of Geotechnical Engineering, 110, 957–975.

Sheikh, V., E. Van Loon, R. Hessel and V. Jetten (2010): Sensitivity of LISEM predicted catchment discharge to initial soil moisture content of soil profile. Journal of Hydrology, 393, 174–185.

SLOAN, P.G. & I.D. MOORE (1984): Modelling subsurface stormflow on steeply sloping forested watersheds. Water Resources Research, 20, 1815–1822.

TESAR, M., M. SIR, O. SYROVATKA, J. PRAZAK, L. LICHNER and F. KUBIK (2001): Soil water regime in head water regions – observation, assessment and modelling. Journal of Hydrology and Hydromechanics, 49, 355–375.

VAN GENUCHTEN, T. (1980): A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44, 892–898.

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