Analysis of parameters for distributed modelling of a hydrological regime in subcatchments of the Kopaninský Tok experimental catchment

P. Tachecí, P. Žlábek and M. Kaplická

Parameteranalyse einer flächenverteilten hydrologischen Modellierung des experimentellen Teileinzugsgebiets Kopaninský Tok

Zusammenfassung

An einem Teilgebiet (P6) des experimentellen Testgebiets Kopaninský Tok wurde das deterministische, verteilte Wasserbilanzmodell MIKE SHE 2009 getestet. Anhand stündlicher Daten wurde die Modellkalibrierung (2006) und Validierung (2007–2009) durchgeführt. Anhand der Modellparameter, die den unterirdischen Transport beschreiben, wurde eine Sensitivitätsbetrachtung durchgeführt. Es konnte kein eindeutiges Optimierungs-Parameterset eruiert werden, da die Modellsensitivität wesentlich von der gewählten zeitlichen und räumlichen Modellauflösung abhängig war. Ebenso waren die Ergebnisse vom gewählten Optimierungsalgorithmus abhängig.

Schlagwörter: Kleineinzugsgebiete, Niederschlags-Abfluss-Modellierung, MIKE SHE, Modellkalibrierung, Sensitivitätsanalyse.

Summary

A model of water movement at P6 subcatchment of the Kopaninský tok experimental catchment, based on available datasets, was calibrated and validated using the MIKE SHE 2009 modelling system and deterministic distributed approach. Hourly average discharge data for the 2006 vegetation period were used for calibration, with 2007–2009 data used for validation. Sensitivity analysis (using 2006 vegetation period data) of a group of subsurface model parameters was conducted. It is concluded that there are no clear local optimum parameter values; optimised parameter values differ according to the time step grid cell size used. Sensitivity analysis results differ according to the method (central/backward difference) and perturbation factor.

Key words: Small catchment, hydrologic regime modelling, rainfall- runoff modelling, distributed deterministic model MIKE SHE, model calibration, sensitivity analysis.

Study catchment and data collection

Kopaninský tok catchment has been the site of a long term (since 1980s) study (Doležal and Kvítek, 2004). It is situated in the crystalline area of the Bohemo-Moravian highland region of the Czech Republic, with dominant cambisol and prevailing agricultural land use. The average annual precipitation is 665 mm and average annual temperature is 7 °C. The altitude ranges from 467 to 578 m a.s.l. Bedrock is rather shallow, comprising partly weathered paragneiss. Soil profile is about 1–2 m depth, formed chiefly by three soil types (Haplic and Dystric Cambisols; Stagnic Cambisols; Histic Gleysols). A survey resulting in reference soil hydraulic properties for individual horizons and a vegetation cover survey including LAI measurement were conducted. Monitoring of crop types was ongoing. Other data were available from previous studies (e.g. Tachecí and Kvítek, 2005). Discharge levels were measured on V-notch weirs equipped with ultrasonic probes and dataloggers (1 min/10 min data). Three rainfall stations (1 automatic, 2 manual), were located within the Kopaninský tok experimental catchment. Time series (discharge, precipitation, climatic parameters etc.) were available at 10 min increments for period 2004–2010.

Three subcatchments, designated P52, P53 and P6 (Figure 1), were the subject of analysis using the deterministic hydrologic modelling system MIKE SHE. These subcatchments differ mainly in the prevailing vegetation (Table 1), ratio of artificially drained area, soil type ratio, and slope angle (5.3–10.5%). Outflow at P53 was measured directly at a drainage tile outlet. Nevertheless, it was assumed that the mechanism of runoff generation was similar for the subcatchments studied. Models of water movement at P52, P53, and P6 based on available datasets were calibrated and validated. Sensitivity analysis of several groups of model parameters was undertaken.

Table 1: Basic data on subcatchments of the Kopaninský tok experimental catchment
Tabelle 1: Gebietskenngrößen der Teilgebiete des Kopaninský tok Gebiets

Subcatchment	P52	P6	P53
Area km^2	0.649	0.157	0.049
Arable land %	31.1	95.9	98
Grassland %	1.4	2.4	0.0
Forest %	64.3	0.0	2.0
Other %	3.2	1.7	0.0
Artificial tile drainage area %	16	61	100

Simulation model

Deterministic mathematical hydrological modelling system MIKE SHE 2009 (e.g. Graham and Butts, 2005) was used. Schematisation used in current models is based mostly on numerical approximations of partial differential equations of water movement by means of the finite difference method in rectangular grid cells. Processes included in current models of subcatchments are:

- overland flow (2D horizontal approximation by diffusive wave equation)
- unsaturated zone flow (1D vertical approximation of Richards equation used in individual grid cells, simple bypass-ratio used for macropore flow)
- saturated zone flow (3D approximation of Boussinesq equation, model schematisation in two computational layers)
- river flow (1D kinematic wave approximation, simplified shape of stream channel used)
- evapotranspiration (actual evapotranspiration calculation followed Kristensen-Jensen, 1975), FAO Penman-Monteith method (Allen et al., 1998) was used to calculate reference evapotranspiration.
- snow melt (degree-day factor method)
- artificial drainage simplified by drainage time constant and drainage depth.

Three models were set-up in a regular computational 15 m grid. Models were initially calibrated for simulation of multi-annual hydrologic regime (hourly data) and then adapted for individual rainfall-runoff event simulation in

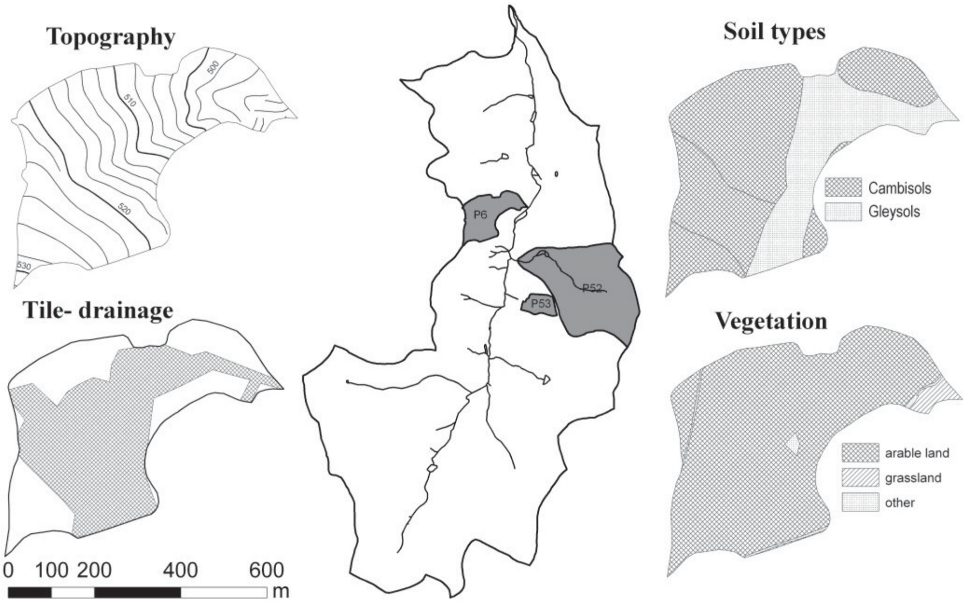

Figure 1: Location of subcatchments P52, P53 and P6 in the Kopaninský tok catchment area (centre). Example of data input for P6 subcatchment: topography (contour lines) and area drained by artificial tile drainage (left), simplified soil map and land use map (right)
Abbildung 1: Lage der Teileinzugsgebiete P52, P53 und P6 des Kopaninský tok Untersuchungsgebiets. P6-Teilgebiet mit Topographie, Dränageflächenanteil, Bodenkarte und Landnutzung

short time steps. The model of subcatchment P6, focusing on hydrologic regime in the vegetation period (based on hourly data) was further used in the current study.

Methods and Results

The model of P6 subcatchment was calibrated using a time series (hourly average data) from 1.11.2004–30.10.2006. A portion (1.11.2004–30.4.2006) of this period was used as a warm-up period of the model to reduce the influence of initial condition errors. The remaining time (1.5.2006–30.10.2006) was used for evaluation of model performance. This period included several common (non-extreme) rainfall-runoff events and one rainless period lasting for nearly two months. Preliminary selection of the most important parameters was conducted based on previous experience. Those parameters were tested by several simulation runs. Parameters of saturated and unsaturated zones were selected for further analysis (Table 2).

The next step focused on calibration of the model. Optimisation procedures (Autocalibration tool, Madsen, 2003) were employed. The Shuffled Complex Evolution method was selected; initial sampling by the Monte Carlo method and 100 model evaluations of an hourly data time series were conducted. Local optimum values for calibration parameters were identified. Root mean square error (RMSE) of simulated hourly discharge in the P6 flow gauge (compared to measured values) was used as output measure.

Performance of the model was tested for vegetation periods 2007–2009. Simulation was conducted continuously, while statistical treatment focused only on vegetation periods to eliminate snow data errors.

It is clear that performance of the model reached notably lower values of R2 coefficient in the validation period, which requires further explanation. For purposes of this analysis we use the calibration period 2006 data where both coefficients have satisfactory values (Table 3).

Calibrated values of parameters were further used for sensitivity analysis of the model using the DHI Autocal tool (central-difference approximation around evaluation point values). Six values of perturbation fraction parameter (0.1, 0.05, 0.02, 0.01, 0.005 and 0.002) were tested. Model parameters were distributed according to root mean square error values (comparison of fit of simulated discharge time series using altered parameter set) for every value of perturbation fraction parameter. Based on this analysis, the three most important parameters were:

1. Vertical hydraulic conductivity, lower layer
2. Macropore flow ratio
3. Horizontal hydraulic conductivity, lower layer

This group of parameters, in the current structure of the model, mainly influences the volume of water infiltrating through the unsaturated zone during large precipitation events. It has also a partial influence on the interflow and baseflow components of the hydrograph.

To explore the limits of current analysis, three further tests were conducted:

- Changing of central-difference approximation to backward difference. This led to alterations in range of two of the three parameters listed above.

Table 2: Calibrated values for model parameters
Tabelle 2: Kalibrierte Modellparameterwerte

Parameter	Value	Parameter	Value
Vertical hydraulic conductivity, upper layer (m/s)	6.00E-07	Horizontal hydraulic conductivity, upper layer (m/s)	3.20E-06
Vertical hydraulic conductivity, lower layer (m/s)	5.00E-07	Horizontal hydraulic conductivity, lower layer (m/s)	2.70E-05
Thickness of upper layer (m)	3.90	Thickness of lower layer (m)	12.70
Macropore flow ratio	0.2	Drainage time constant	1.60E-05

Table 3: Overview of model calibration (comparison of hourly data at P6 outlet and discharge simulated by the model)
Tabelle 3: Modellgüte der Abflüsse (Stundenwerte) bei Kalibrierung und Validierung

Year	R (linear correlation coefficient)	R2 (Nash-Sutcliffe coefficient of efficiency)
2006 (calibration period)	0.86	0.57
2007 (validation period)	0.64	0.20
2008 (validation period)	0.51	0.12
2009 (validation period)	0.41	0.27

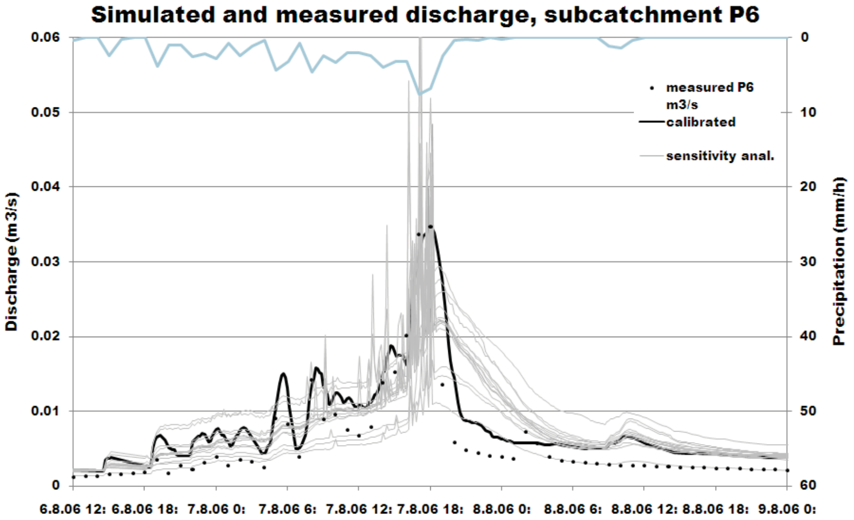

Figure 2: Comparison of measured discharge (dots), simulated values by calibrated model (bold line), and simulated values for sensitivity analysis (gray lines). Hourly averages, subcatchment P6 of Kopaninský tok experimental catchment, selected event
Abbildung 2: Vergleich beobachteter und simulierter Abflüsse

- Influence of different computational grid cell sizes (6, 12 and 15 m).
- Applicability of calibrated parameters for simulation of individual rainfall-runoff events at 10 min intervals.

Conclusions and outlook

Evaluation of the results of calibration at P6 subcatchment model revealed that several combinations of model parameter values gave similar values of minimum RMSE.

During test simulations it appeared that, in the current model setup, at least one year of simulation prior to the evaluation period is necessary to minimise the influence of initial conditions to simulated discharge.

Parameter values optimised for a given grid cells size are not optimum for another (tested 6–15 m grid cells). Calibrated parameters values are grid-dependent.

Parameter values optimised for hourly data are not optimum for simulations using 10 min data. It is clear that, for small sub-catchments, a shorter time step than 10 min may be required for proper simulation and analysis of fast rainfall-runoff processes.

For a given combination of methods and parameters, several hundreds of model runs are necessary to determine an optimum set of parameter values. The period of calibration should contain at least one vegetation season. Calibration using a small number of rainfall-runoff events is not sufficient.

When conducting sensitivity analyses, proper setting of limits (here represented by the perturbation fraction) is important, as is the method of difference approximation.

More information and data on the subsurface aspects of the catchment (e.g. spatial variability of depth of bedrock and groundwater level data) are crucial for improvement of model performance.

Models of water movement at P52, P53, and P6 form a basis for further research in rainfall-runoff mechanisms at the Kopaninský tok experimental catchment. Analysis and comparison of model results at individual subcatchments should be the next step. These three models of water movement form a basis for future modelling of the nitrogen cycle in the area of Kopaninský tok catchment based on water quality samples.

Acknowledgements

This work was supported by the Czech Ministry of Agriculture as a R&D project NAZV QH 82095 (coordinator: Research Institute for Soil and Water Conservation, Prague).

References

ALLEN, R. G., PEREIRA, L. S., RAES, D., SMITH, M. (1998): Crop evapotranspiration – Guidelines for computing crop water requirements, FAO Irrigation and drainage paper 56, Food and Agriculture Organization of the United Nations.

DOLEŽAL, F. and KVÍTEK, T. (2004): The role of recharge zones, discharge zones, springs and tile drainage systems in peneplains of Central European highlands with regard to water quality generation process. Physics and Chemistry of the Earth 29: 775–785.

GRAHAM, D.N. and BUTTS, M. B. (2005): Flexible, integrated watershed modelling with MIKE SHE. In Watershed Models, Eds. V.P. Singh & D.K. Frevert, 245–272.

KRISTENSEN, K. J. and JENSEN, S.E. (1975): A model for estimating actual evapotranspiration from potential evapotranspiration. Royal Veterinary and Agricultural University, Nordic Hydrology 6: 170–188.

MADSEN, H. (2003): Parameter estimation in distributed hydrological catchment modelling using automatic calibration with multiple objectives, in Advances in Water Resources 26: 205–216.

REFSGAARD, J. C. and STORM, B. (1996): Construction, calibration and validation of hydrological models. In: Abbott and Refsgaard (eds.): Distributed hydrological modelling, 41–54.

TACHECÍ, P. and KVÍTEK, T. (2005): The Hydrologic and Nitrate Regime of Kopaninský tok Research Watershed. In: Proceedings of 10th Conference of the Euromediterranean Network of Experimental and Representative Basins (ERB), Paris: UNESCO: 109–114.

Address of authors

P. Tachecí, DHI a.s., Praha, Czech Republic (p.tacheci@dhi.cz)
P. Žlábek, University of South Bohemia, Faculty of Agriculture, Department of landscape management, České Budějovice, Czech Republic (zlabek@zf.jcu.cz) and Research Institute for Soil and Water Conservation
M. Kaplická, Research Institute for Soil and Water Conservation, Praha, Czech Republic (kaplicka@vumop.cz)