Proceedings of the 2006 IASME/WSEAS Int. Conf. on Water Resources, Hydraulics & Hydrology, Chalkida, Greece, May 11-13, 2006 (pp36-41)

Impact of watershed delineations on the SWAT runoff prediction: a case study in the Grote Nete catchment, Flanders, Belgium

HAMED ROUHANI[1], JAN FEYEN[1], PATRICK WILLEMS[2]
[1]Department of Land Management and Economics,[2] Department of Civil Engineering
[1,2] K.U.Leuven
[1]Celestijnenlaan 200E, B-3001,[2] Kasteelpark Arenberg 40, B-3001 Heverlee
[1,2] BELGIUM

Abstract: A study was conducted to examine the effect of the spatial distribution of the model input on the hydrologic performance of a semi-distributed catchment model, using discharge data of the Varendonk outlet station of the Grote Nete catchment. The Soil Water Assessment Tool (SWAT) was used to simulate the stream flow for different scenarios of subdivisions of the catchment and corresponding Hydrologic Response Units (HRUs). Model runs were conducted using the metereological data for the period 01/01/1994-31/12/2002. The model was calibrated using the watershed configuration with 8 sub-basins and 65 HRUs. A Multi-step Automatic Calibration Scheme (MACS) using the Shuffled Complex Evolution (SCE) optimization algorithm was applied for model calibration. The calibration covered a five-year period (01/01/1999-31/12/2002) and the validation phase a four-year period (01/01/1994-12/31/1998). The calibrated model parameters were used for all scenarios with a different number of sub-catchment and HRUs delineations. The number of HRUs was defined on the basis of land use and dominant soil type per sub-catchment division.

The results indicate that the level of spatial distribution of model input has a minor impact on the prediction of the daily average component values of stream flow. The statistical analysis at the other hand revealed that the Nash and Sutcliffe (EF) coefficient for the prediction of the total flow varied when changing the number of sub-watersheds. However, the EF for the slow flow component was not that affected.

Keywords: SWAT, hydrological response units, SCE, watershed delineation

1 Introduction

Numerous models have been developed to analyze the flow patterns in a watershed in response to precipitation. Although most of these models are semi-empirical and lumped parameter formulations, neglecting or oversimplifying the underlying physical processes, they provide after calibration reasonable predictions of the total river flow. In recent years, the trend in hydrological research switched to a more fundamental understanding of the processes affecting the response of watersheds, and modelers therefore increasingly focused on physical-based distributed parameter models. These models are based on rigorous mathematical formulations of physical laws defining the flow of water over a watershed. It is generally assumed that these models provide a better description of the watershed processes [5].

The Soil Water Assessment Tool (SWAT) is one such distributed hydrological model providing opportunities to improve the accuracy of watershed modeling while offering better and more reliable long-term predictions of the hydrologic components such as surface runoff, intermittent and base flow, and evapotranspiration. The model also enables the prediction of long-term non-point source pollution impacts such as sediment, nutrient and pesticide loads [1].

This research investigates how the size or the number of sub-catchments, in which a watershed is spatially distributed, affects the prediction of the flow components using SWAT as modeling tool. Five different sub-catchment size scenarios were generated by varying the threshold area in SWAT. In the past several studies have been conducted on the interaction between the number of sub-watersheds and the modeling process. Brown et al. [4] and Vieux and Needham [12] studied the response of the distributed watershed erosion model ANSWERS and a non-point pollution model AGNPS in function of the size of the grid-cell. Bingner et al. [3] showed that annual fine sediment yield is highly sensitive to the number of sub-basins used to represent a watershed, but the annual stream flow was moderately affected by the partitioning of the watershed. The effect of spatial aggregation on SWAT was examined by Fitzhugh and Mackay [7].

Specifically, this article addresses the analysis of the impact of the size or number of sub-catchments used to partition the watershed on the model output, i.e. the daily total flow and the daily slow flow using the SWAT modeling tool. The effect of the hydrologic response units (HRUs) was examined indirectly, as the number of HRUs varied with the size of the sub-catchment.

2 Study area and model input

Outlet data of the Grote Nete watershed, 383 km^2 in size, with an altitude ranging between 12 and 68 m above sea level, and the most common slopes smaller than 1 percent, situated in the north-eastern part of Flanders (Belgium), were used. The sandy soils (49.57 %) are the dominant soil type in the basin, and the dominant land use is forest, covering 37.17 % of the basin. A detailed description of the study area can be found in Rouhani et al. [9]. See Fig. 1 for the location of the study area in Flanders, situated in the north of Belgium.

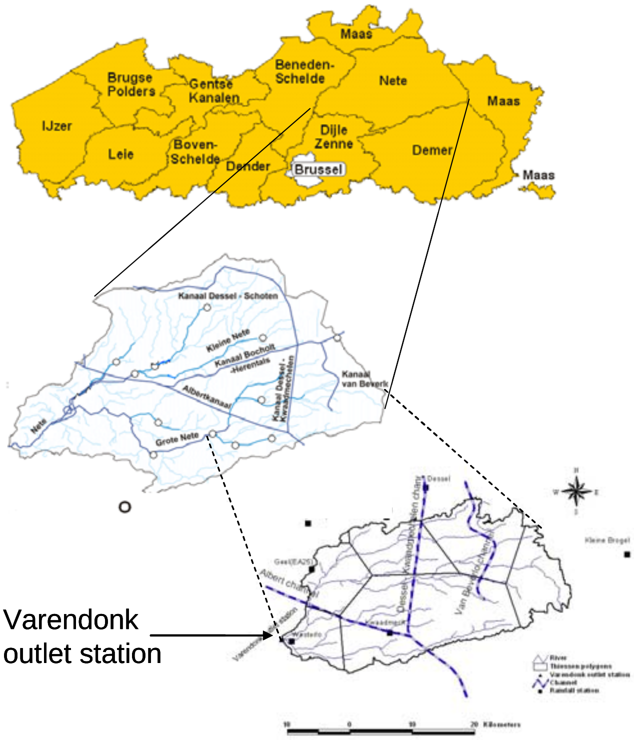

Fig. 1: Location of the Nete basin in Flanders and delineation of the Grote Nete basin

The model was set up using the SWAT2005 version and the daily maximum and minimum air temperature, relative humidity and daily precipitation gathered from the Royal Meteorological Institute of Belgium and the Flemish Water Administration for Land and Water. Discharge data measured at the Varendonk station on the Grote Nete were obtained from the AMINAL administration. The soil map, scale 1:500.000, and the associated soil data were derived from the Aardewerk-BIS Soil Information System [11].

The Grote Nete catchment was partitioned into five different catchment delineations, 1, 4, 8, 20 and 40 sub-catchments, respectively. Each of the sub-catchment delineations was further divided into different numbers of HRUs on the basis of the respective land cover and soil thresholds per scenario. The number of HRUs for the study area as a function of the division of the catchment in sub-catchments was 437 HRUs for the 40 sub-catchment delineation, 169 HRUs for the 20 sub-catchment delineation, 65 HRUs for the 8 sub-catchment delineation, 23 HRUs for the 4 sub-catchment delineation, and 1 HRU for the 1 sub-catchment delineation.

The SWAT2005 model was calibrated versus the runoff data monitored in the Varendonk outlet station using the catchment configuration with 8 sub-catchments and 65 HRUs. The calibrated model parameters were used for all simulations. No attempt to improve the model simulation in different scenarios was made because the main objective of the research was to assess the sensitivity of the SWAT2005 model output to variations in the sub-catchment and HRU delineations.

The simulation runs were conducted on a daily basis to compare the modeling output with the observed daily discharge. Weather and discharge data from January 1, 1999 to December 30, 2002 were used for model calibration but the data for the time period 5 January 2002 till 12 August 2002 were disregarded because the data were either not available or unreliable. Validation was done using the same data locations but a different time period, namely the period 1994-1998. Hereto, the data of the year 1996 were not used either by lack of observations or the unreliability of the available data.

3 Sensitivity analysis, model calibration and validation

For the definition of the sensitivity of the model parameters with respect to the total water flow, the Latin Hypercube Sampling and the One-At-a-Time (LHS-OAT method) design (Van Griensven et al., 2005) was applied. The method is efficient as for m intervals in the LH sampling area and n model parameters a total of m*(n+1) model runs ought to be conducted. The analysis was applied for a predefined set of 17 variables with 10 intervals in the LH sampling area. This means that the SWAT2005 was run 180 times to complete the sensitivity analysis.

The default values of the most sensitive parameters were adjusted in the model calibration exercise using the data for the period 1 January 1994 - 31 December 1998. In order to apply the global optimization technique for model calibration, the Shuffled Complex Evolution algorithm developed at the University of Arizona, US, was applied. The goal of this procedure is to minimize, running the SWAT2005 model, an objective function using different sets of model parameters.

The model performance was evaluated with respect to the measured daily total flow and the daily slow flow. It is assumed that the final values of the sensitive parameters are somewhere located within the ranges given by the two data sets. The SCE run involved 1922 iterations. The values for the parameter multipliers for the five parameters that were adopted for each sub-basin are listed in Table 1. The results of the analysis are in remarkably good agreement with the stream flow sensitivity parameters determined by Van Griensven et al. (2005), which are the CN, Soil-AWC, SURLAG, GWQMN and ALPHA_BF parameters.

The remaining 12 parameters were left uncalibrated due to the model being less sensitive to these parameters and to keep the calibration parsimonious, recognizing concerns regarding over parameterization of distributed models.

Table 1: Parameter range, default and optimal value of the 5 most sensitive parameters

Parameter	Typical range	Default value	Optimum value
CN	35-95	0 %	-29.98 %
Soil-AWC	0-1	0 %	48.20 %
ALPHABF	0-1	0.048	0.34
RECHRGDP	0-1	0.05	0.48
REVAPMN	0-500	1	0.43

Numerical and statistical means used for the evaluation of the model performance included the mean square error, the coefficient of determination (R^2), and the Nash Suttcliffe simulation efficiency (EF). Equations for statistical measures are available in Rouhani et al. [9]. Figure 2 shows the daily observed and simulated total flow of the study catchment with respect to the Varendonk outlet.

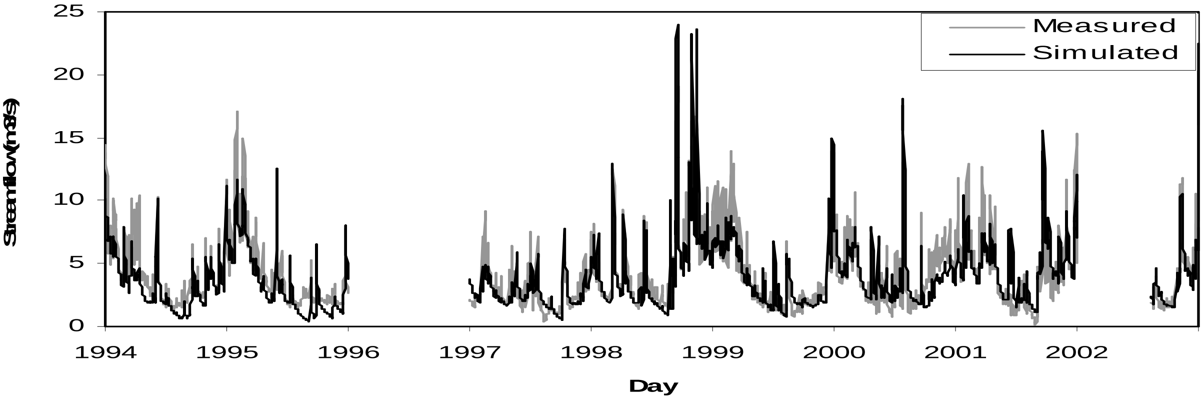

Fig. 2: Observed and simulated daily total flow (m^3 s^{-1}) at the Varendonk outlet station of the Grote Nete River, with a subdivision of the catchment in 8 sub-catchments, for the calibration and validation period

The model fit at Varendonk is good. The high flows in Fig. 2 are well matched, suggesting that the physical processes involved in the generation of high flows were adequately captured by the model although the peaks were usually under predicted. In contrast, the majority of the low-flow periods were over-predicted by the model. The modeling results showed an average daily total flow and slow flow of 4.149 m^3 s^{-1} and 3.363 m^3 s^{-1}, respectively (Table 2). The regression of the measured and simulated average daily flow resulted in a R^2 value of 0.85, and 0.90 for daily total stream flow and daily slow flow, respectively, indicating that the model accurately tracked the average daily flow trends throughout the simulation period. The validation results approved the credibility of the model by demonstrating its ability to replicate runoff patterns.

Table 2: Comparisons between measured and predicted daily average total and slow flow (m^3 s^{-1}) for the Varendonk outlet station

Period	Average daily total flow (m^3 s^{-1})	
	Observed	Simulated
Calibration	4.160	4.149
Validation	4.082	3.522

Period	Average daily slow flow (m^3 s^{-1})	
	Observed	Simulated
Calibration	3.201	3.363
Validation	3.231	2.805

During model verification, using 1994-1998 stream flow data monitored at the outlet gage in Varendonk, an $R^2 = 0.87$ and 0.89 and EF = 0.70 and 0.71 were obtained for respectively the mean daily total flow and mean daily slow flow, respectively (Table 3 and Fig. 3a and 3b).

Table 3: Summary of the statistics for the daily average total and slow flow measured and predicted at the Varendonk outlet station for respectively the calibration and validation period

Statistical criteria	Average daily total flow (m^3 s^{-1}) Calibration	Validation
EF	0.72	0.70
R^2	0.85	0.87

Statistical criteria	Average daily slow flow (m^3 s^{-1}) Calibration	Validation
EF	0.79	0.71
R^2	0.90	0.89

4 Effect of the number of sub-catchments on the SWAT predictions

SWAT was run using stream flow data gathered from January 1, 1994 till December 31, 2002 at the outlet station Varendonk of the Grote Nete river basin. In this section of the manuscript the results, model accuracy and efficiency, are presented running the model for different number of sub-catchments and HRUs. The yearly mean simulated flow discharge for the period 1994-2002 dropped from 3.73 m^3 s^{-1} for the 1 sub-catchment delineation to 3.53 m^3 s^{-1} for the 4 sub-catchment division (Table 4). The mean yearly simulated daily total flow decreased from the 40 sub-catchment delineation to the 4 sub-catchment division. The minimum average yearly discharge, 3.53 m^3 s^{-1}, was predicted when the catchment was subdivided in 4 sub-catchments. Mean CN values range from 51.55 to 60. The analysis revealed higher water flows (mean yearly daily total flow of 3.73 m^3 s^{-1} for the 1 sub-catchment delineation) corresponding to an increase from the reference scenario by 2 %. Table 4 shows no significant change in average yearly stream flow for different watershed delineations.

Fitzhugh and Mackay [7]) found a change in predicted stream flow up to a maximum of 12 % between the coarsest and finest watershed delineations in mean annual and monthly model output. From the results in this study and the results published by Fitzhugh and Mackay [7] it is concluded that the average stream flow is not seriously affected by decreasing the sub-watershed size, i.e. increasing the number of sub-catchments in which the study basin is divided.

Table 4: Comparisons between measured and predicted daily average total and slow flow (m^3 s^{-1}) for different scenarios (number) of sub-catchment division

Average daily flow (m^3 s^{-1})	Total flow	Slow flow
Observed	4.13	3.21
# of sub-catchments		
40	3.70	3.01
20	3.68	2.95
8	3.66	3.02
4	3.53	3.03
1	3.73	3.30

The total daily average flow was split into observed slow and quick flow using the flow separation program of Arnold and Allen [2]. This is an automated digital filter program based on the Rorabaugh hydrograph recession displacement method using daily stream flow.

The slow flow for different number of sub-catchment delineations was compiled for the 8 year period. The yearly mean slow flow increased with about 9 % from the 8 to 1 sub-catchment delineation, and decreased by 0.2 % for the 40 sub-catchment delineation. The value of the yearly mean daily slow flow decreased slightly form 8 sub-catchments to 20 sub-catchments and afterwards, the value increased for the 40 sub-catchment division (see Table 4). The yearly mean daily slow flow continuously increased from the reference number of sub-ctachment division to the 1 sub-ctachment delineation. In contrast Fitzhugh and Mackay [9] carried out event-based simulations, as we did, however the watershed of which outflow data were used was considerably smaller than the size of the Grote Nete catchment. The latter observation suggests that as the sub-watersheds becomes smaller, subsurface flow and groundwater recharge tend to increase but Jha and et al. [6] showed that the SWAT's stream flow components were relatively insensitive to changes in the number of sub-watersheds in which the catchment was split.

In brief, the yearly mean daily stream flow and the yearly mean daily slow flow did not react drastically with a change in the number of sub-catchments the study basin was subdivided.

In a next step the model performance with respect to the daily total flow and daily slow flow were examined as a function of the number of sub-cacthments. For each of the scenarios (delineations) flows were derived for the 1994-2002 period and compared with the model output using the same parameter values. The statistics (R^2, EF) used for quantifying the match between the measured and simulated daily average total flow and slow flow for each of the delineation scenarios, including the results for the reference scenario, are listed in Table 4. The Figs. 3a and 3b depict the variation of the model efficiency (EF) and the coefficient of determination (R^2) for respectively the average daily total flow and average daily slow flow.

A wide range of variability in model efficiency was found for the total flow for the sub-catchment delineation varying from 1 to 40. The poorest efficiency estimation was obtained for the 1 and 4 sub-catchment division. The highest EF occurred for the 8 sub-cacthments division, as clearly depicted in Fig. 3a.

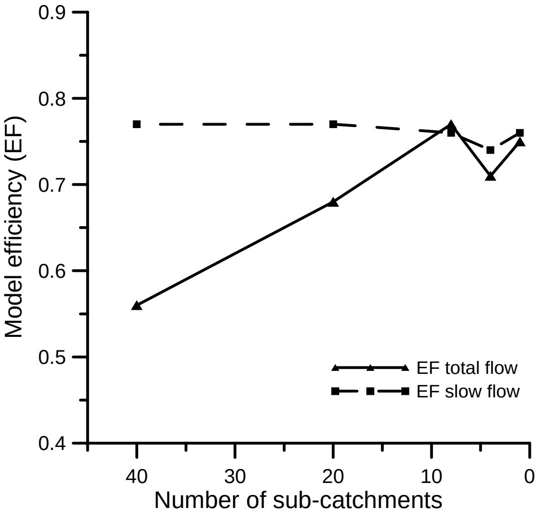

Fig. 3a: Efficiency of daily total flow and daily slow flow for different scenarios of number of sub-catchments

But as is shown in Fig. 3a the value of the model efficiency criteria for the slow flow component hardly changed from the 40 to 8 sub-catchment delineation. For the eight-year simulation period, the model efficiency for the slow flow was 0.77. Reducing or increasing the number of sub-catchments did not significantly affect the model efficiency for the daily slow flow, in contrast the efficiency for the daily total flow drastically changed, increasing the number of sub-catchments. The most significant change of EF was obtained decreasing and increasing the number of sub-catchment to one and 40 sub-catchments, respectively.

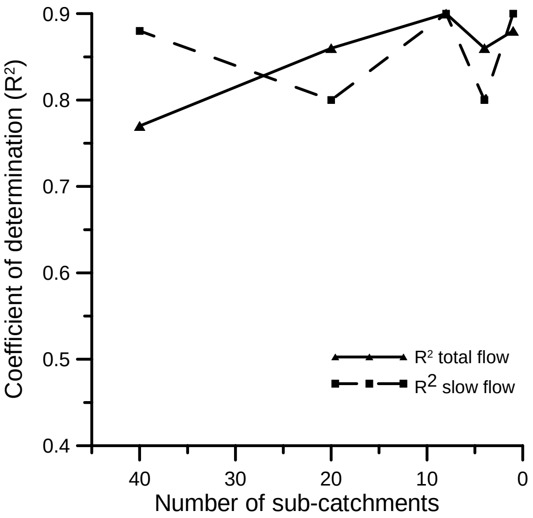

Fig. 3b: R^2 of daily total flow and daily slow flow for different scenarios of number of sub-catchments

Figure 3b shows the change in R^2 between the observed and predicted daily total flow and daily slow flow running the SWAT2005 model for different delineations of sub-catchments using the 1994-2002 dataset. The R^2 value for daily total flow was relatively large for the reference scenario and gradually converged to lower values for the 40 and 1 sub-catchment division. The predicted daily slow flow values are equally good for the 40 to 1 sub-catchment division, with R^2 varying around 0.86. The minimum value (R^2= 0.80) was obtained for the 20 and 4 sub-catchment division.

Mamillapalli et al. [6] found that the accuracy of SWAT stream flow predictions varied depending on the number of sub-watersheds and HRUs used to represent the watershed. Decreases in accuracy at coarser levels of aggregation were apparently due to changes in the distribution of the Soil Conservation Service (SCS) Curve Number (CN) runoff parameter.

4 Conclusion

SWAT2005 is a promising tool for modeling the continuous daily outflow (total and slow flow) of basins with agricultural and forest land uses. In this study 8 year outflow data of a medium scale, flat (Grote Nete catchment, 383 km^2, North of Belgium), and predominantly forest covered catchment were used to examine the effect of the catchment division in sub-catchments and related HRUs, on the daily total and slow flow. As reference, the study catchment was subdivided in 8 sub-basins and 65 HRUs. The number of sub-catchments for which the SWAT2005 model was run varied from +5 times to -8 times the reference number of sub-catchments for which the SWAT2005 model was calibrated and validated.

The first step of our study consisted in a LH-OAT sampling strategy that allows a global sensitivity analysis for a long list of parameters with only a limited number of model runs, and then the SCE algorithm was applied in order to perform the automatic calibration of the rainfall-runoff model for the sensitive parameters with respect to the observed daily total and slow flow. The values of the optimum parameters are comparable to the parameter values derived in other studies, in particular compared to the parameter values obtained by Van Griensven et al. [11].

A comparison of the daily time series of stream flow at the catchment outlet shows that the magnitude and trend in the predicted stream flows agree with the magnitude and trend in the measured data. Based on the value of the statistical criteria (the Nash-Sutcliffe model efficiency and the coefficient of correlation) used in the analysis for measuring the model performance, it might be concluded that the SWAT2005 model for the given study area produces reliable estimates of the daily discharge components.

A comparison between predicted and observed values of the variables considered (total flow and slow flow) over the 1994-2002 period was used to measure the SWAT2005 performance for different delineations of the watershed in sub-catchments. This analysis revealed that the different scenarios of delineation in sub-catchments only slightly affects the average daily total and average daily slow flow, but in contrast the statistical criteria show that the model performance is strongly influenced by changing the number of sub-catchments in which the catchment is subdivided.

In spite of the fact that this study assessed the impact of the number of sub-catchments and HRUs, the threshold value for both as a function of the geomorphological properties and hydrological behavior of watersheds still remains an unanswered question.

References:

[1] Arnold, J.G., Williams, J.R., Srinisavan, R., King, K.W., 1994. SWAT: soil and water assessment tool. U.S. Dept. of Agric., ARS-USDA, Temple, Texas, USA.

[2] Arnold, J.G., Allen, P.M., 1999. Automated methods for estimating base flow and groundwater recharge from stream flow records. J. Am. Water Resour. Assoc., 35(2), 411-424.

[3] Bingner, R.L., Garbrecht, J., Arnold J.G., Srinivasan, R., 1997. Effect of Watershed Subdivision on Simulation Runoff and Fine Sediment Yield. Trans. Am. Soc. of Agric. Eng., 40(5), 1329-1335.

[4] Brown, D.G., Bian, L., Walsh, S.J., 1993. Response of a distributed watershed erosion model to variations in input data aggregation levels. Comput. Geosci., 19 (4), 499–509.

[5] Gunduz, O., 2004. Coupled flow and contaminant transport modeling in large watersheds. Ph.D. dissertation, Georgia Institute of Technology, Atlanta, USA, 467pp.

[6] Jha, M., Gassman Ph.W., Secchi S., Gu R., Arnold, J.G., 2004. Effect of watershed subdivision on SWAT flow, sediment and nutrient predictions, J. Am. Water Resourc. Assoc., 40, 811-825.

[7] Fitzhugh, T.W., Mackay, D.S., 2000. Impacts of input parameter spatial aggregation on an agricultural non-point source pollution model. J. of Hydrol., 236, 35-53.

[8] Mamillapalli, S., Srinivasan, R., Arnold, J.G., Engel, B.A., 1996. Effect of spatial variability on basin scale modeling. Proc. Third Int. Conference/Workshop on Integrating GIS and Environmental Modeling, Santa Fe, New Mexico, January 21-26, 1996. National Center for Geographic Information and Analysis, Santa Barbara, CA, USA..

[9] Rouhani, H., Willems, P., Feyen, J., 2006. Parameter estimation in semi-distributed hydrological catchment modeling using a multi-criteria objective function. Submitted to Hydrol. Process. J.

[10] Van Griensven, A., Meixnerb, T., Bishop, T., 2006. A global sensitivity analysis tool for the parameters of multi-variable watershed modeling. J. of Hydrol., in press.

[11] Van Orshoven, J., Deckers, J.A., Vandenbroucke, D., Feyen, J., 1993. The completed database of Belgian soil profile data and its applicability in planning and management of rural land. Bulletin Recherche Agronomie Gembloux, 28(2-3), 197-222.

[12] Vieux, B.E., Needham, L., 1993. Non-point-pollution model sensitivity to grid-cell size. J. Water Resourc. Plan. & Manage, 119, 141-157.