

# Estimating scale effects of catchment properties on modeling soil and water degradation in Benin (West Africa)

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**Abstract:** Distributed physically-based models require large amount of data, including detailed spatial information (e.g. geology, soil, vegetation). The relevance of spatial information highly depends on the modeling scale and may control the modeling issue, mainly model parameters, which already depend on model assumptions and target processes. In this study, scale dependent catchment properties were used to derive SWAT model parameters (for ungauged basins) using uncertainty thresholds and statistical approaches. Six individual sub-basins of the Ouémé River (Benin) ranging from 586 to 10,072 km<sup>2</sup> in size were investigated, leading to the multi-scale modeling of discharge, sediment and nutrient dynamic. The Sequential Uncertainty Fitting approach was applied for calibration and an uncertainty analysis. Calibrated parameters set were considered only when more than 50% of the measurements were captured by the 95% prediction uncertainty, and when the ratio of the average distance between 2.5 and 97.5 percentiles of the cumulative distribution of the simulated variable and the standard deviation of the corresponding measured variable was less than 0.5. Regression models between the calibrated model parameter sets and linearly independent catchment property sets were established. Following a confidence threshold of 5%, nine predicted model parameters (e.g. soil depth) may fall within the confidence interval with 95 to 99% of chance, and six model parameters (e.g. Curve Number) may be predicted with 83 to 93% of chance. Globally, geology appeared to be a major driver of the regional hydrological response, correlating significantly with eleven out of fifteen model parameters. Validation was performed by applying the derived model parameters at different scales (1,200 and 25,000 km<sup>2</sup>) with goodness-of-fit (to daily measurements) around 0.7 for Nash-Sutcliffe model efficiency and R<sup>2</sup>. This study revealed that runoff-sediment-nutrient dynamic (soil and water degradation) may be simulated for ungauged large scale catchments in Benin with reasonable degree of accuracy.

**Keywords:** SWAT; Uncertainty; Catchment properties; Modeling scale; Soil and water degradation.

## 1 INTRODUCTION

The complexity of hydrological processes depends on the environmental heterogeneity (e.g. soil distribution, topography, geology, vegetation, anthropogenic impacts) and has to be analyzed in connection with the spatial scale.

Multi-scale applications of the Soil and Water Assessment Tool (SWAT) model [Arnold et al., 1998] in the Ouémé-Bonou catchment (about 50,000 km<sup>2</sup>) in Benin have shown a strong spatial scale dependent variations in the model parameters [Lawal et al., 2004; Sintondji, 2005; Busche et al., 2005; Hiepe, 2008; Bossa et al.,

2012]. Although the model parameters highly depend on the model assumptions and the target processes, they vary significantly under physical catchment property influences especially when moving between different catchment scales. For instance when comparing two sub-catchments within the Ouémé catchment (upstream - Donga-Pont (586 km<sup>2</sup>) and downstream – Bétérou (10,072 km<sup>2</sup>), cf. Figure 1), investigated physical catchment properties (e.g. slopes, soil distribution, land cover) differ significantly, causing different behavior, and in consequence completely different model parameters [Hiepe, 2008]. Bárdossy [2007] stated that in principle, if the models are based on the basic principles of physics (mass and energy conservation), the estimation of model parameters should be a straightforward task. Nevertheless, the extreme heterogeneity of the influencing parameters, such as soil properties or the unresolved spatial and temporal variability of meteorological variables (mainly rainfall) limits the applicability of physically-based models to process studies even on small well observed experimental catchments.

Furthermore, an increase in the size of the investigated catchment is often related to a decrease in data availability and to the scale of the underlying information [Bormann et al., 1999]. At the field scale for instance, a soil map or a land use map of 1:5,000 are commonly available, which may decrease to the scale of 1:200,000 or less in regional studies. This is often called parameter crisis [e.g., Stoorvogel & Smaling, 1998], which is felt at almost any scale that is related to initial conditions, boundary conditions and model parameters.

For environmental modeling it is important to know (1) how knowledge of different small-scale processes may efficiently contribute to the simulation of large-scale behavior and (2) how and with which uncertainties model parameters are transferable to ungauged catchments. Several study [Andersen et al., 2001; Wooldridge and Kalma, 2001; Heuvelmans et al., 2004] discussed the significance of the spatial variability in parameter optima for a large-scale model applications and found that the spatially-distributed parameterization obtained by a multi-site calibration leads to a better model fit than the single-site calibration that treat model parameters as spatially invariant. Wale et al. [2009] as well as Gitau and Chaubey [2010] concluded that regression-based parameter sets can be obtained and used for simulating hydrologic responses satisfactorily.

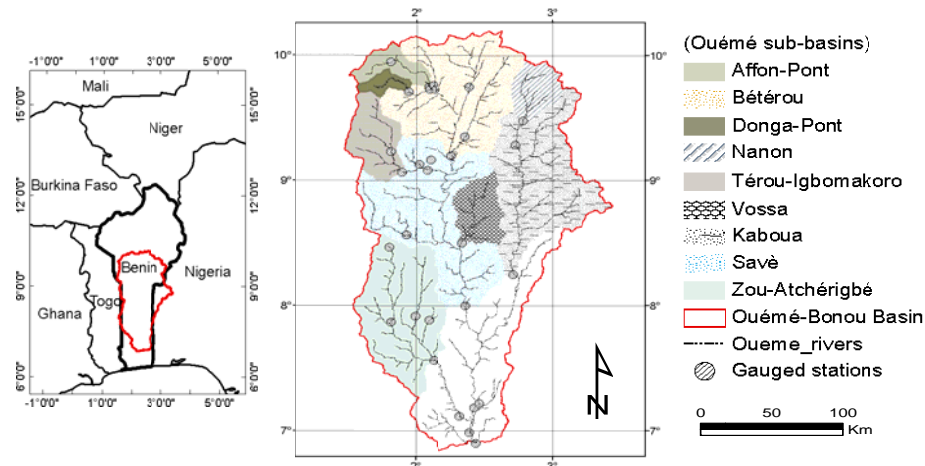
The SWAT model is applied in the current work to simulate the physical and chemical degradation of land and water for six individual sub-catchments of the Ouémé River in Benin. For that, an advanced regionalization methodology has been applied to develop scale dependent regression-based parameter models for accurately simulating water-sediment-nutrient fluxes at ungauged and large scale basins. The methodology considers physical catchment properties depending on spatial scale (ranging from 586 to 10,072 km<sup>2</sup> in size) as explanatory variables for estimating SWAT model parameters. Such an approach avoids the limitations caused by model internal aggregation that often leads to increased uncertainties in the model parameters, and solves at the same time the problem of lack and non-accurate data (e.g. stream water-sediment-nutrient measurements) at the Ouémé-Bonou gauging station (about 50,000 km<sup>2</sup>).

## 2 METHODS

### 2.1 Study area

The Ouémé-Bonou catchment (49,256 km<sup>2</sup>) is located for more than 90% in Benin between 6.8 and 10.2° N latitude (Figure 1) and is mainly characterized by a Precambrian basement, consisting predominantly of complex migmatites granulites and gneisses [Speth et al., 2010]. Benin is situated in a wet (Guinean coast) and dry (Soudanian zone) tropical climate, in which the Ouémé catchment (Soudanian zone) records annual mean temperature of 26 to 30° C and annual mean rainfall of 1,280 mm (from 1950 to 1969) and 1150 mm (from 1970 to 2004) [Speth et al., 2010]. The landscape is characterized by forest islands, gallery forest, savannah,

woodlands, and agricultural as well as pasture land. Rainfall – runoff variability is high in the catchment, leading to runoff coefficients varying from 0.10 to 0.26, with the lowest values for the savannahs and forest landscapes [Speth et al., 2010].



**Figure 1.** Location of the study area. The investigated catchments are Donga-Pont (586 km<sup>2</sup>), Vossa (1,935 km<sup>2</sup>), Térou-Igbomakoro (2,344 km<sup>2</sup>), Zou-Atchéribé (6,978 km<sup>2</sup>), Kaboua (9,459 km<sup>2</sup>), Bétérou (10,072 km<sup>2</sup>), Savè (23,488 km<sup>2</sup>), Ouémé-Bonou (49,256 km<sup>2</sup>).

## 2.2 Multi-scale modeling and statistical analysis

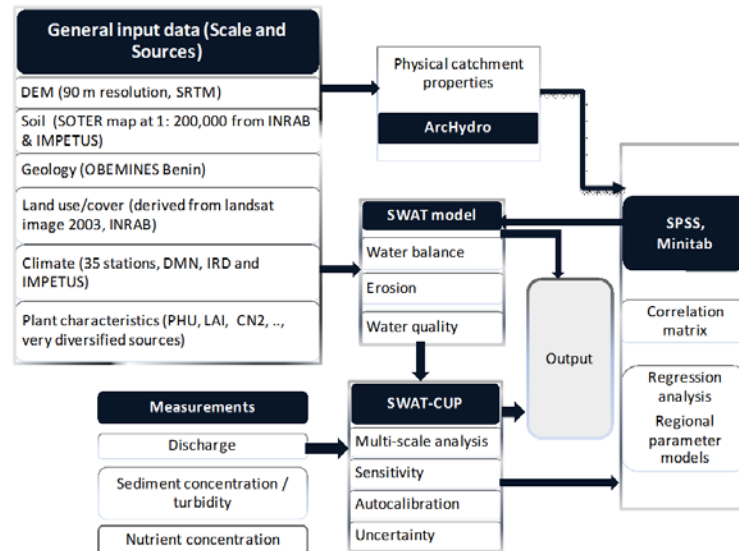
The modeling approach is summarized in Figure 2. General input data such as digital elevation model, soil data and land use data are used to compute selected physical catchment attributes presented in Table 1. They are also used as input for SWAT, which was run for six individual Ouémé sub-catchments. Auto-calibration and uncertainty analysis were performed applying the SUFI-2 procedure (Sequential Uncertainty Fitting version 2), using the SWAT-CUP interface [Abbaspour, 2008], based on SWAT outputs and various measurements from the sub-catchment gauging stations. SPSS and Minitab software were used for statistical analysis, based on a correlation analysis performed to identify physical catchment properties meaningful for each model parameter.

SWAT is a hydrological and water quality model developed by the United States Department of Agricultural-Research-Service (USDA-ARS) [Arnold et al., 1998]. It is a continuous-time model that operates at a daily time-step. It allows the assessment of various subsurface flows and storages and related sediment and nutrient loads, taking into account the feedback between plant growth, water, and nutrient cycle, and helps to understand land management practice effects on water, sediment, and nutrient dynamics. It is a catchment scale model which can be applied from small (km<sup>2</sup>) to regional (100,000 km<sup>2</sup>) scale. The catchment is subdivided into sub-catchments using a Digital Elevation Model (DEM). Each sub-catchment consists of a number of Hydrological Response Units (HRU) which are homogeneous concerning soil, relief, and vegetation.

The successful application of SWAT as well as the whole methodology strongly depends on data availability and data quality, mainly measurements at the different gauging stations within the study area. Besides discharge data continuously available for more or less 10 years (1998 - 2008) at 8 gauging stations, water samples (9 liters per day) were collected in 2004, 2005, 2008, 2009 and 2010 at 4 gauging stations (Donga-Pont, Térou-Igbomakoro, Bétérou, Zou-Atchéribé, cf. Figure 1) and filtered in order to calculate daily suspended sediment concentration. Multi-parameter probes YSI 600 OMS (including one turbidity-broom sensor YSI 6136) were installed at the same stations to register turbidity at a high temporal resolution (used to calculate continuous time series of suspended sediment

concentrations) to consider the hysteresis effects on the relationship between sediment and discharge. After filtration the obtained sediments were analyzed in the laboratory for organic Nitrogen and non soluble/organic Phosphorus content. Weekly water samples were collected (2008-2010) for analyzing Nitrate and soluble Phosphorus.

Together with discharge data these information were required for model calibration and validation for 6 individual sub-catchments. Calibrated parameter sets were considered only when more than 50% of the measurements were captured by the 95% prediction uncertainty, and when the ratio of average distance between 2.5 and 97.5 percentiles of the cumulative distribution of the simulated variable and the standard deviation of the corresponding measured variable was less than 0.5.



**Figure 2.** Schematization of the modeling approach. Soil and land use data are from IMPETUS (Christoph et al., 2008) and INRAB (Institut National de la Recherche Agricole du Bénin; Igue, 2005), Climate data are from IMPETUS, IRD (Institut de Recherche pour le Développement), and DMN (Direction de la Météorologie Nationale), Geology data is from OBEMINES (Office Béninoise des MINES).

**Table 1.** Selected physical catchment properties.

Catchment properties	Description
Catchment area	Reflects volume of water that can be generated from rainfall
Length of longest flow path	Distance from the catchment's outlet to the most distant source on the catchment boundary
Hypsometric integral	Describes the distribution of elevation across the catchment area.
Average altitude	Average elevation of the catchment from SRTM DEM
Average slope of catchment	Calculated from digital elevation model SRTM DEM pixel by pixel
Drainage density	Total stream length for the basin divided by catchment area
Basin shape	Circularity index: the ratio of perimeter square to the area of the catchment. Elongation ratio: the ratio of length of longest drainage to diameter of a circle which has the same area as the basin
Land cover (%)	Forest, grassland, cropland, savannah, ..
Soil (%)	Lixisols, leptosols, vertisols, ..
Geology (%)	Migmatite, granite, alterite, ..

A total of 26 catchment characteristics have been initially used to perform a Variable Inflation Factor (VIF) analysis to avoid collinearity problems. Only one characteristic was considered if a computed VIF between two characteristics exceeded a threshold value of 10. This has resulted in a final use of 16 catchment characteristics to compute a correlation matrix with the calibrated model parameters. Higher correlations than 0.7 for a given model parameter have indicated which catchment characteristics may explain this model parameter.

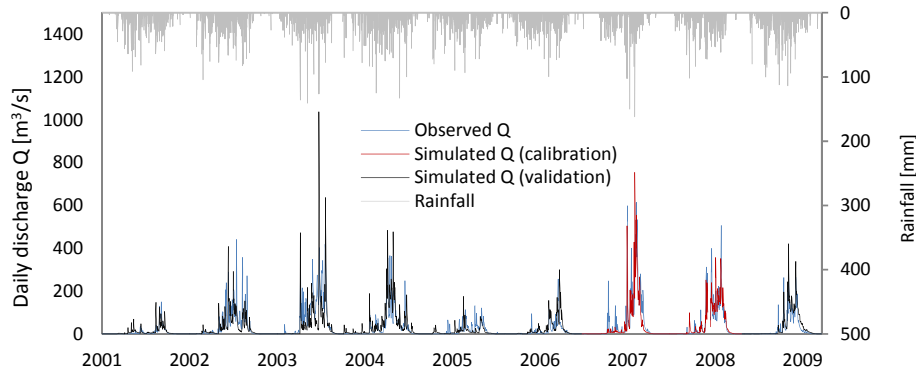
Scale dependent parameter models have been computed (in a multiple linear regression form, using the statistical tool SPSS), where each model input

parameter is explained by one or many catchment properties. Coefficients of determination and Fisher probabilities were the criteria used to select the best parameter models.

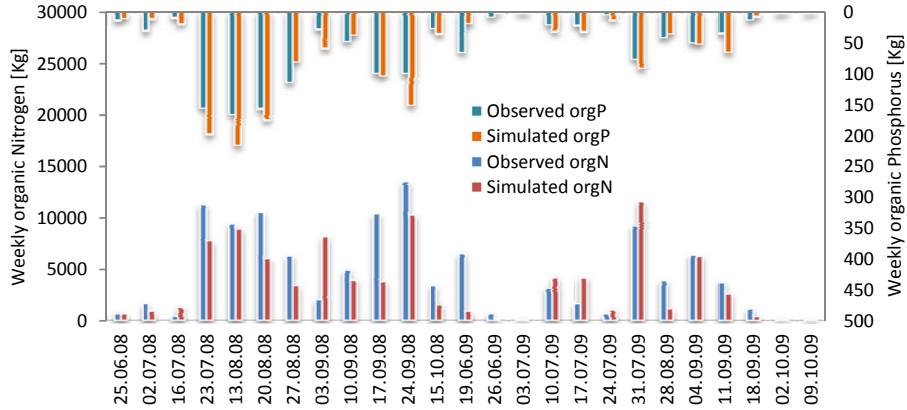
#### 4 RESULTS AND DISCUSSION

Simulated versus observed daily water discharge is shown in Figure 3 for the Zou-Atchéribé sub-catchment (6978 km<sup>2</sup>) (cf. Figure 1) ( $R^2$  ranging from 0.71 to 0.89 and Nash-Sutcliffe model efficiency (ME) ranging from 0.62 to 0.83). The SUFI-2 procedure uses a sequence of steps in which the initial (large) uncertainties in the model parameters are progressively reduced until a certain calibration requirement based on the prediction uncertainty is reached [Abbaspour et al., 2008]. For the Atchéribé sub-catchment and with respect to the daily discharge, the calibrated parameter set was considered with 53% of the measurements captured by the 95% prediction uncertainty, and with 33% of ratio of average distance between 2.5 and 97.5 percentiles of the cumulative distribution of the simulated variable and the standard deviation of the corresponding measured variable. Figure 4 shows weekly simulated versus observed organic N and P delivery at the Zou-Atchéribé gauging station (performed as validation) with acceptable model goodness-of-fit: 0.58 ( $R^2$ ) and 0.78 (ME) for organic Nitrogen and 0.89 ( $R^2$ ) and 0.96 (ME) for organic Phosphorus.

Table 2 shows the developed regression-based parameter models. Globally, with respect to process representation in the SWAT model, one can derive from the equations that in the Ouémé catchment, geology appears to be a major driver of hydrological response, correlating significantly with eleven out of fifteen model parameters. This is consistent with Blöschl and Sivapalan [1995], stating that at the regional scale, geology is often dominant through soil formation (parent material) and controls the main hydrological processes. Slope appears to be powerful to control the channel conductivity (Ch\_K2), groundwater threshold for base flow generation (GWQMN) and soil evaporation compensation (ESCO, accounting for capillary rise, crusting and cracking impacts). Soil type lixisol (a dominant soil type within the Ouémé catchment) partly explains the surface runoff lag (SURLAG) and the maximum retained sediment (SPEXP). Lateritic consolidated soil layer explained the soil susceptibility to erosion (sediment loading) (USLE\_K) and drainage density explains the fraction of deep aquifer percolation (RCHRG\_DP). Following a confidence threshold of 5%, 9 predicted parameters (e.g. soil depth, soil evaporation compensation factor) may fall within the confidence interval with 95 to 99% of chance, and 6 parameters (e.g. Curve Number, USLE practice factor) may be predicted with 83 to 93% of chance. Figure 5 shows examples of the correlation between calibrated and predicted model parameters with the associated 95% confidence interval.



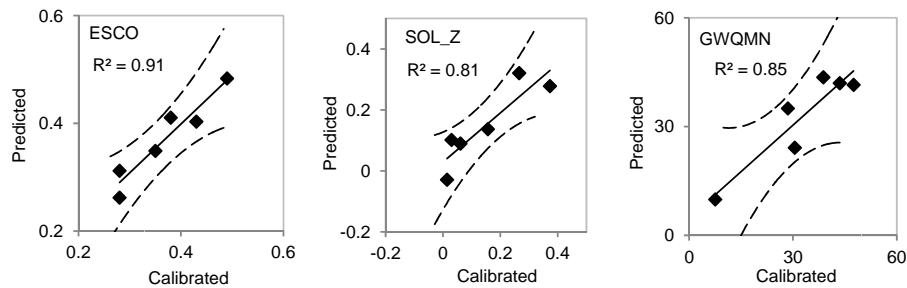
**Figure 3.** Simulated vs. observed daily discharge for the Atchéribé sub-catchment (6978 km<sup>2</sup>). Calibration period was 2007 to 2008 ( $R^2=0.89$  and  $ME=0.83$ ), validation period was 2001-2006, and 2009 ( $R^2=0.71$  and  $ME=0.62$ ).



**Figure 4.** Simulated vs. observed weekly organic N and P for the Atchéribé sub-catchment (6978 km<sup>2</sup>). Only validation was performed from 2008 to 2009 with R<sup>2</sup>=0.58 and ME=0.78 for organic Nitrogen and R<sup>2</sup>=0.89 and ME=0.96 for organic Phosphorus.

**Table 2.** Best regression-based parameter model and resulting values for two independent catchments: Savè: 23,488 km<sup>2</sup> and Ouémé-Bonou: 49,256 km<sup>2</sup>.

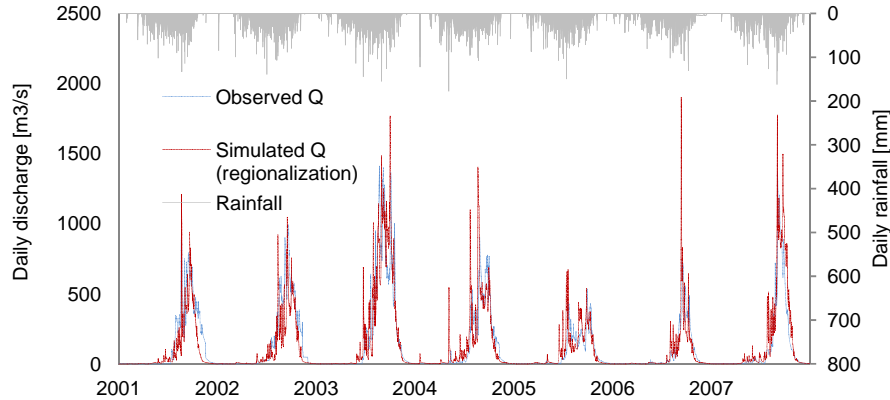
Parameters	Equations	R <sup>2</sup>	Fisher p	Savè	Ouémé-Bonou
ESCO	= 0.935 - 0.217 (Average slope of catchment) + 0.00327 (% Alterites)	0.92	0.022	0.34	0.37
SOL_Z	= 0.758 - 0.01 (% Migmatites)	0.81	0.015	0.02	0.08
SOL_K	= 26.991 - 0.278 (% Percentage of level)	0.92	0.023	-0.58	-0.76
CN2	= 10.0 - 0.0824 Migmatites (%)	0.49	0.12	3.94	4.4
GWQMN	= 185 - 49.2 (Average slope of catchment) - 0.255 (% Migmatites)	0.85	0.05	26.89	37.28
REVAPMN	= 16.5 + 0.769 (% Alterites)	0.6	0.07	20.37	18.56
Ch_K2	= 56.1 - 16.0 (Average slope of the catchment) - 0.461 (% Granites)	0.98	0.033	8.12	11.53
ALPHA_BF	= - 0.0794 + 0.00300 (% Migmatites)	0.87	0.01	0.14	0.12
GW_DELAY	= 19.0 - 0.248 (% Crop land) + 0.165 (% Savannah)	0.98	0.042	22.17	16.82
USLE_P	= 0.129 - 0.0143 (% Lateritic consolidated soil layer)	0.51	0.1	0.06	0.07
USLE_K	= 0.162 - 0.0848 (% Lateritic consolidated soil layer)	0.85	0.01	-0.24	-0.18
NPERCO	= 1.72 - 3.80 (% Hypsometric integral) + 0.00779 (% Circularity Index) - 0.033 (% Elongation ratio)	0.85	0.05	0.08	0.47
RCHRG_DP	= - 0.758 + 0.462 (Drainage density (km/ km <sup>2</sup> ))	0.55	0.09	0.24	0.99
SPEXP	= 1.47 - 0.00454 (% Lixisol) + 0.00011 (% Migmatites)	0.7	0.169	1.22	1.47
SURLAG	= 0.109 + 0.003 (% Lixisol) - 0.016 (% Lateritic consolidated soil layers)	0.93	0.104	0.19	0.22



**Figure 5.** Example of predicted vs. calibrated model parameter with associated 95% confidence interval. ESCO is the soil evaporation compensation factor [-], SOL\_Z is the depth of the soil layer, and GWQMN is the threshold depth for ground water flow to occur [mm].

Scale dependent parameter sets were calculated from the regression models for independent sub-catchments (e.g. Savè, 23,488 km<sup>2</sup>, cf. Figure 1, Table 2 and Figure 6), and were used for validation. Satisfactorily model goodness-of-fit to the daily discharge were obtained (0.71 for R<sup>2</sup> and 0.67 for model efficiency) at the Savè gauging station. At the whole Ouémé-Bonou catchment scale (49,256 km<sup>2</sup>, cf. Figure 1), sediment yield was computed to 0.3 ton ha<sup>-1</sup> a<sup>-1</sup> (with a spatial pattern

ranging from 0 to 10 ton ha<sup>-1</sup> a<sup>-1</sup>) and lost soil organic Nitrogen was computed to 1.2 kg ha<sup>-1</sup> a<sup>-1</sup> (with a spatial pattern ranging from 0 to 20 kg ha<sup>-1</sup> a<sup>-1</sup>) for the period 2000 to 2009. The methodology applied here opens the perspective of predicting more accurately water, sediment and nutrient transport in ungauged catchments and assessing climate and land use impacts at large catchment scale in a data-poor environment in Bénin.



**Figure 6.** Observed vs. simulated total discharge using the regression-based parameters for the Savè sub-catchment (23,488 km<sup>2</sup>), with 0.71 for R<sup>2</sup> and 0.67 for model efficiency (ME).

## CONCLUSION

Facing the contemporary environmental challenges (impacts of global change) and the uncertainties (induced by the lack of data) for land and water management in Benin, the development of advanced regionalization methods is crucial. In this study, scale dependent physical catchment properties are used to explain (statistically) and derive SWAT model parameters for ungauged catchments. Although the computed regression-based parameter models are physically meaningful and consistent with the theoretical fundament of the model parameters, they contain uncertainty due to the non-uniqueness of the considered calibrated parameter set, which is caused by limited available information. For improving the data base, a new data collection policy must be developed. However the model parameter uncertainty issues were acceptable, since a clear coherency appeared in the final parameter matrix, which was successfully correlated with the scale dependent catchment physical properties. This is partly due to the robustness of the Sequential Uncertainty Fitting approach. Repetitive applications of the here-tested regionalization approach (using different simulation models) should lead to further understanding of scale dependent physical controls on the hydrological response in order to improve the physical meaning of the developed statistical relationships.

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