SWAT 2015

PULA / SARDINIA / ITALY

Conference Proceedings

International Soil & Water Assessment Tool Conference

June 24-26, 2015

CRS4

IDEAS BECOME LIFE

The Soil and Water Assessment Tool (SWAT) is a public domain model jointly developed by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, part of The Texas A&M University System.

SWAT is a small watershed to river basin-scale model to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds.

Contents

Foreword

The organizers of the 2015 International SWAT Conference want to express their thanks to the organizations and individuals involved and their preparation and dedication to coordinate a successful conference. We would also like to thank the Scientific Committee for their support in preparing the conference agenda and allowing for scientists and researchers around the globe to participate and exchange their scientific knowledge at this conference.

A special thank you to the Center for Advanced Studies, Research & Development in Sardinia (CRS4) along with Pierluigi Cau and Fabrizio Murgia for their countless hours and efforts to host the SWAT Community. On behalf of the SWAT Community, we extend our sincere gratitude to you and your university for the kind invitation and welcoming hospitality.

The following Book of Abstracts contains abstracts for presentations covering a variety of topics including but not limited to large scale applications; climate change applications; model development; database and GIS application and development; environmental applications; hydrology; best management practices (BMPs); sensitivity, calibration and uncertainty; pesticide, bacteria, metals and pharmaceuticals; sediment, nutrients, and carbon, urban processes and management; the EPIC/APEX modeling system; and more.

The Conference Organizers hope you enjoy the conference and continue to view these SWAT gatherings as a positive opportunity for our international research community to share the latest innovations developed for the Soil and Water Assessment Tool.

Organizing Committee

Pierluigi Cau, CRS4, Italy

Fabrizio Murgia, CRS4, Italy

Rossella Serri, CRS4, Italy

Antonio Lo Porto, IRSA-CNR, Italy

Marcella Dalla Cia, Sardegna Ricerche, Italy

Roberto Deidda, UNICA, Italy

Jeff Arnold, USDA-ARS, USA

Raghavan Srinivasan, Texas A&M University, USA

Jaclyn Tech, Texas A&M University, USA

Scientific Committee

Karim Abbaspour, EAWAG – Switzerland

Jeff Arnold, USDA-ARS – USA

Claire Baffaut, USDA-ARS – USA

José María Bodoque Del Pozo, UCLM – Toledo, Spain

Pierluigi Cau, CRS4 – Italy

Indrajeet Chaubey, Purdue University – USA

Jarosław Chormański, Warsaw University of Life Sciences – Poland

Debjani Deb, Texas A&M University – USA

Nicola Fohrer, Christian-Albrechts-University – Kiel, Germany

Philip Gassman, Iowa State University – USA

A.K. Gosain, Indian Institute of Technology – India

Jaehak Jeong, Texas A&M AgriLife Research – USA

C. Allan Jones, Texas A&M AgriLife Research – USA

Valentina Krysanova, PIK – Germany

Pedro Chambel Leitão, IST-MARETEC – Portugal

Antonio Lo Porto, IRSA-CNR – Italy

Eduardo Mario Mendiondo, USP-EESC – Brazil

Venkatesh Merwade, Purdue University – USA

Suzana Gico Montenegro, UFPE – Brazil

Balaji Narasimhan, Indian Institute of Technology-Madras – India

Mikołaj Piniewski, Warsaw University of Life Sciences – Poland

José Miguel Sánchez-Pérez, CNRS-ECOLAB – France

Sabine Sauvage, CNRS-ECOLAB – France

Raghavan Srinivasan, Texas A&M University – USA

Ann van Griensven, UNESCO-IHE – Netherlands

Martin Volk, Helmholtz Centre for Environmental Research - UFZ – Germany

Hirozumi Watanabe, Tokyo University of Agriculture and Technology – Japan

Mike White, USDA-ARS – USA

Xuesong Zhang, Pacific Northwest National Laboratory – USA

The impact of woody biomass production on the water balance of the North German Lowlands

-Model setup and calibration-

Jens Hartwich*, Christian Reinhardt Imjela, Jens Bölscher, Achim Schulte
Institute of Geographical Science, Applied Geography –Environmental Hydrology and Resource Management, Freie Universität Berlin, Berlin, Germany
(jens.hartwich@fu-berlin.de - corresponding author)

Abstract

The rising demand for woody biomass in recent years has lead to the agricultural cultivation of fast-growing tree species like willow and poplar. These tree species are planted in so-called short-rotation coppices (SRC), and have a harvesting cycle of 3 to 5 years. However, several studies suggest that, due to high water consumption linked to the phenology of trees and shrubs, SCRs have a negative impact on groundwater recharge and the base flow in river basins. In the research project AGENT this thesis is investigated using a water balance model that focuses on areas in the North German lowlands with a particularly high potential for cultivation. In order to characterize the North German Plain with its climatic as well as morphological and pedological heterogeneity, the Ems, Treene, Uecker, Randow, Welse and Aland were selected as river basins for the model. For the water balance modeling, the "Soil and Water Assessment Tool" (SWAT) was used because it is suitable for the hydrological modeling of large and meso-scale river basins. This study aims to establish a valid model concept and shows two stages for a model setup and calibration strategy. The first stage model concept combined all selected catchments into one model, which lead to high calculation times and no satisfying calibration results. After splitting up the models in the second stage, runtimes decreased, an efficient calibration strategy was found and the results in the calibration and validation were classified as "good" and "very good".

Keywords: SWAT model setup, model calibration, woody biomass, SRC, water balance, North German Lowlands

Introduction

In Germany, broad political support drives the expansion of renewable energies. In 2013, renewable energy represented 12.0 % of the overall energy consumption (Bundesministerium für Wirtschaft und Energie, 2014). One-third of this renewable energy is produced by biomass. The increasing demand for renewable energy has led to the implementation of biomass on agricultural land as an energy source. In the case of renewable heat production, woody biomass is most commonly used, but conventional forestry methods cannot provide sufficient amounts of timber. To counteract this problem, fast growing tree species like willow and poplar were applied to agricultural land in so-called short rotation coppices (SRC). These crops have a lifecycle of 3 to 5 years before they are harvested.

However, according to several studies, the implementation of SRC seems to have a significant effect on the water balance (Petzold et al., 2009; Webb et al., 2009, Wahren et al., 2014). This effect results from physiological differences in the plants and differences in plant management as compared to conventional annual crops used in agriculture. Like other tree species, the often used poplar and willow have a higher interception loss then conventional arable crops, which naturally persists at a lower level during the winter (Nisbet 2011, Dimitriou et al. 2009). Hall (2003) and Dimitriou et al. (2009) assume an average interception of 15% for regular annual crops, while Ettala (1988) reports 31% for willow SRC in Finland and Hall (1997) reports 21% for a poplar stand in the UK. These higher interception amounts reduce the quantities of effective rainfall, although the interception varies due to location characteristics and stand age. In comparing the total evapotranspiration between SRC and grassland, SRCs showed 20% higher rates (Allen et al. 1998; Dimitriou et al. 2009; Nisbet et al. 2011; Hartwich et al. 2014).

Thanks to the work of Aust (2012) and previous studies conducted for the research project AGENT (Hartwich et al. 2015), it is indicated that the North German Lowland has a high local potential for growing willow SRCs, a condition that is primarily implied by water availability (e.g. large areas with shallow groundwater levels). However, a cultivation of SRC could also affect the water balance through a reduction of groundwater recharge and base flow. As a consequence, the suitability of the production potential and the influence on the water balance has to be considered within the cultivation process. Therefore, the regional differences of the Northern German Lowlands in climate conditions, geomorphology, landscape evolution and soil properties are reflected through a series of selected river basins to be used as central project areas for hydrological modeling, namely the Ems, Aland, Treene, Uecker, Randow and Welse basins. In order to quantify the potential impact of SRC on the landscape hydrology, the Soil and Water Assessment Tool (SWAT) is used as a hydrological model for these six different catchment areas of the North German Lowland.

The aim of this study is to outline the methodological approach for establishing an effective and valid modeling concept for the selected river systems. This concept includes the model setup and the calibration process using a high performance computer cluster as well as the automatic calibration in SWAT-CUP, which includes the statistical method of Sequential Uncertainty Fitting Version 2 (SUFI-2) (Abbaspour et al. 2007).

Materials and Methods

Selection and characteristics of the river basins

The different catchment areas of the North German lowlands were selected according to their climatic and environmental characteristics, which have a specific impact on the catchment hydrology (Figure 1). Primarily, the climatic factors have been taken into account, which show a strong west-east gradient between maritime and continental conditions in the Northern German Lowlands. Additionally, morphological and soil genetic factors were included in the selection of areas, which were characterized by glacial and periglacial processes in the past.

Climatically, the Treene in Schleswig-Holstein and the Ems in Lower Saxony and North Rhine-Westphalia represent maritime conditions. In contrast, continental climatic conditions are represented by the catchments of Uecker, Randow and Welse in Brandenburg and Mecklenburg-Vorpommern. The Aland basin represents the transition zone between maritime and continental climates.

In the context of morphology and soil genesis, Ems and Aland represent older Pre-Weichselian glacial landscapes while Uecker, Randow and Welse are examples of young Weichselian landscapes. The Treene drains a catchment area in which both morphological and genetic soil zones occur.

Because of the spatial variety of climatic and landscape conditions in the Northern German Lowlands, all of the selected river basins are needed to represent these heterogeneous conditions. In accounting for the heterogeneous characteristics of each basin, as a whole the environmental conditions in the Northern German Lowlands are adequately represented.

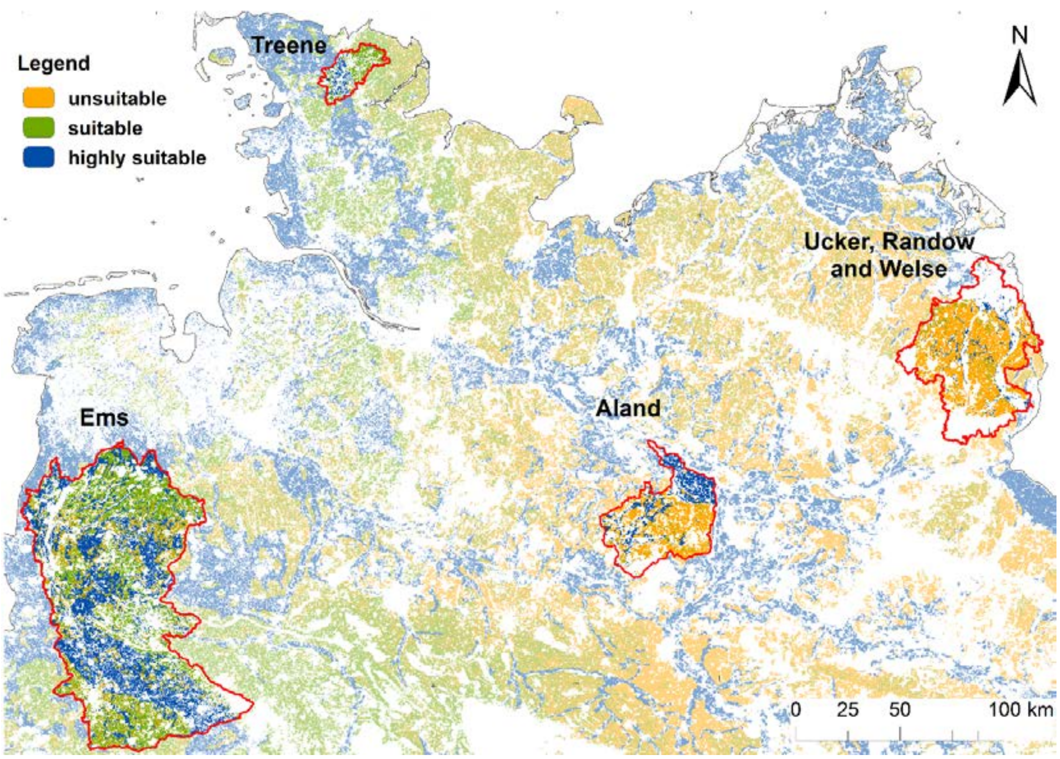


Figure 1: Selected catchments and their suitability level for willow SRC based on Hartwich et al. (2015).

The model system and parameterization

The Soil Water Assessment Tool 2012 (SWAT 2012) is used in this study as the water balance modeling system. With this system, it is possible to characterize the spatial and temporal flow dynamics and also implement detailed land use scenarios to determine the influence on the water balance. In particular, it is possible to implement different scenarios with specific vegetation types and management options to generate a realistic setup (Arnold et al. 1998, Srinivasan et al. 1998).

The implemented records are divided into hydrotopes to reflect the individual hydrological characteristics of each sub-basin. A grouping of the same hydrological characteristics is described as a "Hydrologic Response Unit" (HRU) in the SWAT model. Within these units, water balance components are calculated (Arnold et al. 1998).

The SWAT 2012 model for the different catchments was set up with a daily time step from 01/01/1990 to 12/31/2013 using the data in table 1.

Table 1: Datasets used to set up the model

Datasets	**Source**
• Digital Elevation Model, resolution 25 m • Digital land cover model 2009, true to area	Federal Agency for Cartography and Geodesy, Frankfurt am Main
Soil information • Soil survey maps 1: 200.000 (Germany) • Soil database of the soil survey maps 1: 1.000.000 (Germany) • Soil database of the soil survey maps 1: 300.000 (Brandenburg)	Federal Institute for Geosciences and Natural Resources State Office for Mining, Geology and Minerals Brandenburg
Climate Data • Precipitation data of 117 stations • Temperature data of 33 stations • Relative humidity data of 33 stations • Solar radiation data of 8 stations • Wind speed data of 24 stations	German Weather Service
Discharge data of 73 flow gauges	Lower Saxony State Office for Water Management, Coastal and Nature Conservation State Office for Environment, Health and Consumer Protection Brandenburg State Office for the Environment, Nature Conservation and Geology Mecklenburg Vorpommern

	State Agency for Nature, Environment and Consumer Protection North Rhine-Westphalia Country for Coastal Defence, National Park and Marine Reserve Schleswig-Holstein

According to the model requirements, the datasets were processed using ArcSWAT, which is a SWAT-specific implementation used for ESRI ArcGIS to preprocess data. In the first stage, a single model was set up in which all selected river catchments were included. After unsatisfying results, especially concerning the run time of the calibration process, separate models were established for each individual basin.

However, the first-stage model did implement data representing 64 different soil types and 12 land use classes (table 2), and it was able to define 24,592 HRUs. These HRUs cover a total model area of 14,767 km² and are allocated to 1047 sub-basins.

Table 2: Land use definition

<table>
<tr><th>Land use type</th><th>Percentage</th><th>Source</th></tr>
<tr><td>Water</td><td>2 %</td><td rowspan="7">Digital land use model (2009) - Federal Agency for Cartography and Geodesy, Frankfurt am Main</td></tr>
<tr><td>Urban</td><td>8 %</td></tr>
<tr><td>Forest Evergreen</td><td>10 %</td></tr>
<tr><td>Forest Mixed</td><td>6 %</td></tr>
<tr><td>Deciduous Forest</td><td>4 %</td></tr>
<tr><td>Pasture</td><td>17 %</td></tr>
<tr><td>Agricultural land</td><td>53 %</td></tr>
<tr><td>- Winter Wheat</td><td>14 %</td><td rowspan="6">Statistical agricultural data (period 1995-2013) – Statistisches Bundesamt [Federal Statistical Office]</td></tr>
<tr><td>- Corn</td><td>9 %</td></tr>
<tr><td>- Winter Barley</td><td>6 %</td></tr>
<tr><td>- Rapeseed</td><td>6 %</td></tr>
<tr><td>- Rye</td><td>5 %</td></tr>
<tr><td>- Other agricultural land</td><td>13 %</td></tr>
</table>

The characteristics of the second stage, which consists of four different models representing a particular catchment, are shown in table 3. This stage used the same data as the first stage model. By splitting up the stage into four models, it was possible to focus more on the individual environmental characteristics of each basin. Furthermore, the uncalibrated water balances of each model showed that the Hargreaves-Method for evapotranspiration estimation fits much better than the Penman-Monteith-Method to the values of evapotranspiration presented by Neumann & Wycisk (2003).

Table 3: Model characteristics of the 4 individual setups from the second stage

Basin	Model feature	Feature size
Treene	Area	477 km²
	Sub-basins	34
	HRU's	4,574
Ems	Area	9,093 km²
	Sub-basins	86
	HRU's	4,486
Ücker, Randow and Welse	Area	3,290 km²
	Sub-basins	56
	HRU's	6271
Aland	Area	1,907 km²
	Sub-basins	36
	HRU's	6,630

In a future step, the long term measurements for willow and poplar plants (e.g. leaf area index) performed by the Hochschule für Nachhaltige Entwicklung Eberswalde will be implemented to optimize the parameterization of SRC. By using these data sets, an implementation of land use scenarios will be applied for SRC in the next steps of the research project.

Calibration

In the calibration process, as well as in the model setup, the two stages remained distinct. Both models were integrated into the auto calibration software SWAT-CUP (v. 5.1.6) using Windows 7 and Scientific Linux. For the statistical method in the auto calibration process, SUFI2 was used (Abbaspour et al. 2007, Rouholahnejad et al. 2012). Further discharge data with daily time steps were implemented for 73 flow gauges, covering the time period from 01/01/1990 to 12/31/2013 in the calibration and validation process. Figure 2 illustrates the major steps of parameterization, model runs and evaluation with their different objective functions in the calibration process. The runtimes in figure 2 are related to the first stage model.

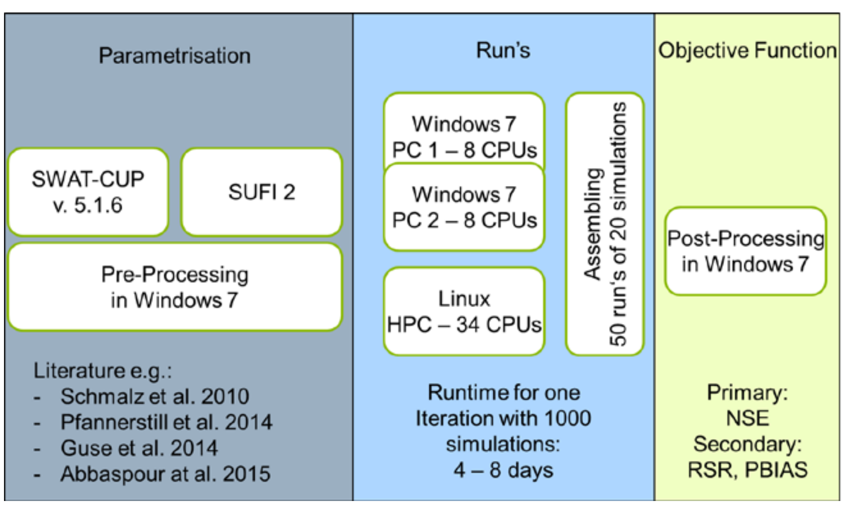


Figure 2: Schematic illustration of the calibration process; runtimes are related to the first stage model

The implementation and parameterization setup was done in Windows 7. The parameterization was oriented on state-of-the-art SWAT approaches, focusing on Europe and the Northern German Plain (Schmalz et al. 2010, Pfannerstill et al. 2014, Guse et al. 2014, Abbaspour et al. 2015). To implement parallel processing on Windows 7 and Scientific Linux, Python and Batch scripts were used as well as Linux shell scripting. For the model runs in Windows, two Windows 7 PCs with Intel Core i7-2600 (3.40GHz), 512 GB Samsung SSD 840 PRO Series and 16 GB DDR3 Ram were used. Through this setup, 16 parallel runs could be established in Windows 7. Additionally, 34 simultaneous simulations were implemented on the High-Performance Computing cluster (HPC) "*Soroban*" at ZEDAT, Freie Universität Berlin. However, for the first stage model, even with this parallelization on 50 cores, one iteration with 1000 simulations takes 4 to 8 days of runtime. The second stage models had a runtime of 1 to 2 days each with 2000 simulations per iteration, which made it much easier to establish an effective calibration strategy. After a successful run of an iteration, the data from the HPC were transferred to a Windows 7 computer where the assembling of all simulation results was done via a python script. The post processing in SWAT-CUP focused on Nash-Sutcliffe efficiency (NSE, Nash & Sutcliffe 1970, Eq. 1). However, due to the classification of Moriasi et al. (2007), the standard deviation ratio of the root mean square error (RSR, Eq. 2) as well as the percentage bias (PBIAS, Eq. 3) were also used to classify the quality level of the simulation in the calibration and validation process. After each iteration, a new parameter set was created with SWAT-CUP and implemented into the next iteration.

Equation 1

Nash-Sutcliffe efficiency (NSE):

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]$$

Equation 2

The standard deviation ratio of the root mean square error (RSR):

$$RSR = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{mean}^{obs}\right)^2}\right]}$$

Equation 3

Percentage bias (PBIAS):

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right]$$

Results and Discussion

Figure 3 illustrates the Nash-Sutcliffe efficiency changes during the different iterations in the first stage model for the implemented calibration gauges. Iteration 0 corresponds to the uncalibrated model with generally negative NSE. As expected, after the first iteration, the majority of the calibration gauges respond with an increase in NSE and, therefore, more positive values can be observed. The reaction after the second iteration is much weaker, an effect that is related to the calibration strategy. This strategy limits the used parameter range within the calibration process so that the number of possible solutions decreases by considering the best optimization for all implanted gauging stations. If non-weighting exists for the gauges (e.g. as related to the observed data quality), an optimization for every single gauge cannot be applied. Because the calibration was set up in the first stage model, no further improvement of individual gauges can be achieved by using SUFI2.

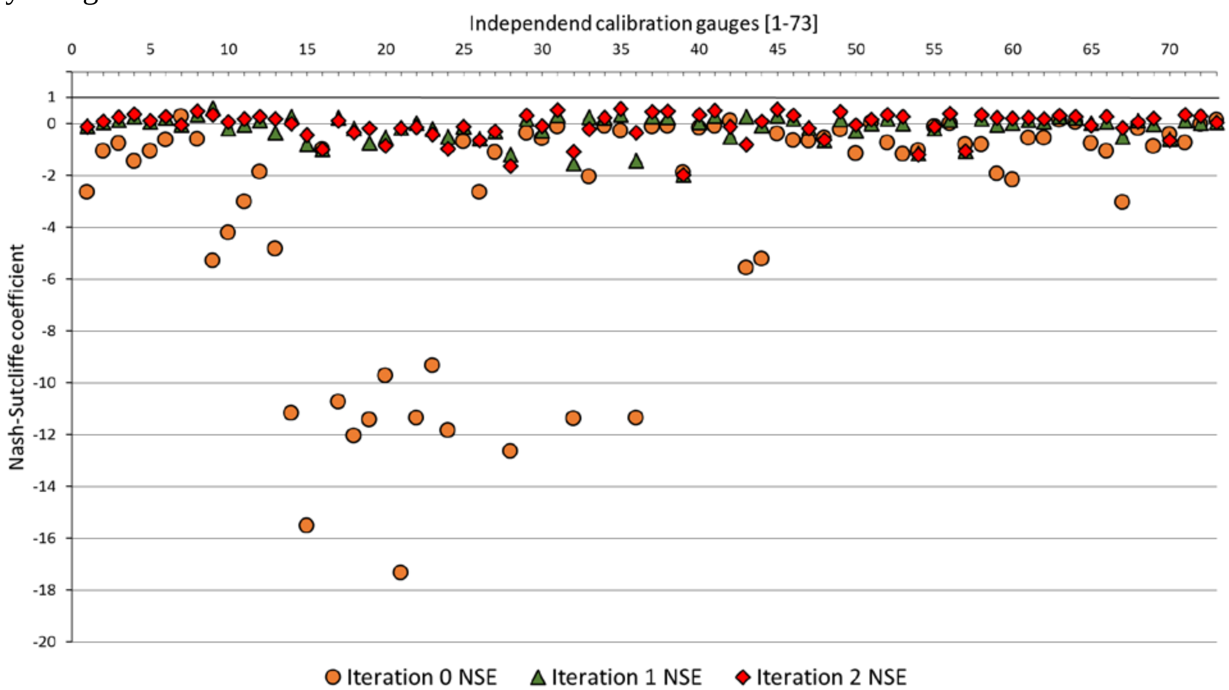


Figure 3: Nash-Sutcliffe efficiency change during the iterations in the first stage model. Iteration 0 model without calibration, Iteration 1 model after the first iteration, Iteration 2 shows second iteration that is in some cases worse than iteration 1.

Long runtimes in the calibration process and results showing unsatisfying efficiencies led to a split up of the first model. The second stage model, with separate models for the different catchments, sped up the calibration process and improved the results. Figure 4 shows a flow duration curve for the Treier gauging station (Treene basin) between 01/01/1993 and 31/12/2013 (simulation period excludes warm-up of the model run). The results from the best parameter set of the second stage model gave a better fit to event occurrences than the second iteration of the first stage model. In particular, the second stage model has a good representation of the low flow situations, which are of major interest for this project.

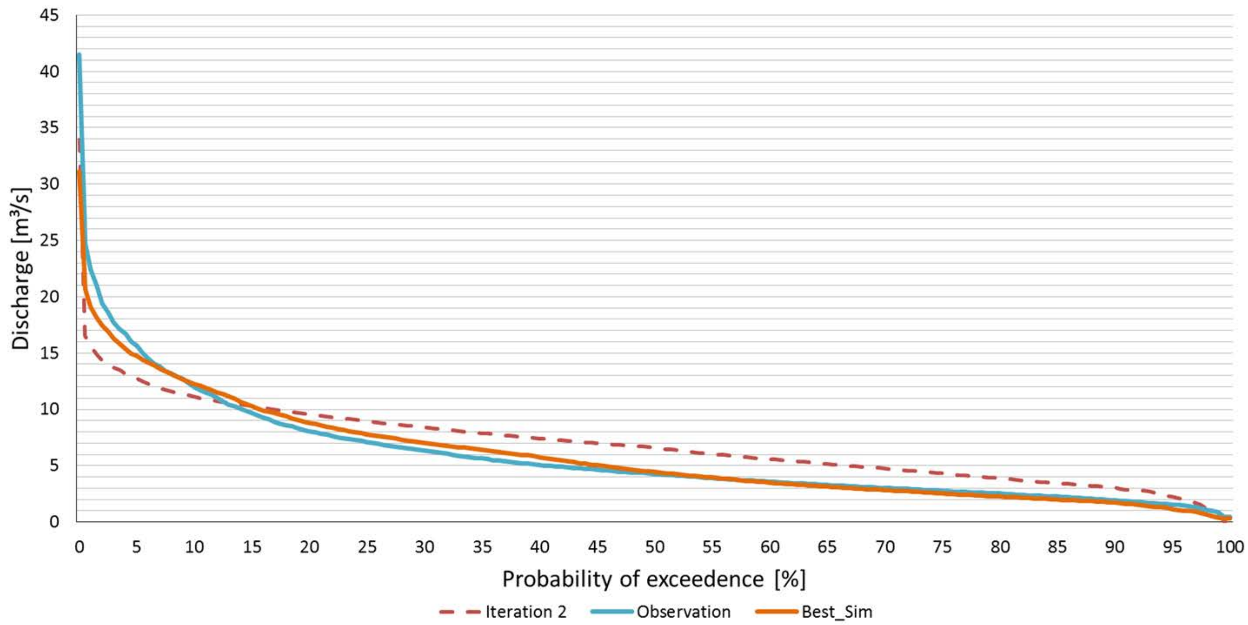


Figure 4: Treier Gauge (477 km², Treene basin) comparison of flow duration curve from the period of 01/01/1993 to 31/12/2013; Iteration 2 is characterized as second Iteration of the first stage model, Best_Sim is the best simulation of the second stage model.

The results from the Treier gauging station are also shown in table 4, which shows the selected objective functions for the calibration gauges of the Treene basin. These values are classified in table 5 using the classification of hydrological model performance as given by Moriasi et al. (2007). The Treier gauge (the outlet of the Treene basin) is classified as "very good" in the calibration as well as in the validation period.

Table 4: Results of the selected objective functions and gauging station for the second stage model of the Treene basin

Calibration (Monthly; Periode 1993-2006)		**NSE**	**PBIAS**	**RSR**	**Rank**
FLOW_OUT_1		0.84	19.2	0.39	1.7
FLOW_OUT_2		0.916	-7.5	0.288	1.0
FLOW_OUT_3		0.82	-2.3	0.419	1.0
FLOW_OUT_14		0.836	-13.7	0.4	1.3
FLOW_OUT_23		0.85	5.3	0.38	1.0
FLOW_OUT_34 (Treier)		0.926	-7.4	0.27	1.0
Validation (Monthly)	**Periode**	**NSE**	**PBIAS**	**RSR**	**Rank**
FLOW_OUT_1	2007-2010	0.74	25.8	0.49	2.3
FLOW_OUT_2	2007-2011	0.799	-6.1	0.44	1.0
FLOW_OUT_3	2007-2011	0.73	2.7	0.5	1.3

FLOW_OUT_14	2007-2011	0.765	-12.8	0.477	1.3
FLOW_OUT_23	2007-2012	0.547	23.5	0.665	3.0
FLOW_OUT_34 (Treier)	2007-2012	0.83	-5.3	0.405	1.0

To generate an overall evaluation of the used gauges, including all three objective functions, a ranking was established using four different classes ranging from 1 (very good) to 4 (unsatisfactory). Overall, the calibration of the gauges showed an average rank of 1.2, while the validation phase reached a mean rank of 1.7. Both rankings show that the model has a good to very good response when compared to the measured outflow.

Table 5: Classification of hydrological model performance according to Moriasi et al. (2007) and combined gauge assessment by rankings

Classes	Rank	NSE	PBIAS	RSR
Very good	1.0	0.75 < NSE ≤ 1.00	PBIAS < ±10	0.00 ≤ RSR ≤ 0.50
Good	2.0	0.65 < NSE ≤ 0.75	±10 ≤ PBIAS < ±15	0.50 < RSR ≤ 0.60
Satisfactory	3.0	0.50 < NSE ≤ 0.65	±15 ≤ PBIAS < ±25	0.60 < RSR ≤ 0.70
Unsatisfactory	4.0	NSE ≤ 0.50	PBIAS ≥ ±25	RSR > 0.70

Conclusion

Splitting up the first stage model, which included all catchments, was an improvement not only for calculation and calibration time, but also for the output of results.

After the calibration, a selection of scenarios will be applied based on the respective percentage of agricultural land that is potentially available for SRCs. On this basis, maximum scenarios will be implemented, where the suitable agricultural areas are fully tilled with SRC. Further realistic simulations will be implemented on the suitable agricultural land by using different selected proportions of SRC (e.g. 5, 10, 15, 20 or 25%). However, increasing the area cultivated with SRC also serves the aim of the project AGENT to determine its influence on landscape hydrology.

Acknowledgements

This work was kindly supported by the Federal Ministry of Food and Agriculture, Germany and Fachagentur Nachwachsende Rohstoffe e. V. (FNR) [grant number 2012410]. In addition, our thanks go to the Federal Agency for Cartography and Geodesy, the Institute for Geosciences and Natural Resources; State Office for Mining, Geology and Minerals Brandenburg; the Lower Saxony State Office for Water Management, Coastal and Nature Conservation; the State Office for Environment, Health and Consumer Protection Brandenburg; the State Office for the Environment, Nature Conservation and Geology Mecklenburg Vorpommern; the State Agency for Nature, Environment and Consumer Protection North Rhine-Westphalia; the country's Agency for Coastal Defence, National Park and Marine Reserve Schleswig-Holstein, the German Weather Service and the High Performance Computing at the ZEDAT, Freie Universität Berlin for providing the data, provision of calculation time and service.

References

Abbaspour K. C., J. Yang, I. Maximov, R. Siber, K. Bogner, J. Mieleitner, J. Zobrist, R. Srinivasan. 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *Journal of Hydrology* 333(2-4): 413-430.

Abbaspour, K. D., E. Rouholahnejad, S. Vaghefi, R. Srinivasan, H. Yang and B. Kløve. 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology* 524: 733-752.

Allen, G., S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements – FAO Irrigation and drainage paper 56. Rome: FAO. Available at: http://www.fao.org/docrep/x0490e/x0490e00.htm. Accessed 20 October 2015.

Arnold, J.; R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large area hydrologic modeling and assessment part I: model development. *Journal of the American Water Resource Association* 34 (1): 73-89.

Aust, C. 2012. Abschätzung der Nationalen und regionalen Biomassepotentiale von Kurzumtriebsplantagen auf landwirtschaftlichen Flächen in Deutschland. PhD diss. Fakultät für Forst- und Umweltwissenschaften. Albrecht-Ludwigs-Universität. Freiburg im Breisgau, Germany.

Bundesministerium für Wirtschaft und Energie, eds. 2014. *Erneuerbare Energien in Zahlen. Nationale und internationale Entwicklung im Jahr 2013*. Paderborn: Bonifatius GmbH.

Dimitriou, I., G. Busch, S. Jacobs, P. Schmidt-Walter, and N. Lamersdorf. 2009. A review of the impacts of Short Rotation Coppice cultivation on water issues. *Landbauforschung – vTI Agriculture and Forestry Research*, 3 (59): 197-162.

Ettala, M. O. 1988. Evapotranspiration from Salix aquatic plantation at a sanitary landfill. *Aqua Fennica*, 18: 3-14.

Guse, B., D. E. Reusser and N. Fohrer. 2014. How to improve the representation of hydrological processes in SWAT for a lowland catchment – temporal analysis of parameter sensitivity and model performance. *Hydrological Processes* 28: 2651-2670.

Hall, R. L. 2003. Short rotation coppice for energy production - Hydrological guidelines. Report of the DTI New and Renewable Energy Programme. Centre for Ecology and Hydrology: Available at: http://nora.nerc.ac.uk/2631/1/HallShortRotationReport.pdf. Accessed 20 October 2015.

Hall, R. L. 1997. Water use of poplar clones grown as short-rotation coppice at two sites in the United Kingdom. *Aspects of Applied Biology*. 49: 163–172.

Hartwich, J., J. Bölscher and A. Schulte. 2014. The impact of short rotation coppice on land and water resources. *Water International* 39 (6): 813-841.

Hartwich, J., J. Bölscher, A. Schulte, M. Schmidt, C. Pflugmacher and D. Murach, 2015. Das Transpirationswasserdargebot als steuernder Faktor für die Produktion von Energie aus Weiden in Kurzumtriebsplantagen – Abschätzung des Bioenergiepotentials für Deutschland. *Hydrologie und Wasserbewirtschaftung* 59 (5): 217-226.

Nash, J. E. and Sutcliffe, J. V., 1970. River flow forecasting through conceptual models. Part I: Discussion of principles. *Journal of Hydrology* 10, 282-290.

Neumann, J. and P. Wycisk. 2003. Mittlere jährliche Grundwasserneubildung. *Bundesrepublik Deutschland Nationalatlas – Relief, Boden und Wasser*, 144-145. H. Liedtke, R. Mäusbacher and K.-H. Schmidt. Heidelberg eds. Berlin: Spektrum Akademischer Verlag.

Nisbet, T., H. Thomas and N. Shah. 2011. Short Rotation Forestry and Water. In *Short Rotation Forestry: Review of growth and environmental impacts*. 13-34. H. McKay eds. Forest Research Monograph, 2. Forest Research Surrey

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel and T. L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers* 50 (3): 885-900.

Petzold, R., K.-H. Feger and K. Schwärzel. 2009. Wasserhaushalt von Kurzumtriebsplantagen. In *Anbau und Nutzung von Bäumen auf landwirtschaftlichen Flächen*, 181-192. Reeg, T., A. Bemmann, W. Konold, D. Murach and H. Spiecker eds.: Weinheim: Wiley-VCH Verlag

Pfannerstill, M., B. Guse and N. Fohrer. 2014. A multi-storage groundwater concept for the SWAT model to emphasize nonlinear groundwater dynamics in lowland catchments. *Hydrological Processes* 28: 5599-5612.

Rouholahnejad, E., K. C. Abbaspour, M. Vejdani, R. Srinivasan, R. Schulin and A. Lehmann. 2012. A parallelization framework for calibration of hydrological models. *Environmental Modelling & Software* 31: 28-36.

Schmalz, B., F. Tavares and N. Fohrer. 2008: Modelling hydrological processes in mesoscale lowland river basins with SWAT - capabilities and challenges. *Hydrological Sciences Journal* 53 (5): 989-1000.

Srinivasan, R., T. S. Ramanarayanan, J. G. Arnold, and S. T. Bednarz. 1998. Large area hydrologic modeling and assessment part II: model application. *JAWRA Journal of the American Water Resources Association* 34: 91-101.

Webb, J., P. Cook, U. Skiba, P. Levy, T. Sajwaj, C. Parker, and A. Mouat. 2009. Investigation of the Economics and Potential Environmental Impacts of the Production of Short Rotation Coppicing on Poorer Quality Land. Report to the Scottish Government

Wahren, A., S. Julich and K.-H. Feger. 2014. Modellgestützte Untersuchung zum Einfluss von Energieholz-Anbau auf ein mesoskaliges Einzugsgebiet (Hoyerswerdaer Schwarzwasser, Sachsen). In *Wasser – Landschaft – Mensch in Vergangenheit, Gegenwart und Zukunft. Beiträge zum Tag der Hydrologie am 20./21. März 2014 an der Katholischen Universität Eichstät-Ingolstadt.* 245-252. B. Cyffka, eds. Forum für Hydrologie und Wasserbewirtschaftung. 34.14: 245-252.

Determining the effect of land use change on streamflow using soil water assessment tool (SWAT) Model

John P. O. Obiero
Department of Agricultural and Rural Engineering, University of Venda, South Africa.
john.obiero@univen.ac.za or pobiero2003@yahoo.com

Mohammed A. Hassan.
Department of Biosystems and Environmental Engineering, Technical University of Kenya, Nairobi, Kenya.

Abstract

Changes in land use influence catchment water resource availability. The purpose of this study was to assess the effect of land use change on streamflow for Naro Moru river catchment, Kenya. Satellite images was obtained for the years 1984 and 2010 and processed to derive land use classes. Land use data was obtained directly for the year 2000 from Kenya Soil Survey, Nairobi, Kenya. The Soil Water Assessment Tool (SWAT) model was used to predict streamflow during the period 1992 to 2000 under different land use practices based on the years 1984, 2000 and 2010. Other input model parameters were kept constant while varying the land use during flow simulation. Between the years 1984 and 2000, the area under natural forest cover increased by 14% while that under agriculture reduced by 21%. The area under grassland during this period was negligible at less than 1%. The simulated average daily streamflow in month decreased by 40% in the period 1984 to 2000. This decrease was attributed to increase in forest cover. During the period 2000 to 2010, there was a further decrease in simulated average daily streamflow in month by 14% attributed to further increase in forest cover which may have increased soil infiltration thereby reducing surface flow. There was an increase in land area under agriculture during this period, however relatively less compared to that under forest cover. Changes in other land use practices including bushland, bare soil and rock was negligible. Assessment of changes in catchment hydrologic response under changing land use is important in watershed water resources management.

Key words: Land use change, Streamflow simulation, Model calibration and validation.

Introduction

Land use practices in a watershed influences streamflow and hence surface runoff in a catchment. Changes in land use alter the hydrologic response of a catchment through its effects on various hydrologic processes that include infiltration, interception, evapotranspiration, subsurface flow, erosion and sedimentation. As a result, water availability for various purposes that include irrigation, crop production, hydroelectric power generation and ground water exploration are determined by the kind of land use/land cover prevailing in a watershed. Kim et. al. (2014) recognized that serious environmental problems related to land use change by human activity decreases water quality through siltation and water pollution. For the purposes of planning and management of future water supply capabilities in a watershed and to evaluate catchment water resources, especially under changing land-use scenarios, it is important that potential effects of land use on the water resources is predicted with certainty. This may be done through watershed hydrologic modeling. Shewangizaw and Michael (2010) investigated the effect of land use change on catchment hydrologic response and reported an increase in inflow to Lake Awassa, Ethiopia because of land cover change. The Soil Water Assessment Tool (SWAT) has been used worldwide to study the effect of land use on catchment hydrology in a number of watersheds. In Technical brief 2 (2007) watershed modeling, based on SWAT, was carried out to estimate runoff from various land use types in upper Malalprabha catchment, India. Various land use scenarios were built into the model to study the impact of water availability in irrigated agriculture. Based on an existing trend in irrigation water demand at a downstream section, an ideal land use to guarantee the required river flow was modeled. Such a study presents a modeling approach in which the predicted impact of land use on stream flow may be used for planning land use for irrigation water management in agriculture. Land use scenario analysis has also been carried out by Heuvelmans et al. (2005) to predict the impact of land allocation on the hydrology and erosion on selected watersheds in which the rate variables used to describe the land use impacts included evapotranspiration, surface runoff, discharge, ground water recharge, and soil loss through erosion. Such variables can be simulated using the SWAT model. Hydrologic modeling has also been used to understand the effects of land use/land cover changes on the hydrological behavior of a watershed. A study to investigate land use/land cover dynamics and impacts on stream flow has been conducted by Tadele and Förch (2007) at a 167.3km^2 Hare river watershed, Ethiopia. This was in recognition of the fact that knowledge of the influence of land use/land cover changes would serve as an important tool for use by local governments and policy makers in formulating and implementing effective and appropriate response strategies intended to minimize undesirable effects of future land use/land cover changes. The study provided insight to understanding upstream-downstream linkages with respect to irrigation water use by relating seasonal stream variability to land use/land cover dynamics. The study demonstrates a typical application of modeling land use/land cover for the purposes of water resources management in irrigated agriculture. Runoff simulation was based on the use of SWAT model and land cover maps used to analyze land use/land cover dynamics were chosen for years 1967, 1975 and 2004. An assessment of the fact that land use influences stream flow was done by performing simulations for a chosen period using different maps. The purpose of this study was to determine the effect of land use change on streamflow on the Naro Moru River catchment, Kenya.

Methodology

Study Area

The study was conducted on a sub catchment in the Naro Moru river, Kenya. The sub-catchment covers an area of about 85km^2 falling within the broader catchment of 172 km^2. The catchment lies between latitudes 0^o 03' and 0^o 11' South and longitudes 36^o 55' and 37^o 15' East. The catchment altitude ranges from 5200m at the peak of the mountain to 1800m above mean sea level at its confluence with Ewaso Ng'iro river. The catchment lies on the leeward side of Mt Kenya and therefore is characterized by low amount of rainfall as presented by Ngigi (2006) who also reported that the mean annual rainfall within the catchment increases from 650mm at the outlet to 1500mm at 3300m altitude and drops to 500mm in the moorland. On average the annual potential evaporation is above 2500mm. The climatic conditions that prevail in the catchment and agro-ecological zones are documented by Thomas et al. (1993) varying from the glaciated peaks of Mount Kenya (5200m) to the semi- arid Laikipia plateau (1800m) above mean sea level. The catchment has five different ecological zones being peak, moorland, forest, foot zone and savannah with diversity of vegetation/land use and soil types. Location of the study area in Kenya is shown in **Figure 1.**

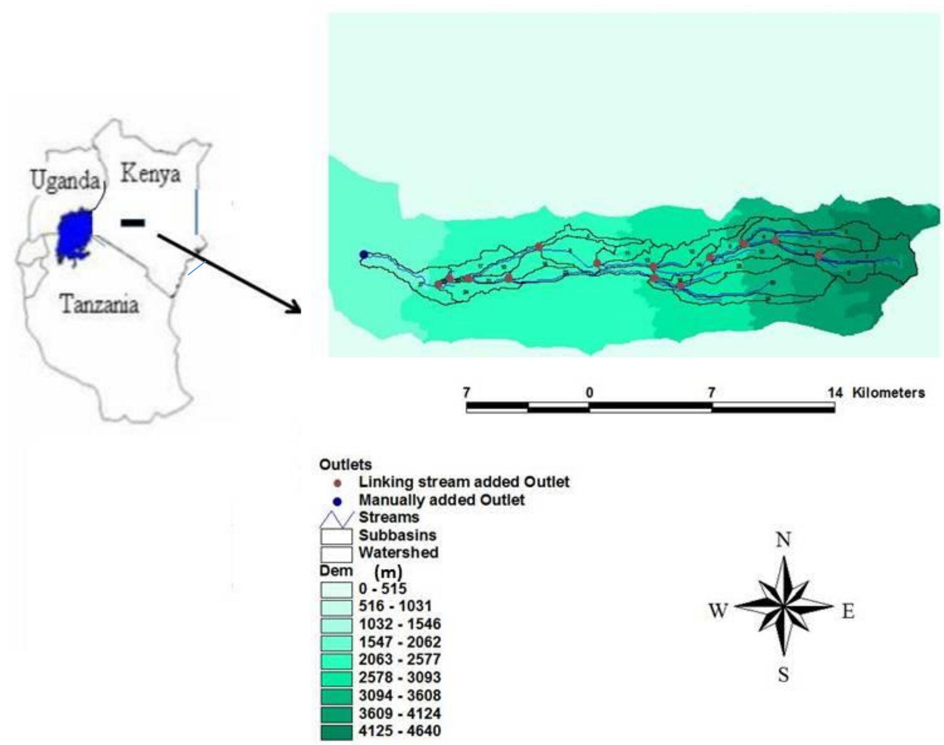


Figure 1. The Naro Moru river catchment.

Model choice and set up

The SWAT model was used for simulation of streamflow in this study. A detailed description of the model, its origin and applications has been presented by Obiero et al. (2011) who noted that model has been used worldwide for modeling impact of land use and land cover changes on catchment hydrologic response. The watershed was divided into 27 sub basins with surface runoff prediction based on the United States Soil Conservation Service (SCS) curve number technique.

Data acquisition and processing

Land use data aquisition and processing

Data on land use was obtained for the years 1984, 2000 and 2010. Satellite image for the years 1984 and 2010 were acquired from the Regional Centre for Mapping of Resources for Development (RCMD), Kenya. Readily available land use map for the year 2000 was obtained from the Kenya Soil Survey, Nairobi, Kenya. The satellite images were classified to obtain the land use maps in the said years (2000 and 2010). The land use types were reclassified into SWAT land uses for use in streamflow simulation. Land use maps for the years indicated are presented in Figures 2, 3 & 4.

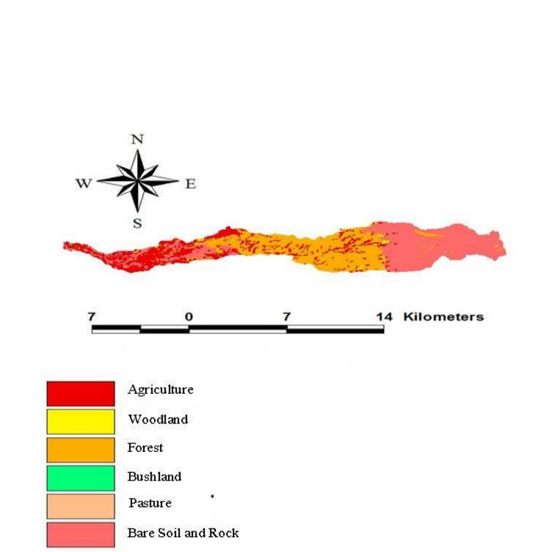


Figure 2. Land use classes for the year 1984

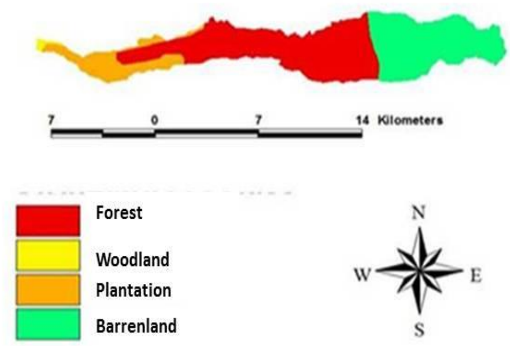


Figure 3. Land use classes for the year 2000

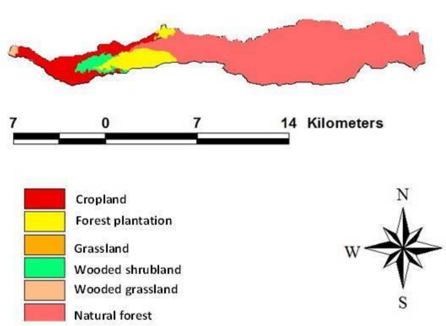


Figure 4. Land use classes for the year 2010

Tables 1 illustrate the reclassification of the acquired land use types to SWAT land use classes.

Table 1. Reclassification of land use types to SWAT land use classes.

1984			2000			2010		
Kenya land use	**SWAT Landuse**	**SWAT landuse code**	**Kenya land use**	**SWAT Landuse**	**SWAT landuse code**	**Kenya land use**	**SWAT Landuse**	**SWAT landuse code**
Agriculture	Agric. land-generic	AGRL	Plantation	Mixed forest Land	FRST	Grassland	Pasture	PAST
						Forest plantation	Forest-mixed	FRST
Bare soil or rock	Strip mines	SWRN	Agriculture (sparse)	Cropland and pasture	AGRL	Cropland	Agricultural Land- Generic	AGRL
Bushland	Hay	HAY	Woodland	Evergreen Forest Land	FRSE	Wooded shrubland	Range - brush	RNGB
Forest	Forest-mixed	FRST				Shrubbed grassland	Bermuda Grass	BERM
Grassland	Pasture	PAST	Forest	Deciduous Forest Land	FRSD	Wooded grassland	Range-grasses	RNGE
Water	Water	WATR				Built up area	Residential-Medium density	URMD
Woodland	Evergreen forestland	FRSE	Barren Land	Strip Mines	SWRN	Natural forest	Forest-Evergreen	FRSE
						Rangeland	Range -brush	SWRN
						Cultivated land	Agricultural land-rowcrops	AGRR

Data input and streamflow simulation

The data used as input for streamflow simulation using the SWAT model included daily rainfall, maximum and minimum temperatures, relative humidity, digital elevation model, land use, soils information and digitized stream network obtained from different sources. The model was calibrated for the years 1992 to 1995 and validated for the years 1998 to 2000 at a gauging station located at the outlet of the catchment (85km^2). Monthly Streamflow simulation was carried out for the years 1992 to 2000 using input parameters that were obtained after model validation. The simulations were conducted using land use data for the years 1984, 2000 and 2010 while keeping all the other parameters constant. The curve numbers were changed for each of the 27 sub basins based on the soil and land use type combination.

Results and discussion

Land use change analysis

Table 2 shows the land cover types and their proportions for the years 1984, 2000 and 2010.

Table 2. Land use types for various years between 1984 and 2010

	1984		2000		2010	
Land use	**Area (ha)**	**%**	**Area**	**%**	**Area**	**%**
Grassland	0.932	0.01	0	0	2.1638	0.03
Wooded shrubland (grazing)	0	0	0	0	311.79	3.65
Natural Forest	047.13	35.67	4239.35	49.56	6452.1367	75.49
Plantation (mixed forest land)	0	0	1153.59	13.49	727.0565	8.51
Bare soil or rock	3644.73	42.67	3102.57	36.27	0	0
Bushland	10.20	0.12	0	0	0	0
Agriculture/ Cropland	1782.65	20.87	0	0	1053.3637	12.33
Woodland	56.55	0.66	58.4213	0.68	0	0
Total	**8542.2**		**8553.9**		**8546.5**	

From Table 2, it is observed, in general, that area under natural forest increased from 3047 ha (35.7% of total area) to 4239 ha (49.6% of total area) during the period 1984 to 2000 reflecting an increase of about 14% of the total area. The area under agriculture was however, decreased from 1783 to nil reflecting a decrease of about 21% of total area. This resulted from change in land use from agriculture to mainly forest plantation which increased by about 13% during the same period. This occurred mainly in the lower end of the sub-catchment under study. The area under grassland occupied a negligible area of less than 1% in the years 1984, 2000 and 2010. The area under forest plantation increased by 13.5% between 1984 and 2000 and decreased from 13.5% in 2000 to 8.5% in 2010. Between 2000 and 2010, there was a further increase in forest cover from 4239km^2 to 6452km^2 amounting to 25% increase. Agricultural land area also increased between 2000 and 2010 by about 12%. This may have been as a result of replacement of parts of area under woodland and plantation by agriculture. The increase in agricultural land between 2000 and 2010, however was relatively smaller compared to the increase in natural forest cover.

Simulated streamflow response to land use change

Table 3 shows the average daily flow in month based on monthly flow simulation for the years 1984, 2000 and 2010. The average daily flow decreased from 2.47m^3/s to 1.49m^3/s between the years 1985 and 2000. This reflected a decrease of about 40% which was attributed to the increase in forest cover and decrease in area under agriculture. Githui et al. (2009) observed that forests have the effect of reducing runoff and further points out that higher runoff flows are expected in cropland than in forests due to the fact that rainfall satisfies the soil moisture deficit in agricultural land more quickly than in forests thereby generating more runoff in agricultural land. Less runoff was generated in the year 2000 than in 1984 as a result of increase in forest cover and reduction in agricultural land area. Besides, forest cover intercepts precipitation and increases the infiltration opportunity time thereby resulting into more water being infiltrated into the soil. The resulting effect is a decrease in surface runoff and hence streamflow. Lower infiltration rates are associated with agricultural land due to soil compaction and increase in bulk density arising from tillage activities. Between the years 2000 and 2010, there was a further decrease in average daily streamflow from 1.49m^3/s to 1.28m^3/s amounting to about 14% decrease. This was attributed to a further enormous increase in the forest cover. The increase in area of land under agriculture rose during this period but to a lesser extent than that of forest cover explaining the decrease in streamflow. The percentage decrease in streamflow between the period 2000 and 2010 was lower that between 1985 and 2000 by 26%. The relatively lesser decrease in streamflow between 2000 and 2010 compared to between 1985 to 2000 may have been as a result of the increase in agricultural land which is associated with increased runoff thereby moderating the effect of forest cover.

Table 3. Average daily flow in month for the years 1992 to 2000

Year of land use data input	1984	2000	2010
Average daily flow in month (m^3/s)	2.47	1.49	1.28

Conclusion

The effect of land use change on streamflow was established in the study. There was a significant increase in forest cover between 1985 and 2000 and also between 2000 and 2010 though to a lesser extent. Model simulated streamflow was reduced from 2.47m^3/s to 1.49 m^3/s (40%) between 1984 and 2000 and further reduced from 1.49 m^3/s to 1.28 m^3/s (14%) during the period 2000 to 2010. Increased forest cover and replacement of agricultural land by forests yield a significant increase in streamflow attributed mainly to the fact that forests generate less runoff than agricultural land. A Lesser reduction in streamflow between 2000 and 2010 compared to that between 1984 to 2000 due to increased forest cover was attributed to increase in cropland which generated more runoff and hence adding to streamflow. The findings may not necessarily reflect the picture on the ground due to model limitations and input data deficiencies. In loading the land use data during SWAT model set up, the sub basins were loaded with the dominant land use implying that the areal coverage for the various land use practices may not have been accurate but based on approximations. In addition, classification of satellite images and further reclassification of land use practices to SWAT land uses may not have been as accurate as anticipated. Nonetheles the findings provide a general view in land use change analysis which may be used in water resources planning.

Acknowledgements

The author wishes to thank the Dean's committee research grant, University of Nairobi for funding the research work from which a significant proportion of the manuscript has been derived. I also wish to thank the University of Venda, Limpopo, South Africa for providing the funding that enabled an oral presentation of the paper SWAT conference 2015 held in Sardina, Italy. Special thanks to the Kenya Soil Survey for processing of satellite images to produce land use maps used in the study.

References

Githui, F., F. Mutua, and W. Bauwens. 2009. Estimating Impacts of Land Cover Change on Runoff using the Soil Water Assessment Tool (SWAT): Case study of Nzoia Catchment, Kenya, *Hydrological Sciences Journal*, 54(5): 899-908.

Heuvelmans, G, J. F. G. Qujano, B. Muys,; J. Feyen, P. Coppin. 2005**.** Modelling the water balance with SWAT as part of the land use impact evaluation in a life cycle study of CO_2 emission reduction scenarios. *Hydrological Processes Journal***,** *19 (3) : 729-748.*

Kim, I., Q. Bao Le., S. J. Park, J. Tenhunen., T. Koellner. 2014. Driving forces in Archeptypical Land-Use Changes in a Mountaineous Watershed in East Asia. *Land 2014*, 3: 957-980.

Ngigi, S N. 2006. Hydrological Impacts of Land Use Changes on Water Resources Management and Socio-economic Development of Upper Ewaso Ng'iro River Basin in Kenya. PhD diss. Netherlands: Delft University of Technology.

Obiero, J. P. O., M. A. Hassan, and L. O. M. Gumbe. 2011. Modeling of Streamflow of a catchment in Kenya. *Journal of Water Resource and Protection* 3 (9): 667-677.

Shewangizaw, D., and Y. Michael. 2010. Assessing the Effect of Land Use Change on the Hydraulic Regime of Lake Awassa,. *Nile Water Science and Engineering Journal*, 3(2): 110-118.

Tadele, K. and Förch, G. 2007. Impact of Land Use/Cover Change on Stream flow: The case of Hare river watershed, Ethiopia. *Catchment and Lake Research*. LARS 2007: 80-84.

Technical Brief 2. 2007. Hydrological Modelling of the Upper Malaprabha Cachment using ArcView SWAT, Development of Tools and Methodologies to Implement the Payment for Environmental services Concept in Watersheds in India (PES India Project): Nowegian Institute for Water Research.

Does the use of fine climate stations grid and sub-basins delineation improve the modelling of river discharge at hourly time-step? Application of the SWAT model to Mediterranean flash floods

Laurie BOITHIAS
University of Toulouse; INPT, UPS; Laboratoire Ecologie Fonctionnelle et Environnement (EcoLab), Avenue de l'Agrobiopole, 31326 Castanet Tolosan Cedex, France. CNRS, EcoLab, 31326 Castanet Tolosan Cedex, France l.boithias@gmail.com

Danielle de Almeida BRESSIANI
University of São Paulo, Departamento de Hidráulica e Saneamento (SHS-EESC-USP), Av. Trabalhador Sãocarlense, 400 CP, 359, São Carlos- SP, 13566-590, Brazil

Sabine SAUVAGE
University of Toulouse; INPT, UPS; Laboratoire Ecologie Fonctionnelle et Environnement (EcoLab), Avenue de l'Agrobiopole, 31326 Castanet Tolosan Cedex, France. CNRS, EcoLab, 31326 Castanet Tolosan Cedex, France

Karim C. ABBASPOUR
Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland

Raghavan SRINIVASAN
Spatial Sciences Laboratory, Texas A&M University, College Station, Temple, Texas 76502 USA

Wolfgang LUDWIG
Centre de Formation et de Recherche sur l'Environnement Marin (UMR 5110 – CNRS/Université de Perpignan), Université de Perpignan, 52 avenue Paul Alduy, 66860 Perpignan Cedex, France

Evelyne RICHARD
University of Toulouse; Laboratoire d'Aérologie (LA), 14 avenue Belin, 31400 Toulouse, France. CNRS, LA, 31400 Toulouse, France

José-Miguel SANCHEZ-PEREZ
University of Toulouse; INPT, UPS; Laboratoire Ecologie Fonctionnelle et Environnement (EcoLab), Avenue de l'Agrobiopole, 31326 Castanet Tolosan Cedex, France. CNRS, EcoLab, 31326 Castanet Tolosan Cedex, France

Abstract

Global change is expected to increase the frequency of intense rainfall events and consequent flash floods across the Mediterranean coastal basins in the next decades. To date, few models are able to simulate hydrological processes at basin-scale at a reasonable time scale to describe these flash events with accurate details. They are often complex physically-based distributed models and do not capture below-ground processes. The SWAT model assumes several simplifications but has recently been upgraded to sub-daily time-step calculations. However, its sub-daily module has only been tested in small catchments (~1 km²). The objectives of this study were (1) to assess the ability of the SWAT model to simulate discharge at hourly time-step in the ~1,400 km² Têt Mediterranean river basin (southwestern France) and (2) to assess the possible gain of model's performance when using fine grids of climate stations and sub-basins representation. We modelled the Têt basin with two sub-basin delineations of 1,500 and 100 ha drainage areas, and with three hourly rainfall dataset grids (NCEP CFSR, 30 km; SAFRAN, 8 km; and measurements from 20 rain gauges). We calibrated the Têt SWAT models resulting from the different combinations of delineations and rainfall datasets at both daily and hourly time-steps with the upgraded version of the SWAT-CUP autocalibration tool, based on both daily and hourly measured discharge at 3 gauging stations (2009-2011). Nash-Sutcliffe indices range from -1.12 to 0.78 depending on the gauging station, on the sub-basin delineation on the rainfall datasets and on the calibration time-step. Despite lower Nash-Sutcliffe values at hourly time-step, hourly simulations allowed capturing the timing of the flood peak more accurately than the daily simulations. The most sensitive parameters of hourly run appear to be the soil saturated hydraulic conductivity which is hence the key parameter in the Green&Ampt equation. This preliminary study provides guidance for future hourly time-step modelling with the SWAT model and is the first step before modelling suspended sediment loads during floods.

Keywords: Sub-daily simulation, Meteorological grid, Sub-basin mesh, Flash floods, Mediterranean watershed, SWAT-CUP.

Introduction

Global change is expected to increase the frequency of intense rainfall events and consequent flash floods across the Mediterranean coastal basins in the next decades (IPCC, 2013, 2014). To date, few models are able to simulate hydrological processes at basin-scale at a reasonable time scale to describe these flash events with accurate details. Some complex distributed physically-based models, such as the MARINE model (Roux et al., 2011), are able to simulate hydrological processes at the flood time-scale but they do not capture below-ground processes.

The SWAT model (Arnold et al., 1998, 2012) has recently been upgraded to sub-daily time-step calculations (Jeong et al., 2010, 2014), even though it assumes several simplifications. However, its sub-daily module has only been tested in small catchments (~1 km^2) (Jeong et al., 2010, 2011, 2014; Maharjan et al., 2013; Furl et al., 2015).

The objectives of this preliminary study were:

1. To assess the ability of the SWAT model to simulate discharge at hourly time-step in a ~1,400 km^2 river basin;
2. To assess the possible gains in model's performances when using fine grids of climate stations and sub-basins representations.

Materials and methods

Green&Ampt infiltration equation

The sub-daily module of SWAT is based on the Green and Ampt Mein Larson (GAML) excess rainfall method (Mein and Larson, 1973) as stated in Eq. 1:

$$f(t) = K_e \cdot \left(1 + \frac{\Psi \cdot \Delta\theta}{F(t)}\right) \qquad \text{Eq. 1}$$

Where f is the infiltration rate at time t (mm/h), K_e is the effective hydraulic conductivity (mm/h) in which the impact of land cover is incorporated, Ψ is the wetting front matric potential (mm), $\Delta\theta$ is the change in volumetric moisture content across the wetting front (mm/mm), and F is the cumulative infiltration at time t (mm $H_2$0).

Therefore, the parameters from SWAT that are involved in the GAML equation are the saturated hydraulic conductivity (SOL_K), curve number (CN2), soil texture parameters related to clay, sand and bulk density (SOL_CLAY, SOL_SAND, SOL_BD) and the soil available water content (SOL_AWC).

Case study description and data for model set up

The case study is the Mediterranean coastal Têt River basin (1,400 km^2), located in the south of France (Figure 1). The Têt River is a typical Mediterranean river which responds quickly to weather variations, such as storms. The river length is about 120 km and the average discharge is 10 m^3/s. The altitudes range from 2,800 m.a.s.l. in the Pyrenees Mountains to sea level (Figure 2a). The basin is mostly covered by range land (35.9%) and forests (36.8%). Agricultural land covers 19.9% of the basin's area and includes vine, orchards and annual crops (Figure 2b). Soils are mostly shallow (~1.4 m) and sandy (Figure 2c).

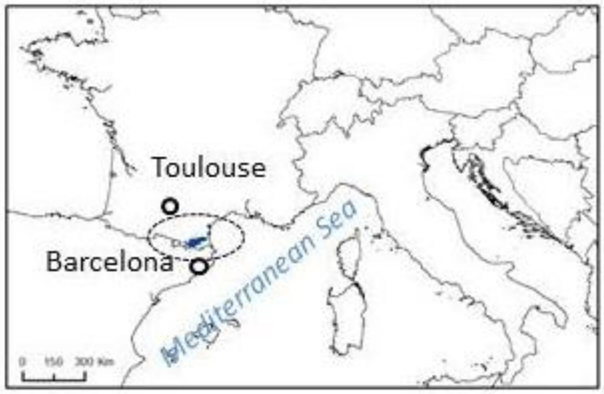


Figure 1. Location of the Têt river basin.

The SWAT model was set up with the following maps (shown in Figure 2):

- the 90 m SRTM Digital Elevation Model (Jarvis et al., 2008),
- the 100 m 2006 Corine Land Cover map (Source: European Environmental Agency) and
- the FAO Digital Soil Map of the World (Source: Land and Water Development Division, FAO, Rome) with associated soil properties from the French National Institute for Agricultural Research (INRA, 1998; Wösten et al., 1999)

The basin embeds two reservoirs (Figure 2b): (i) a reservoir in the lower part of the basin for irrigation purpose (Vinça reservoir, 24 hm^3, daily reservoir outflow available until 2013), and (ii) another reservoir in the upper part of the basin, for hydropower generation (Bouillouses reservoir, 17 hm^3, no outflow data available). For the latter, the average daily principal spillway release rate was set to 1 m^3/s according to the average discharge at Mont-Louis gauging station (13 km downstream to Bouillouses dam).

The climate in the Têt basin is typical Mediterranean. In the upper part of the basin, the elevation above 2500 m.a.s.l. makes the area regularly snow-covered during winter (Garcia-Esteves et al., 2007; Kim et al., 2007). Daily temperature, humidity, wind speed, and radiation data were gathered from the SAFRAN (*Système d'Analyse Fournissant des Renseignements Adaptés à la Nivologie*) meteorological model with a 8 km x 8 km grid resolution (Durand et al., 1993; Quintana-Seguí et al., 2008; Vidal et al., 2010). Two hourly rainfall datasets were used: (i) the SAFRAN meteorological model simulation outputs (SAF) and (ii) rain gauges measurements (OBS). OBS data were collected from the operational hourly rain gauge network for flood monitoring purposes provided by the regional flood forecasting service for the Languedoc Roussillon region (SPCMO: *Service de Prévision des Crues Méditerranée Ouest*). The Figure 3 shows the spatial distribution of the rain gauges (OBS) and the grid (SAF) together with the monthly average rainfall. Monthly modelled SAF rainfall is similar to measured OBS rainfall, although slightly overestimated. Hourly precipitations from Climate Forecast System Reanalysis (CFSR) were first considered, but then discarded given the large overestimations (e.g. up to +85% in 2009) of rainfall over the whole catchment.

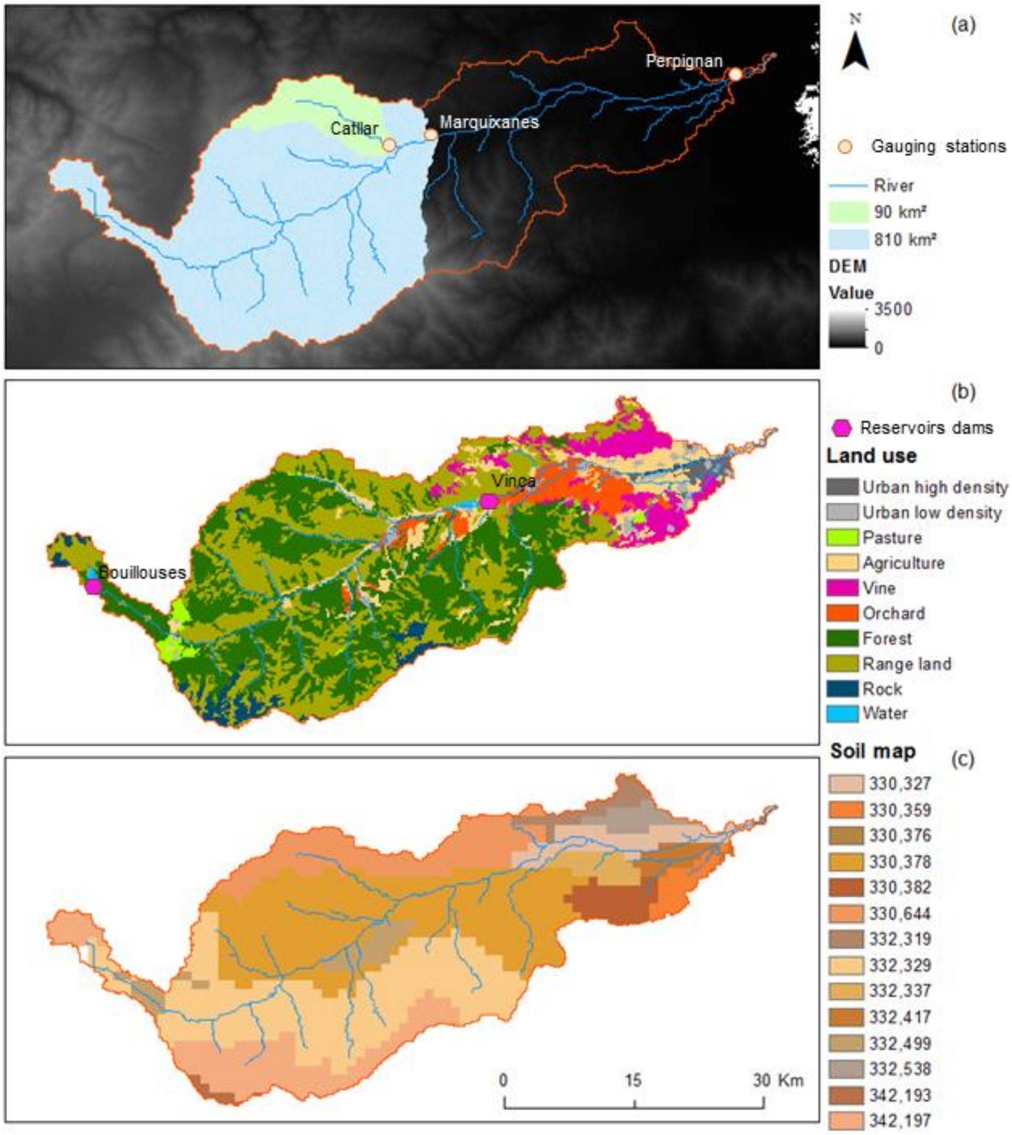


Figure 2. Properties of the Têt river basin (1,400 km²): (a) altitudes (m), sub-basins of interest (90 and 810 km²) and gauging stations; (b) land use and reservoirs; (c) soil classes.

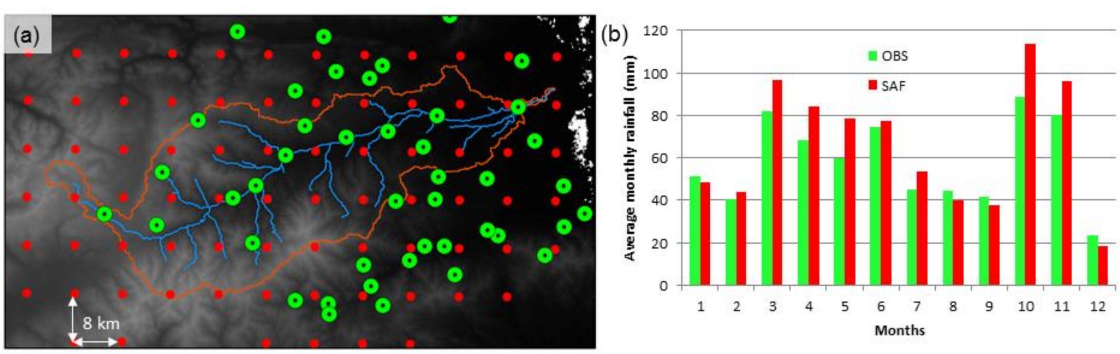


Figure 3. (a) Spatial distribution of rain gauges from measurements (OBS, green dots) and SAFRAN model (SAF, red dots); (b) Monthly rainfall at Marquixanes (2009-2011).

Sub-basins' delineations

Two sub-basins' delineations were used to assess the impact of rain gauges spatial distribution on models performances: (i) a minimal drainage area of 1,500 ha and (ii) a minimal drainage area of 100 ha (Figure 4). In the first case, 66 sub-basins including 549 Hydrological Response Units (HRUs) were delineated, and in the second one, 691 sub-basins with 2,342 HRUs.

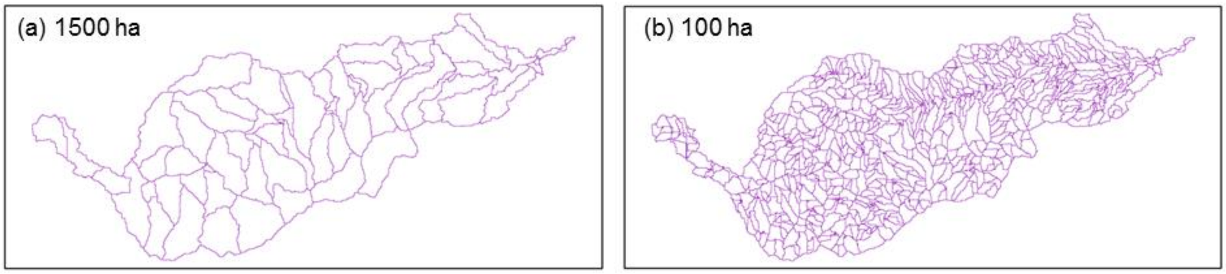


Figure 4. Sub-basin delineations with minimal drainage areas of (a) 1,500 ha and (b) 100 ha.

Hence, the SWAT project with the 1,500 ha minimal drainage area included 19 OBS rain stations and 25 SAF while the SWAT project with the 100 ha minimal drainage area included 20 OBS and 37 SAF.

Measured discharge for calibration

To calibrate the model, we compared the simulated discharge to the observed discharge (http://www.hydro.eaufrance.fr/) at 3 gauging stations (Catllar, Marquixanes and Perpignan outlets, Figure 2a), thus focusing the study on 3 embedded catchments of 90, 810 and 1,400 km^2, respectively. The 1,400 km^2 catchment is delimited by the Perpignan outlet which is located downstream the Vinça reservoir. The 810 km^2 catchment is delimited by the Marquixanes outlet which is just upstream the Vinça reservoir. The 90 km^2 catchment is not impacted by any infrastructure.

The number of hourly discharge measurements (2009-2011 period) at the 3 outlets is 14,977 at Catllar, 18,765 at Marquixanes and 25,909 at Perpignan. A 4 year warm up period (2005-2008) was used prior to the calibration period (2009-2011). In this preliminary study we did not deal with validation.

Parameters for SWAT-CUP autocalibration set up

The SWAT-CUP SUFI2 autocalibration tool (Abbaspour, 2014) was set up with 21 parameters described in Table 1. The autocalibration was performed at both daily and hourly time steps. Nash-Sutcliffe (NS) indices (Nash and Sutcliffe, 1970) were calculated to assess the performance of the simulation. At the same time, SWAT-CUP was used to assess the relative sensitivity of the 21 parameters.

Experimental design

In this study we considered 3 outlets, 2 rainfall data set, 2 sub-basin delineations and 2 time-steps (daily and hourly). Therefore, there were 24 combinations and hence, 24 calibrations performed for the 2009-2011 period (Appendix A).

Table 1. Parameters and ranges used for autocalibration and sensitivity analysis with SWAT-CUP. Two types of changes were used: "R" means the existing parameter value is multiplied by (1+ a given value); "V" means the existing parameter value is to be replaced by a given value.

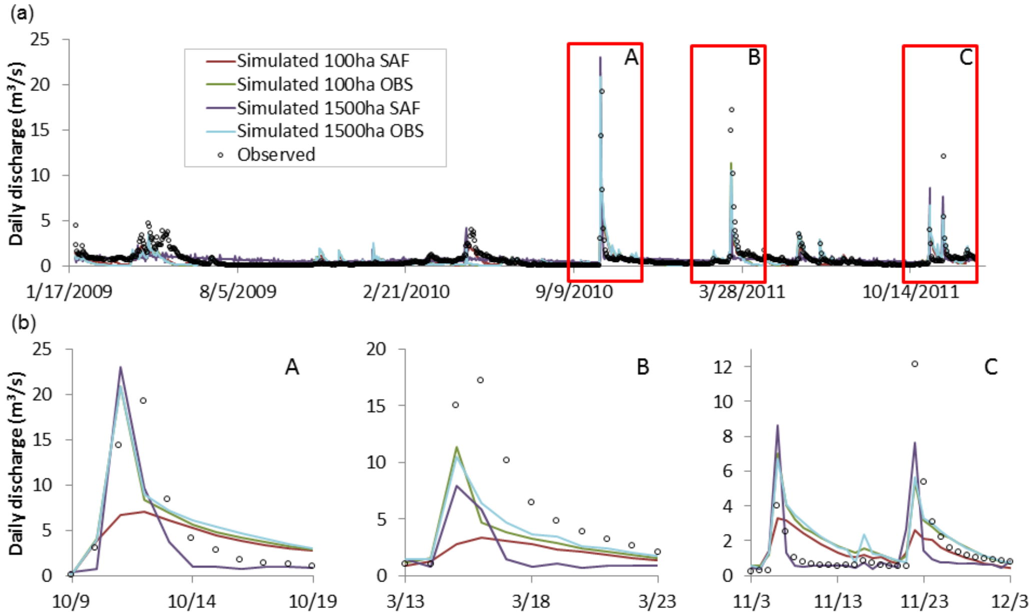
Parameter	Input file	Type of change	Min	Max	Units
CN2	.mgt	R	-0.1	0.1	-
ALPHA_BF	.gw	V	0.01	1	1/days
GW_DELAY	.gw	V	0	500	days
GW_REVAP	.gw	V	0.02	0.2	-
GWQMN	.gw	V	0	5,000	mm H_20
RCHRG_DP	.gw	V	0.01	0.99	-
REVAPMN	.gw	V	0	500	mm H_20
CH_K2	.rte	V	0.01	10	mm/hr
CH_N2	.rte	V	0.025	0.15	-
CH_K1	.sub	V	0.01	10	mm/hr
CH_N1	.sub	V	0.025	0.15	-
ESCO	.hru	V	0.7	0.9	-
EPCO	.hru	V	0.7	1	-
LAT_TTIME	.hru	V	0	180	days
CANMX	.hru	V	0	100	mm H_20
OV_N	.hru	V	0.01	0.6	-
SOL_K	.sol	R	0	9	mm/hr
SOL_AWC	.sol	R	-0.1	0.1	mm H_20/mm soil
SOL_BD	.sol	R	-0.1	0.1	g/cm^3
SOL_CBN	.sol	R	-0.1	0.1	%
SURLAG	.bsn	V	0.05	24	-

Results and discussion

Daily discharge at Catllar (90 km²)

The Figure 6 shows the daily discharge simulated from the 4 combinations of delineations and rainfall data, together with observed daily discharge, at Catllar outlet (90 km^2 catchment). The simulated discharge is in the range of the observed one for both low flow and high flow (Figure 6a). The NS indices for the 2009-2011 period are mostly over 0.5 (Table 2) and hence considered satisfactory (Moriasi et al., 2007).

The detail of the 3 major flood events during the 2009-2011 period shows that the highest values of NS were obtained (i) when using the 1,500 ha delineation regardless of the rainfall dataset or (ii) when using the measured rainfall dataset (OBS) regardless of the delineation (Figure 6b). The lower performance of the SAF dataset may be due to the meteorological model inconsistencies (Figure 3b) which could be smoothed by larger sub-basins delineations. However, the assessment of the uncertainty propagation of the meteorological model into the hydrological model was beyond the scope of this study.

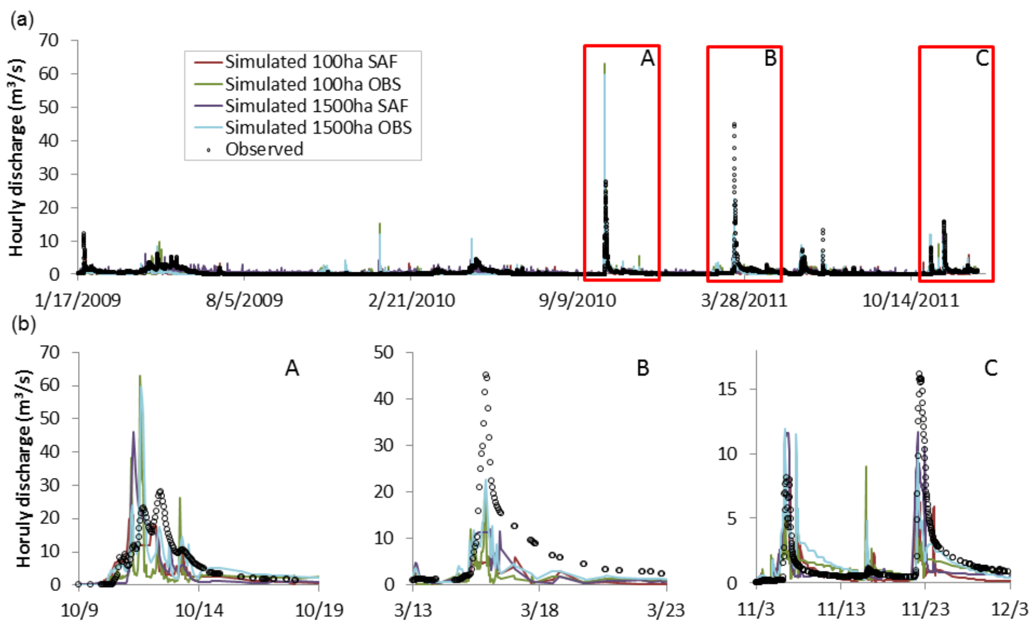


NASH	OBS	SAF
100 ha	0.65	0.59
1500 ha	0.65	0.64

NASH	OBS	SAF
100 ha	0.56	0.22
1500 ha	0.64	0.40

NASH	OBS	SAF
100 ha	0.48	0.28
1500 ha	0.50	0.55

Figure 6. Daily simulated discharge at Catllar outlet (90 km^2 catchment) with 2 rainfall dataset and 2 sub-basins delineations for (a) the 2009-2011 period and (b) the 3 major flood events (A, B and C) with respective Nash-Sutcliffe indices.



NASH	OBS	SAF
100 ha	-0.97	-0.02
1500 ha	-0.13	-0.41

NASH	OBS	SAF
100 ha	-0.11	-0.14
1500 ha	0.36	0.23

NASH	OBS	SAF
100 ha	0.06	0.18
1500 ha	0.28	0.40

Figure 7. Hourly simulated discharge at Catllar outlet (90 km^2 catchment) with 2 rainfall dataset and 2 sub-basins delineations for (a) the 2009-2011 period and (b) the 3 major flood events (A, B and C) with respective Nash-Sutcliffe indices.

Hourly discharge at Catllar (90 km²)

The hourly discharge simulated from the 4 combinations of delineations and rainfall data at the Catllar outlet (90 km^2 catchment) is in the range of the observed discharge for both low flow and high flow (Figure 7a). NS indices for the 2009-2011 period are positive, but below 0.5 (Table 2). The lower values of NS calculated for hourly discharge compared to the daily NS indices are explained by the higher degree of uncertainty when simulating discharge variations at smaller time step: the amplitude and the frequency of sub-daily discharge fluctuations are smoothed at daily time step. Despite lower NS values, hourly simulations seem to capture the timing of the flood peak more accurately than do daily simulations.

Similar to daily results, the details of the 3 major flood events during the 2009-2011 period show that the highest values of NS were mostly obtained (i) when using the 1,500 ha delineation regardless of the rainfall dataset or (ii) when using the measured rainfall dataset (OBS) regardless of the delineation (Figure 7b).

Summary of the performances

The Table 2 shows the performances (NS values) of the SWAT model for the 8 combinations at the outlets of the 3 embedded catchments. The overall performance at Catllar gauging station (90 km^2 catchment) is already described above. The performance is on the whole weaker for the 810 km^2 catchment, mostly with negative NS indices. One explanation could be that the constant 1 m^3/s daily outflow rate from the upstream Bouillouses reservoir is not accurate enough to simulate the discharge at the Marquixanes gauging station where average discharge is 8 m^3/s. The performance of the model at the Perpignan outlet (1,400 km^2 catchment) is mostly over 0.5. The combination of measured rainfall (OBS) and 1,500 ha sub-basin delineation gives the highest performance. However, the higher performance isn't surprising because the discharge at both daily and hourly time steps at the Perpignan outlet are fully controlled by the outflow from the Vinça reservoir (Figure 8): the Têt river acts like a pipe from the reservoir down to the gauging station with little flow contribution from the downstream area of the watershed. The weaker performances of the SAFRAN rainfall dataset (SAF) in comparison with the observed one (OBS) may be explained by its overall overestimation of rainfall, especially in the rainiest months (Figure 3b).

Most sensitive parameters

For each combination, the 3 most sensitive parameters are shown in Table 2. Only 9 parameters out of 21 seem to be sensitive, namely LAT_TTIME, CN2, GWQMN, RCHRG_DP, SOL_K, SOL_BD, SURLAG, ALPHA_BF and CH_N2. Three of them are directly related to the infiltration (and hence runoff) calculation with GAML equation (SOL_K, CN2 and SOL_BD).

Comparing one-by-one daily/hourly, 1,500 ha/100 ha and OBS/SAF rainfall datasets, the most sensitive parameter appear to be the soil saturated conductivity (SOL_K). Next is the curve number (CN2), and then the Manning "n" coefficient in the main channel (CH_N2). Discriminating by catchment size, and for the two upstream catchments, the most sensitive parameters are the soil saturated conductivity (SOL_K) and the lateral flow travel time (LAT_TTIME). Considering the whole Têt basin, the most sensitive parameters appear to be the Manning coefficient in the main channel (CH_N2) and the recharge from the deep aquifer percolation fraction (RCHRG_DP). Again, the difference in behavior is explained by the fact that the discharge at Perpignan outlet is fully controlled by the daily outflow from the Vinça reservoir.

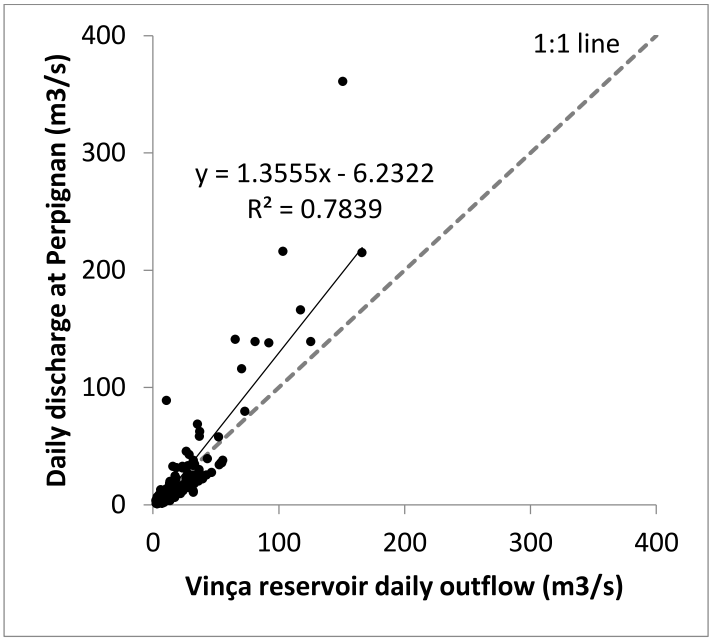


Figure 8. Daily outflow from Vinça reservoir and daily discharge at Perpignan gauging station (m^3/s).

Conclusions

For large catchments including reservoirs, the quality of the simulation depends on the quality of the daily dam discharge data (*.day file). For small catchments without reservoirs:

- Hourly simulations catch sub-daily discharge peaks but hourly model performances are lower than daily;
- Rainfall distribution and sub-basin delineation are sensitive model inputs. Simulations with measured rainfall (OBS) seem more reliable than the simulations with modelled precipitations grids (SAF), even though the SAFRAN model outputs had a finer grid resolution than the rain gauges network; it seems that there is no need to discretize the basin with a 100 ha minimal drainage area;
- The soil saturated hydraulic conductivity SOL_K appears to be the most sensitive parameter and needs to be accurately estimated.

The perspectives of this preliminary study are manifold:

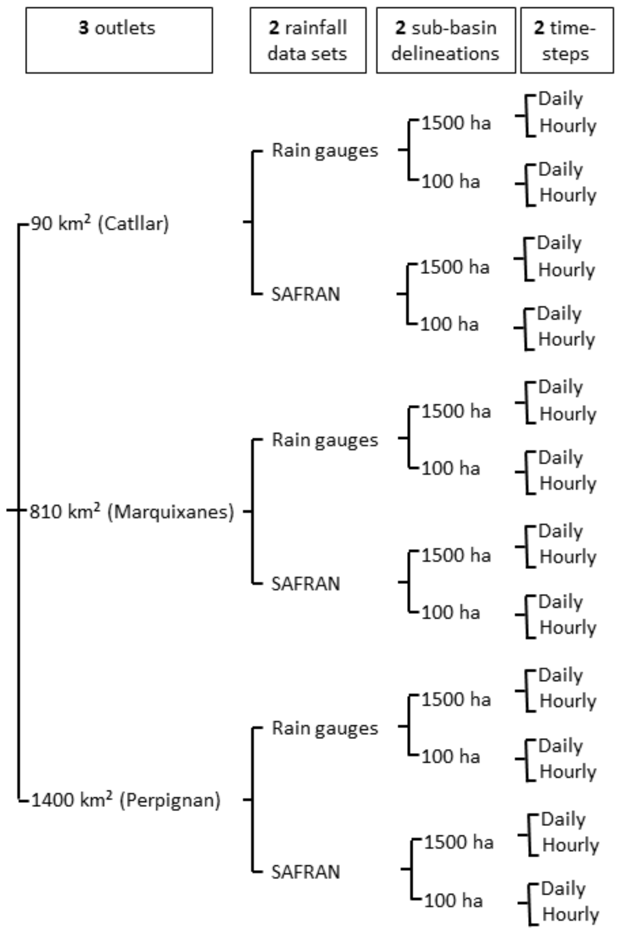
- Suspended sediments will be simulated at hourly time-step;
- The rainfall grid will be refined by using a 500 m x 500 m precipitation dataset from the Meso-NH meteorological model (Lafore et al., 1998);
- The results will be extended to the other coastal flash-flood prone basins of the Lion Gulf, to allow estimating hourly sediments loads into the Mediterranean Sea and their possible detrimental effect on marine ecosystems.

Table 2. Performances of the SWAT model (expressed as NS index calculated over the 2009-2011 period) and most sensitive parameters with final values for the 24 combinations of sub-basins, rainfall datasets and minimal drainage area.

Outlet	Rainfall data	Min. drain. area	NS index		Most sensitive parameters (final values)	
(km²)		(ha)	Daily	Hourly	Daily	Hourly
90	SAF	1,500	0.50	0.38	LAT_TTIME (116) CN2 (0.06) GWQMN (475)	CN2 (0.06) SOL_K (0.31) LAT_TTIME (116)
		100	0.45	0.29	LAT_TTIME (6) CN2 (0.06) GWQMN (3,875)	CN2 (0.08) LAT_TTIME (2.7) SOL_K (3)
	OBS	1,500	0.55	0.40	SOL_K (8) LAT_TTIME (6) SOL_AWC (0.04)	SOL_K (6) CH_N2 (0.13) SURLAG (16)
		100	0.52	0.14	SOL_K (8) LAT_TTIME (6) GWQMN (3,875)	SOL_K (6) CN2 (-0.04) SURLAG (16)
810	SAF	1,500	-0.86	-1.00	SOL_K (5) CN2 (-0.05) SOL_AWC (0.06)	SOL_K (5) CH_N2 (0.14) CN2 (-0.05)
		100	0.46	0.18	SOL_K (5) GWQMN (625) ALPHA_BF (0.69)	SOL_K (6) SURLAG (9) ALPHA_BF (0.72)
	OBS	1,500	-0.55	-1.12	SOL_K (5) CN2 (-0.05) CH_N2 (0.14)	SOL_K (5) CH_N2 (0.14) CN2 (-0.05)
		100	-0.75	-0.93	SOL_K (6) CN2 (0.01) SOL_BD (0.04)	SOL_K (6) CN2 (0.01) SOL_BD (0.04)
1,400	SAF	1,500	0.35	0.24	SOL_K (5) RCHRG_DP (0.50) GWQMN (625)	CH_N2 (0.13) RCHRG_DP (0.28) GWQMN (4,775)
		100	0.78	0.68	SOL_K (3) CH_N2 (0.05) RCHRG_DP (0.04)	CH_N2 (0.15) RCHRG_DP (0.09) CN2 (-0.02)
	OBS	1,500	0.56	0.38	CH_N2 (0.05) SOL_K (0.05) GWQMN (2,375)	CH_N2 (0.11) RCHRG_DP (0.64) GWQMN (4,275)
		100	0.62	0.52	CH_N2 (0.15) LAT_TTIME (26) SOL_BD (0.04)	CH_N2 (0.11) LAT_TTIME (33) SOL_K (8)

Acknowledgements
This research was supported by the CRUE-SIM project, funded by the Fondation RTRA-STAE and by the the National EC2CO Programme Biohefect/Ecodyn/Dril/Microbien (Multi-scale modelling to quantify the role of wetlands on biogeochemical transfers across watersheds). We thank the *Service de Prévision des Crues Méditerranée Ouest* in Carcassonne for rain gauge measures records and INRA Infosol for soil properties. LB also sincerely thanks Yves Auda and Grégory Espitalier-Noël for data processing.

Appendix A: Experimental design of the autocalibration process: 24 calibrations (2009-2011) corresponding to 24 combinations of outlets, rainfall data sets, sub-basin delineations and time-steps.



References

Abbaspour, K.C. 2014. SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs - A User Manual. EAWAG, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland. 106p.

Arnold, J.G., D.N. Moriasi, P.W. Gassman, K.C. Abbaspour, M.J. White, R. Srinivasan, C. Santhi, R.D. Harmel, A. Van Griensven, M.W. Van Liew, and others. 2012. SWAT: Model use, calibration, and validation. *Trans. ASABE* 55(4): 1491–1508.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment. I. Model development. *J. Am. Water Resour. Assoc.* 34(1): 73–89.

Durand, Y., E. Brun, G. Merindol, G. Guyomarc'h, B. Lesaffre, and E. Martin. 1993. A meteorological estimation of relevant parameters for snow models. *Ann. Glaciol.* 18: 65–71.

Furl, C., H. Sharif, and J. Jeong. 2015. Analysis and simulation of large erosion events at central Texas unit source watersheds. *J. Hydrol.* 527: 494–504.

Garcia-Esteves, J., W. Ludwig, P. Kerhervé, J.-L. Probst, and F. Lespinas. 2007. Predicting the impact of land use on the major element and nutrient fluxes in coastal Mediterranean rivers: The case of the Têt River (Southern France). *Appl. Geochem.* 22(1): 230–248.

INRA. 1998. Base de Données Géographique des Sols de France, version 1.0 du 10/09/1998. Inra, Infosol, Orléans, France.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535p.

IPCC. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Final draft dated 28 October 2013.

Jarvis, A., H.I. Reuter, A. Nelson, and E. Guevara. 2008. Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from http://srtm.csi.cgiar.org.

Jeong, J., N. Kannan, J. Arnold, R. Glick, L. Gosselink, and R. Srinivasan. 2010. Development and Integration of Sub-hourly Rainfall–Runoff Modeling Capability Within a Watershed Model. *Water Resour. Manag.* 24(15): 4505–4527.

Jeong, J., N. Kannan, J.G. Arnold, R. Glick, L. Gosselink, R. Srinivasan, and R.D. Harmel. 2011. Development of sub-daily erosion and sediment transport algorithms for SWAT. *Trans. ASABE* 54(5): 1685–1691.

Jeong, J., J.R. Williams, W.H. Merkel, J.G. Arnold, X. Wang, and C.G. Rossi. 2014. Improvement of the Variable Storage Coefficient Method with Water Surface Gradient as a Variable. *Trans. ASABE* 57(3): 791–801.

Kim, J.-H., W. Ludwig, S. Schouten, P. Kerhervé, L. Herfort, J. Bonnin, and J.S. Sinninghe Damsté. 2007. Impact of flood events on the transport of terrestrial organic matter to the ocean: A study of the Têt River (SW France) using the BIT index. *Org. Geochem.* 38(10): 1593–1606.

Lafore, J. P., J. Stein, N. Asencio, P. Bougeault, V. Ducrocq, J. Duron, C. Fischer, P. Hereil, P. Mascart, J. P. Pinty, J. L. Redelsperger, E. Richard, and J. Vila-Guerau de Arellano. 1998: The Meso-NH Atmospheric Simulation System. Part I: Adiabatic formulation and control simulations. *Annales Geophysicae* 16: 90-109.

Maharjan, G.R., Y.S. Park, N.W. Kim, D.S. Shin, J.W. Choi, G.W. Hyun, J.-H. Jeon, Y.S. Ok, and K.J. Lim. 2013. Evaluation of SWAT sub-daily runoff estimation at small agricultural watershed in Korea. *Front. Environ. Sci. Eng.* 7(1): 109–119.

Mein, R., and C. Larson. 1973. Modeling infiltration during a steady rain. *Water Resour. Res.* 9(2): 384–394.

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50(3): 885–900.

Nash, J.E., and V. Sutcliffe. 1970. River flow forecasting through conceptual models. Part I - A discussion of principles. *J. Hydrol.* 10: 282–290.

Quintana-Seguí, P., P. Le Moigne, Y. Durand, E. Martin, F. Habets, M. Baillon, C. Canellas, L. Franchisteguy, and S. Morel. 2008. Analysis of Near-Surface Atmospheric Variables: Validation of the SAFRAN Analysis over France. *J. Appl. Meteorol. Climatol.* 47(1): 92–107.

Roux, H., D. Labat, P.-A. Garambois, M.-M. Maubourguet, J. Chorda, and D. Dartus. 2011. A physically-based parsimonious hydrological model for flash floods in Mediterranean catchments. *Nat. Hazards Earth Syst. Sci.* 11(9): 2567–2582.

Vidal, J.-P., E. Martin, L. Franchistéguy, M. Baillon, and J.-M. Soubeyroux. 2010. A 50-year high-resolution atmospheric reanalysis over France with the Safran system. *Int. J. Climatol.* 30(11): 1627–1644.

Wösten, J.H.M., A. Lilly, A. Nemes, and C. Le Bas. 1999. Development and use of a database of hydraulic properties of European soils. *Geoderma* 90: 169–185.

Modeling Dynamic Soil Properties in APEX for U.S. Soil Survey

Candiss O. Williams
U.S. Department of Agriculture, Natural Resources Conservation Service, Charles Kellogg Soil Survey Laboratory, 100 Centennial Mall North, Lincoln, NE

Skye Wills
U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Center, 100 Centennial Mall North, Lincoln, NE

Evelyn Steghlich
U.S. Department of Agriculture, Natural Resources Conservation Service, Blackland Research Station, Temple, TX

Abstract

Historically, soil survey products described inherent soil properties for an entire soil profile under common land use. The National Cooperative Soil Survey (NCSS) recognizes the need to provide enhanced information about soil change in response to land use, management or climate changes. Projects are ongoing to collect and aggregate dynamic soil properties (DSPs). These projects focus on surface layers that respond most rapidly to changes in management or land use. While changes in DSPs are best measured over time through long-term studies and monitoring, changes in DSPs can be estimated using soil survey methods by careful space-for-time substitution comparing land use or management conditions (i.e. vegetation, tillage, chemical, and organic inputs) on the same soil. A combination of modeling and data collection will allow soil survey to quickly populate a comprehensive DSPs database and inform conservation tools. APEX, a comprehensive model (weather, hydrology, soil erosion-sedimentation, plant growth, nutrient cycling, soil temperature, soil moisture, tillage, and plant environment control) was evaluated for use in populating DSPs for soil survey. Soil survey DSPs can be used in conservation tools to assist land managers in their evaluations of likely management impacts on soil properties. Of particular interest is the resistance and resilience of soils to change when disturbed by cultivation.

Keywords: APEX, soil survey, soil change, dynamic soil properties.

Introduction

Soil survey data is increasingly used by land managers and policy makers to evaluate land management on natural resources (Karlen et al., 1997). Historically, soil survey has collected information on inherent soil properties for an entire soil profile under common land use (i.e. agriculture, forestry) used primarily for inventory and interpretations. Increased knowledge of soils and application of soil information to other than agricultural uses, such as land use planning, environmental concerns, food security, energy security, water security, and human health, among others, requires new ways to communicate what we know about mapped soils (Brevik et al., 2015) and this would require the collection of management data beyond land use. Soil survey recognizes the need to collect information on land management effects on soil properties to address critical natural resource management needs. This includes capturing cultural information about the soils being evaluated to document soil change. Soil change has been defined as temporal variation in soil properties at a specific location at the human time scale as a result of disturbance (Tugel et al., 2005). Disturbance represents activities that could modify morphology, composition, or processes, and the capacity of a soil to function (Karlen et al., 1997; Seybold et al., 1999; Tugel et al., 2005). Soil properties that change with land use or management practice change are use-dependent and are referred to as dynamic soil properties (Grossman et al., 2001). Dynamic soil properties are important to U.S. soil survey because changes to these properties affect the capacity of the soil to function. While changes in dynamic soil properties have been traditionally measured over time through long-term studies and monitoring, potential changes in dynamic soil properties are being estimated using soil survey methods by careful space-for-time substitution comparing land use or management conditions (i.e. vegetation, tillage, climate) on the same soil. Soil survey is also evaluating incorporating predictive models to provide comprehensive information about the range of soil and management conditions and to complement theoretical models that hypothesize causes and effects of soil change by predicting the time frame in which it takes for changes in soil properties to be measureable as a result of disturbance. Predictive modeling can also assist U.S. soil survey to extrapolate from current soil conditions to potential future soil conditions.

Soil Survey and Dynamic Soil Properties

Soil survey data has gone through many stages but the procedures for mapping, classification, correlation, interpretation, and publication have remained consistent (NSSH – 627.03; USDA, 2015). Soil survey collects information about the position of a soil on the landscape, its profile characteristics, relationship to other soils, suitability for various uses, and needs for types of land management (NSSH – 627.03; USDA, 2015). Soil survey organizes the soil information based on mapping units which have common soil properties, characteristics, and classification and differ from other mapping units in some way (NSSH – 627.03; USDA, 2015). Soil survey currently assigns information related to typical land use (agriculture, forestry, military) at time of sampling and correlation to map units (Brevik et al., 2015); management information is not captured. To incorporate land management into soil survey, information must be associated to soil map units.

It is well understood that mapping units behave differently in response to differing land management (Bouma, 1994; Wills et. al, 2015) which supports the need to collect the information that will aide land managers and policy makers in applying sustainable practices. The U.S. soil survey is addressing this through the systematic measurement of use dependent variables (Grossman et al., 2001) commonly referred to as dynamic soil properties. Dynamic soil properties are properties that change with land use or management practice change within the human time scale (Tugel et al., 2008). Differences in these properties can impact soil performance. Tugel et al. (2008) formalized a systematic approach (Soil Change Guide) for U.S. soil survey to collect DSPs to assist soil scientists and others collect interpretable data about soil change by developing a guide that describes a sampling system that measures DSPs for most major land use types.

The procedures in the Soil Change Guide (Tugel et al., 2008) are designed to capture the change that occurs due to management through a space-for-time sampling strategy using locations having the same soil type but different conditions (land use and management). The Soil Change Guide defines fluctuation as the temporal variation in soil properties that can be related to seasonal climatic factors or changes in management. Only short-term monitoring can determine fluctuation, and it is not currently a focus of soil survey. The Soil Change Guide defines trend as the general direction of change and can be increasing, decreasing, or steady-state equilibrium. Trend is commonly observed through long-term monitoring studies but can be inferred through comparison studies of two systems that had the same initial conditions such as the comparison studies that evaluate DSPs Rate reflects the changes in process which is commonly not constant. For example, a land manager may want to know the yearly change of soil organic carbon on their land. Thresholds are an important ecological concept. A threshold is crossed when process rates have changed and ecological feedbacks are such that the state of the system has been changed (Bestelmeyer, 2006; Tugel et al., 2008) Once a threshold has been crossed, the altered state of the system is such that potential functions and soil properties have been fundamentally altered.

Soils information gathered from these attributes have historically come from long-term studies, however, soil survey can also provide information for these types of soil change attributes by coupling space-for-time field sampling and strategies with predictive modeling. Here we explore the use of the Agricultural Policy Environmental eXtender (APEX) model to simulate temporal trends in DSPs, direction of soil change, rate of soil change, and the threshold of soil change.

Dynamic Soil Property Data Needs

For consistency and comparability of data amongst DSP studies, a minimum data set was developed (Soil Change Guide). In order for DSPs to be included in the minimum data set, they had to meet the following criteria: the soil property should be sensitive to disturbances or management within the human time scale; the relationship between soil properties and the functions they reflect should be clearly defined; they should be insensitive to daily or seasonal fluctuations in environmental conditions unless the fluctuations are well-understood and can be predicted; the soil properties should be easy to measure accurately and precisely, and be repeatable; and the collection and analysis of the data should be cost and time efficient. The dataset for current DSP studies include soil organic matter, pH, EC, bulk density and soil porosity, structure and macropores, aggregate stability, and total N. Other physical, chemical, and biological soil properties analyzed are included in table 1 and may not be analyzed for all sites. Soil properties important for data interpretation are also analyzed and include soil horizon thickness, particle size distribution, rock fragments, CEC, and mineralogy.

Table 1. Soil property information analyzed for DSP studies to include the minimum data set. Highlighted properties are those that APEX simulates with time.

PHYSICAL PROPERTIES	CHEMICAL PROPERTIES	BIOLOGICAL PROPERTIES
Particle Size	**Soil organic matter**	β-glucosidase
Bulk Density	**pH**	Permanganate extractable carbon
Infiltration	Ca Mg, Na, K	Particulate organic matter
Aggregate stability	Exchangeable Na	
Soil moisture	As, Co, Cr, Cu, Zn, Hg, Al, Fe, Mn, Sr	
Ksat	Readily available P	
	$CaCO_3$	

APEX Model

The ability of models to predict future soil conditions is very useful to U.S. soil survey. Modeling is therefore a complementary tool to DSP field studies. In the case of U.S. soil survey, models are a reflection of our understanding of management and land use impacts on soil properties. As with any predictive tool, results from model simulations are dependent on how they are applied and the quality of the simulated outputs are as good as the quality of the user’s understanding of the tool and the processes contained within. For the purposes of U.S. soil survey, predictive models are necessary to evaluate differences in management on soil properties and the time and conditions it takes for soil properties to change.

The Agricultural Policy Environmental eXtender (APEX; Williams et al., 1995; Williams et al., 2015) model was developed for use in whole farm and small watershed management. The model was constructed to evaluate various land management strategies considering sustainability, erosion (wind, sheet, and channel), economics, soil quality, water quantity and quality, pests, plant competition, and weather. Management capabilities of interest to NRCS include irrigation, drainage, furrow diking, filter strips, terraces, waterways, fertilization, manure management, crop rotation and selection, herbicide application, grazing, and tillage. In addition to these farm management functions, APEX can be used to evaluate the effects of alternative climate change scenarios. APEX operates on a daily time step and is an extension of the Environmental Policy Integrated Climate (EPIC) model which is capable of simulating drainage areas that are characterized by homogenous crop management, landscape, soil, weather, and management system parameters. The model can be run at either a field or watershed scale. APEX allows the user to divide the landscape into fields, each with its own soil type, landscape position, management, weather, or other desirable configuration. APEX enables dynamic soil layers associated with soil erosion and removal of eroded material, and it provides eight options (including RUSLE 2) for estimating water erosion. APEX simulates tillage with functions for mixing nutrients and crop residue, and changing bulk density.

Why use APEX to populate DSPs for Soil Survey?

APEX was chosen to populate DSPs for soil survey due to an extensive assessment of its performance for estimating impacts of conservation practices conducted by USDA-NRCS Conservation Effects Assessment Project (CEAP) Modeling Team (Wang et al., 2011). The Conservation Effects Assessment Project was initiated by the USDA in response to a general call for better accountability of how society would benefit from the conservation program funding (Mausbach and Dedrick 2004; Duriancik et al., 2008). Soil survey is interested in inventorying soils with great extent (i.e. benchmark soils) and current activities with CEAP cropland, grazing land, and wetland assessments have been conducted on these soils. This provides soil survey with benchmark databases for comparisons with space-for-time studies currently underway. In addition, the value of APEX to U.S. soil survey is that many of the model's input parameters can be measured, therefore, an ability to obtain satisfactory model validation without adjusting measured parameters. This provides great value to soil survey because of the need to understand changes in soil properties as it relates to land management. As mentioned previously, the use of simulation models to predict soil change in response to management is beneficial to answer questions related to soil change attributes: rate, trend, fluctuation, and threshold.

Modeling Strategy

The U.S. soil survey program has chosen the space-for-time comparison study approach to document the effects of land management over time. It is fully explained in the Soil Change Guide: Procedures for Soil Survey and Resource Inventory (Tugel et al., 2008). A study is conducted for an important extensive soil (i.e. benchmark soil) within a management zone. Data (management history and soil properties) collected from study sites is then used to initialize the APEX model. APEX input variables include weather, land use, management, soil properties by layer, and site information. Required weather variables to execute the model include daily precipitation, maximum and minimum air temperature, and solar radiation. Solar radiation can be generated internally in APEX using monthly weather statistics developed for a specific site. Climate information can be obtained from historical datasets and modeled datasets (i.e. PRISM). Required soil variables include layer depth (user defined), bulk density, wilting point, field capacity, percentage sand and silt, percentage organic C, and pH. Required management information includes planting and harvest dates, tillage type and dates, and fertilizer applications and dates. It is important to note that predictive models may not work well for every scenario, but the outputs are only as good as model inputs.

Many of the soil input variables required for APEX are measured as part of the DSP minimum data set. Other input variables may be collected from measured laboratory data, SSURGO, weather stations, and land owners. The APEX model simulates changes in soil properties as a result of on-field management and include organic C (simulates the complete C cycle), bulk density, and total N (simulates the complete N cycle). Additional soil properties simulated in APEX with output variables include soil moisture, total P, infiltration (soil porosity), and soil loss from water and wind erosion (aggregate stability).

Verifying and Validating APEX

The field-scale application of APEX for DSP studies for soil survey will simulate one soil with multiple management scenarios. For example, a DSP soil survey study would select a representative soil (e.g. Crooksford soil series), ideally one that has wide extent and is representative (benchmark) of the area (Tugel et al., 2008; USDA, 2015). Three management scenarios are then evaluated which represent the area of interest, with one site being the reference. The reference site represents the natural state or highest functioning/least disturbed managed or naturalized state (i.e. native grasses) which is compared (space-for-time) with one or two alternative states or management scenarios (i.e. conventional tillage corn).

DSP study sites are located on land that has been under consistent management for 10 years or until a steady equilibrium in soil properties is expected to have been met. Initial model inputs would come from measured soil data (minimum data set), management records (crop yields, soil fertility reports, soil survey reports), and climate records for the area being evaluated. Evaluation of the model would utilize parameterizations used for CEAP in addition to data collected from the land managers (crop yield, soil test reports). When measured data are not available to validate the model, parameterization of the simulations can be gleaned from literature, previous experience, or studies near the area of interest with closely matched field characteristics, management, and observed weather, similar to that used in the CEAP cropland study (Wang et al, 2011; Wang et al., 2012). The validated model would then be used to evaluate alternative management scenarios. For example, DSP studies compare at least 2 states, a reference (best representative of least disturbance), and one or two alternatives (such as cropping management scenarios). Depending on project objectives, the scenario simulations in APEX would be conducted by simulating each the reference and alternative sites and then replacing each scenario simulation with the other. The effects of management on soil properties for each of the scenarios would then be compared from each of the APEX outputs. Simulated changes in organic C, total N, bulk density, soil loss, and infiltration among others would then be compared.

In addition to the data analyzed from the space-for-time comparison studies and used to initialize APEX, the model is able to then gauge fluctuation, capture overall trend, estimate rate, and identify threshold attributes. Coupling the comparison studies with the use of models such as APEX, the following questions can then be answered:

1. What is the condition of the soil?
2. If degraded, can it be restored?
3. How long will it take?
4. What land uses are at risk of irreversible change?

In addition to addressing these, DSPs would be populated using APEX predictions over time (could be collected daily, monthly, and/or yearly). The information can then be used to assist land managers and policy makers assess how soil changes impact future management options.

Summary

The NCSS has recognized the need to address the impact of management on soil properties by collecting Information about DSPs. Collecting information on DSPs in combination with existing soil survey information, can be used to interpret and predict the effects of human activities and management on soil function within the human time scale. The use of predictive models can be then used to fill in gaps to answer questions related to the condition of the soil and the length of time for changes in soil properties to be measurable. Field projects across the U.S are underway to collect and aggregate DSPs with focus on surface layers that respond most rapidly to changes in management or land use. The use of APEX as a tool to evaluate management practices indicates that it may provide useful information that would aid decision makers in identifying, targeting, are recommending site-specific conservation practices and systems and identify soils at risk of irreversible change. The combination of field studies and predictive models will assist U.S. soil survey to maintain high quality soils information, productive soils, and a healthy environment. The outcomes of these projects along with interpretations can help meet customer needs which include soil products for education, management, and policy.

References

Bestelmeyer, B.T. 2006. Threshold concepts and their use in rangeland management and restoration: The good, the bad, and the insidious. Restor. Ecol. 14(3):325-329.

Bouma J., P. Droogers P. 2007. Translating soil science into environmental policy: A case study on implementing the EU soil protection strategy in The Netherlands. Environmental Science and Policy 10:454–463.

Brevik, E.C., C. Calzolan, B.A. Miller, P. Pereira, C. Kabala, A. Baumgarten, and A. Jordán. 2015. Soil mapping, classification, and pedologic modeling: History and future directions. Geoderma. *In Press*.

Duriancik, Lisa F.; Bucks, Dale; Dobrowolski, James P.; Drewes, Tom; Eckles, S. Diane; Jolley, Leonard; Kellogg, Robert L.; Lund, Daryl; Makuch, Joseph R.; O'Neill, Michael P.; Rewa, Charles A.; Walbridge, Mark R.; Parry, Roberta; and Weltz, Mark A., "The first five years of the Conservation Effects Assessment Project" (2008). P*ublications from USDA-ARS / UNL Faculty.* Paper 289.

Grossman, R.B., D.S. Harms, C.A. Seybold, and J.E. Herrick. 2001. Coupling use-dependent and use-invariant data for soil quality evaluation in the United States. J. Soil Water Conserv. 56:63-68.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Sol Quality: A concept, Definition, and Framework for Evaluation. Soil Sci. Soc. Am. J. 61:4-10.

Mausbach, M.J., and A.R. Dedrick. 2004. The length we go—measuring environmental benefits of conservation practices. Journal of Soil and Water Conservation 59(5):96A-103A.

Seybold, C.A., J.E. Herrick, and J.J. Brejda. 1999. Soil resilience: a fundamental component of soil quality. Soil Science 164: 224-234.

Tugel, A.J., J.E. Herrick, J.R. Brown, M.J. Mausbach, W. Puckette, and K. Hipple. 2005. Soil Change, Soil Survey, and Natural Resources Decision Making: A Blueprint for Action. Soil Sci. Soc, Am. J. 69:738-747.

Tugel, Arlene J., Skye A. Wills, and Jeffrey E. Herrick. 2008. Soil Change Guide: Procedures for Soil Survey and Resource Inventory, Version 1.1. USDA, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

U.S. Department of Agriculture, Natural Resources Conservation Service. National soil survey handbook (NSSH), title 430-VI. Available online. Accessed June 8, 2015.

Wang, X., N. Kannan, C. Santhi, S. R. Potter, J. R. Williams, and J. G. Arnold. 2011. Integrating APEX output for cultivated cropland with SWAT simulation for regional modeling. Transactions of the ASABE 54(4): 1281-1298.

Wang, X., J.R. Williams, P.W. Gassman, C. Baffaut, R.C. Izaurralde, J. Jeong, and J.R. Kiniry. 2012. EPIC and APEX: Model Use, Calibration, and Validation. Transactions of the ASABE. 55(4):1447-1462.

Williams, J. R. 1995. The EPIC model. In *Computer Models of Watershed Hydrology*, 909-1000. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Williams, J.R., R.C. Izaurralde, C.O. Williams, and E.M. Steglich. 2015. Agricultural Policy/Environmental eXtender Model: Theoretical Documentation Version 0604. BREC Report No. 2008-17. Texas A&M University. Blackland Research and Extension Center, Temple, TX.

Williams, J.R., J.G. Arnold, and R. Srinivasan. 2000. The APEX Model. BREC Rep. No. 00-06. Texas A&M University. Blackland Research and Extension Center, Temple, TX.

Wills, S.A., C.O. Williams, C. Seybold, L. Scheffe, Z. Libohova, D. Hoover, C. Talbot, and J.R. Brown. 2015. Using Soil Survey to Assess and Predict Soil Condition and Change. In Proceedings of the Global Soil Security Symposium of Soil Science Society of America at Texas A&M University, May 19-21, 2015

IDENTIFICATION OF ENVIRONMENTALLY SENSITIVE AREAS AND SUBSIDIES TO A MANAGEMENT PLAN FOR WATERSHED THROUGH MODELING TECHNIQUES AND GIS

MACHADO, R.E.
School of Technology/UNICAMP
machado@ft.unicamp.br
RIBEIRO, L. C. L. J.
School of Technology/UNICAMP
LOPES, M. S.
School of Technology/UNICAMP

Abstract

The indiscriminate removal of original vegetation has generated serious environmental degradation, especially for agricultural and livestock occupations. An example is the siltation of rivers and water sources deterioration that supply cities and rural areas lending themselves to various projects. The Pinhal stream water source for Limeira city (State of São Paulo, Brazil) falls within this context, as it suffers from degradation in the region. This work is the first to identify using GIS (Geographic Information System) technique three Environmentally Sensitive Areas (ESA's) that have suffered a degradation process in the Pinhal watershed. Using the Soil and Water Assessment Tool (SWAT) we carried out simulations with current and alternative land scenarios, considering the ESA's identified in the study that are protected by forest cover. The simulated scenarios were compared with the current scenario condition in terms of sediment and water production. There was a significant reduction in the production of sediments between scenarios, while the water availability in the watershed was also reduced.

Keywords: mathematical models, pollution from diffuse sources, GIS.

1. INTRODUCTION

Environmental degradation has become a problem in the entire world. The deterioration of water quality by pollution from point sources and non-point (diffuse) has become one of the biggest environmental problems (Meijerink et al., 1994). Agriculture has been identified as the largest contributor of water resources pollution from non-point source. Agricultural pollution extension is difficult to assess because of its non-point nature (Ribaudo, 1998).

Despite efforts done to mitigate adverse impacts of agriculture an investigation in the real system is, in most cases, impossible to be conducted. This happens due to the long-term pilot projects and high costs of measurement and monitoring. Real system investigation involves measurements of all variables that influence a process on a larger scale (Person, 1997). Therefore, to identify areas with diffuse pollution problems in watersheds models are being increasingly and frequently used.

Hydrological and water quality models have been developed to predict the impact of agriculture on the quality of surface and groundwater. The increasingly demand in the use, proposition and validation of real mathematical models and simulators exists because the possibility of creating alternative scenarios, many of them still unexplored in real experiments.

Soil and Water Assessment Tool (SWAT) is a relatively new model been used in many parts of the world for different applications. SWAT allows great flexibility in setting up river watersheds (Peterson & Hamlett, 1998). Its model was developed to predict the effect of different management scenarios on water quality, sediment yield and pollutant loads in agricultural watersheds (Srinivasan & Arnold, 1994). The SWAT considers the watershed divided into sub-watersheds based on relief, soil and land use. Thus, SWAT keeps the homogeneous characteristics inside the watershed and the spatially distributed parameters of the entire watershed.. Many researches related whit SWAT applications have shown promising results (Arnold & Srinivasan, 1994; Rosenthal et al, 1995; Cho et al., 1995).

Machado et al. (2003a and 2003b) and Machado & Vettorazzi (2003) simulated runoff, sediment yield and alternative scenarios of land use in the watershed Ribeirão dos Marins (Piracibaca tributary river) in the biennium 1999-2000 using the SWAT model. Simulation results show the monthly average water flow and sediment yield compared to the observed data of a gauge station located in the upper third of the watershed. The comparison used the efficiency coefficient of Nash and Sutcliffe (COE) and the deviation of simulated data to the observed data (Dv). Simulations of two alternative scenarios of land use were compared with the conditions of the current usage scenario in terms of reducing sediment yield. According to the authors, simulations and GIS models allow not only evaluate simulated data and observed data but also make simulations with scenarios to explore the possible effects of land use changes in the context of dynamics landscape. These scenarios can form the basis of alternative management analysis aimed at reducing the impact of human activities in watersheds.

Lessa et al. (2014) evaluated the spatial dependence ratio of the average production of sediments and water for six years generated by the SWAT model. The study was conducted in the early part of the Rio Parto – SP watershed and a geostatistical tool was used to check and quantify the degree of dependence spatial data production of sediment and water using variograms and maps interpolated by kriging.

The major limitation to the use of these models is the difficulty in working with many data describing the heterogeneity of natural systems. The complexity of handling large volumes of spatial and non-spatial data can limit the use of distributed parameters models.

For these reasons Geographic Information Systems (GIS) are used in database creation for these models. Using GIS successive analyzes of spatial data can split large heterogeneous areas in small hydrologically homogeneous units, which models are applied (Tim, 1996). Models have been interfaced to GIS since the mid-1980s, but from the beginning of the 1990s many simulation models of sediment and non-point pollution have been applied in combination with GIS. This combination enable spatial and temporal analyzes, which determine the ability of these systems to improve and provide information on erosion and pollution. Hydrological modeling and water quality together with GIS have evolved to a point where the advantages of each system can be fully integrated into a powerful tool for watersheds analysis.

This work aims to identify the Environmentally Sensitive Areas (ESAs) in the watershed under study and simulate alternative scenarios of land use and compare them with the current usage scenario taking in account the production of sediment and water.

2. METHODOLOGY

2.1 Study area and input data

The Ribeirão Pinhal watershed is located in Peripheral Depression of the State of São Paulo and it belongs to Limeira-SP city (22º33'52 "south latitude and 47º24'17" West longitude). It has an area of approximately 300 km^2 (Figure 1) and altitudes ranging between 520 and 740 m (Figure 2). The Pine is a Jaguari tributary river, which is a Piracicaba tributary river, and assumes importance for its supply capacity for Limeira-SP city.

The local climate is tropical type of altitude - Cwa according to the Köppen classification. The summer is hot and humid and the winter is cold and dry. The annual average temperature is around 25° C. The average annual rainfall from January/2012 to December/2014 - registered at the post Limeira with prefix D4-064 and altitude 640 m was 1240 mm.

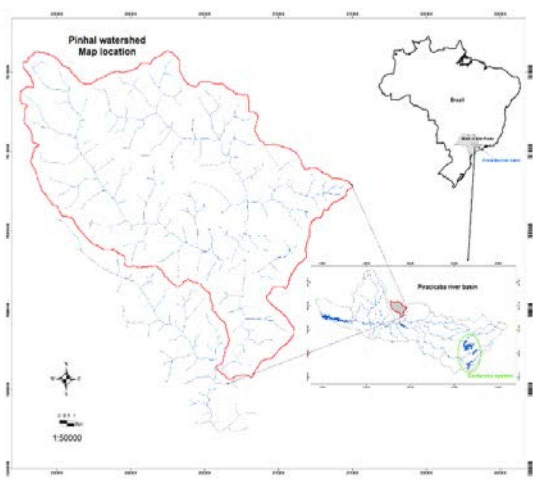


Figure 1 – Ribeirão Pinha watershed location.

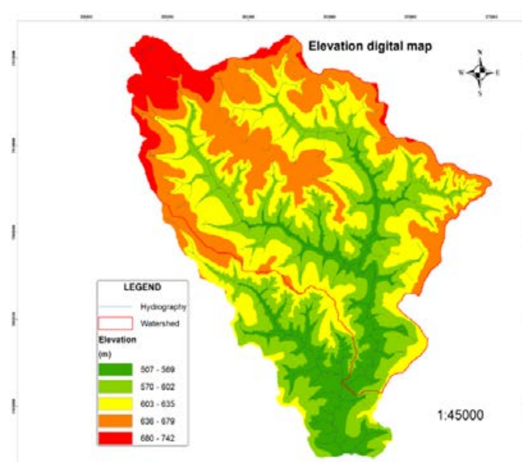


Figure 2 – Ribeirão Pinha watershed Digital Terrain Model (DTM).

The current land use was obtained from the map Use and Land Cover of UGRHI May 2013 - Secretariat of Environment of the State of São Paulo (SMA) (Figure 3). Eight predominant categories of land use were classified. Sugarcane culture occupies most of the area in the watershed (42.3%) while citrus culture occupies approximately 30%. The original forest vegetation is almost non-existent due to the evolution of the use and occupation of land. It is occupies 9% and is scattered in a few fragments on the banks of waterways. The built area occupies 6.7% and is located in the western part of the watershed. The types of dominant soils are Oxisols (72%) and cambisols (19%) (Figure 4).

The Ribeirão Pinhal watershed has suffered in recent decades a growing environmental degradation. This situation may compromise the condition of this supply source if the degradation process not ceases.

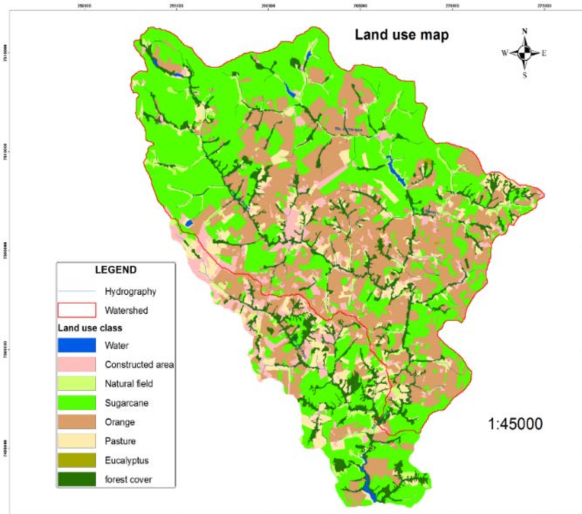


Figure 3 – Ribeirão Pinhal watershed land use.

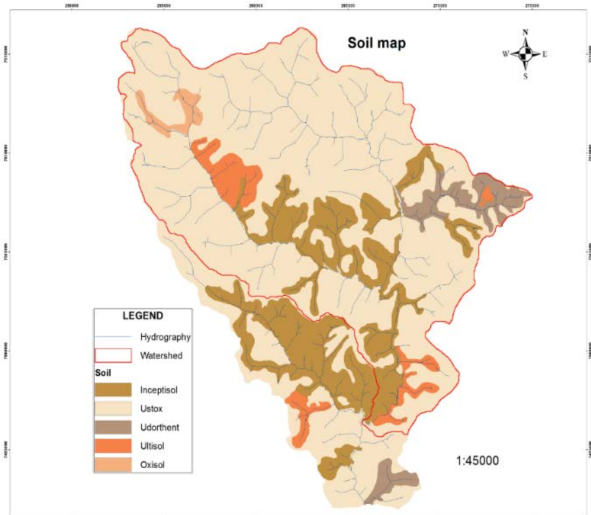


Figure 4 – Ribeirão Pinhal watershed Soil Map.

2.2 The SWAT model

The SWAT is a mathematical distributed model that allows a number of different physical processes being simulated in river watershed with proven success in watershed assessment scenarios. SWAT analyzes the impacts of changes in land use on surface and underground runoff, sediment yield and water quality in agricultural watersheds not instrumented (Srinivasan & Arnold, 1994). The model operates on a daily time step and is able to simulate long periods (one hundred years or more) to compute the effects of handling variations. The SWAT model has been widely applied in studies of hydrological modeling, water resource management and water pollution problems (Douglas, 2010).

The SWAT is based on a command structure to propagate the water flow, sediment and pesticides across the watershed. The model components include hydrology, climate, sediments, soil temperature, plant growth nutrients, pesticides and agricultural management (Arnold et al., 1998). The hydrological component model includes runoff subroutines, percolation, subsurface lateral flow, return flow and evapotranspiration of the shallow aquifer. The model requires daily data of precipitation, maximum and minimum air temperatures, solar radiation, wind speed and relative humidity.

The SWAT uses a modified formulation of the number Curve Method (CN) (USDA-SCS, 1972) to calculate the runoff. The number Curve Method relates runoff to soil type, land use and management practices (Arnold, 1995). The sediment production is estimated with Modified Universal Soil Loss Equation (MUSLE) (Williams & Berndt, 1977).

Data entry in SWAT (plans of cartographic information - PCIs and alphanumeric data) is performed via an appropriate interface. PCIs necessary are: Digital Terrain Model (DTM), soils and land use. An interface was developed between SWAT and the GIS called ArcGis (Arnold et al., 2012). The interface automatically divided the watershed in sub-watersheds from the MDT and then extracts the input data of each sub-watershed from the PCI's and the relational database. The interface allows the model outputs are displayed using maps, graphs and tables in ArcGIS.

2.3 Environmentally Sensitive Areas (EASs)

The concept of Environmentally Sensitive Areas emerged in industrialized countries approximately 30 years ago and the interest was stimulated due to the increase and severity of land and water degradation (Rubio, 1995). This degradation has been caused by uncontrolled in forest destruction, water pollution, erosion by water and wind, salinization and inappropriate management of soil under cultivated and uncultivated regimes, (Gourlay, 1998).

ESAs are landscape portions that contain important natural or cultural features for the functioning of an ecosystem and may be adversely impacted by human activities. Ndubisi et al. (1995) defined ESAs as elements in the landscape that are vital to the long-term maintenance of biological diversity, soil, water, or other natural features in the local or regional context. They included habitat areas for wildlife, areas with steep slopes and wetlands.

The environmental sensitivity of an area is a broad concept since depending on its context it can be defined by many different factors often acting in concert. An environmentally sensitive area can be regarded generally as a specific and delimited entity in which environmental and socioeconomic factors are not balanced or are not sustainable for that particular environment (Gourlay, 1998).

The ESAs in a watershed exhibits different sensitivities to degradation for several reasons. For example, there are areas that have a high sensitivity to the occurrence of extreme weather events due to the scarcity of vegetation, steep slopes and high soil erodibility. High sensitivity may be related to land use and in certain cases promotes soil degradation. For example, annual crops in high lands, in areas with steep slopes and shallow soils can present high risk of degradation. On the other hand, there are areas that are very sensitive to degradation such as areas with risk of forest fire.

A system that considers the main elements and their interrelations is a very useful tool for decision making specially if it take into account critical situations of varying severity. In this context, the main objective of the evaluation and mapping of ESAs in Ribeirão Pinhal watershed was to contribute to a proper EASs planning and identification.

The types of ESAs in environmental degradation context was identified by a GIS using key indicators for the diagnosis of natural resources capacity to degradation resistence or the suitability of the land to support certain uses. Key indicators in the definition of ESAs in the context of environmental degradation, here used in watershed level, were divided in four categories: soil, climate, vegetation cover and management. Each of these categories was a grouping of different classes that reflect their behavior related to degradation. With the four groups Information Plans (IPs) generated ((a) soil; (b) climate; (c) vegetation cover; and (d) Management) the ESAs was defined after the automated processing via GIS and the results obtained by Adami et al. (2012) (Figure 5).

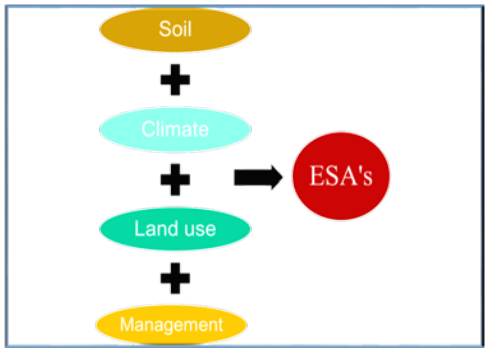


Figure 5 – Methodology for ESAs identification in Ribeirão Pinhal watershed.

Three main types of ESAs can be identified (Steiner et al., 2000) based on theirs state of degradation (Figure 6):

- Type A: areas already quite degraded due to improper use posing a threat to the environment in the vicinity. As an example, severely eroded areas subject to high levels of runoff and soil loss. In this case can occur higher water flow peak rates with some seriousness and siltation of water bodies. These are the critical ESAs.
- Type B: areas where any change in the delicate balance between the natural environment and human activities can drive the ecosystem towards environmental degradation. A change in land use, for example, towards the cultivation of annual crops in soils with high sensitivity. These can produce an immediate increase runoff and erosion and also pollution problems downstream due to pesticide entrainment and fertilizer. Finally, this category can move up to type A category. These are the fragile ESAs.
- Type C: areas threatened by degradation in the face of a particular combination of land uses is implemented. Areas where external impacts can cause serious problems such as the transfer of pesticides and nutrients along the slopes and waterways for downstream areas subject to a variety of land uses and socio-economic conditions. This is a less severe form of the Type B, which an integrated management is necessary. These are the Potential ESAs.

Based on the total watershed area (Table 1), 54% were identified as potential ESAs. These areas include agricultural activities although they are appropriate to the Use of Land Capacity and to need simple practices of soil conservation to erosion control, require care due to the use of external agents such as pesticides (widely used in sugarcane crops sugar and citrus).

Table 1. Percentage of classes of ESA's identified on total area of Ribeirão Pinhal.

Classes	*Area (ha)*	*Area (%)*
Critical ESAs	4801	16
Fragile ESAs	7471	25
Potential ESAs	16155	54
Water	149	0.5
Urban or rural use	1522	5

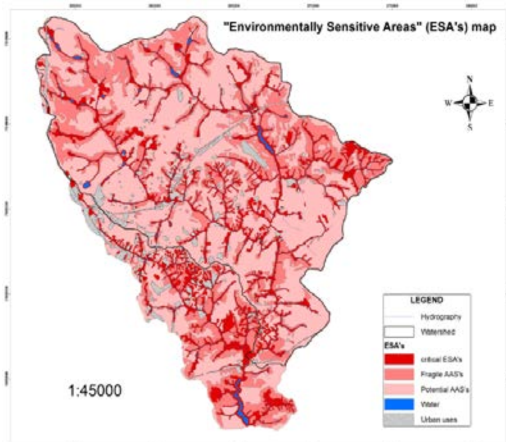


Figure 6 –Ribeirão Pinhal watershed ESA's Map.

2.4 Scenarios Simulation

Simulations of alternative scenarios of land use were made using the SWAT interfaced with ArcGIS. The simulations were conducted in order to verify the effect of the scenarios on the spatial distribution of sediment yield (sediments transported from sub-watersheds to the main channel during the step of time) and water regime of the watershed (water flow, runoff, water production and evapotranspiration).

Critical and Fragile ESAs were identified in Ribeirão Pinhal watershed by the intersection of ICPs via GIS. After, they were superimposed on the map of current land use. The simulation scenario considered the ESAs covered by native forest vegetation and the results compared to the conditions of the current scenario. These simulations illustrate the application and integration of hydrological models and water quality with GIS to evaluate management options watershed. Thus, this integration allows varying only the Information Plan (IP) of land use and occupation.

To evaluate the reduction of sediment yield and compare the water behavior in the watershed between the scenarios was used as the statistical criterion the deviation (Dv) of the analyzed event:

$$D_v[\%] = \frac{E - E^*}{E} * 100$$

where ***E*** are the events considered as standard (current use) in the analyzed period and ***E**** represents the results of the alternative event (ESAs) in the period. The calculation of the deviation (Dv) of th analyzed event is important to consider the potential error between the compared data. With this method, the higher the value of Dv the greater the reduction of sediment production and also changes in the water regime between scenarios.

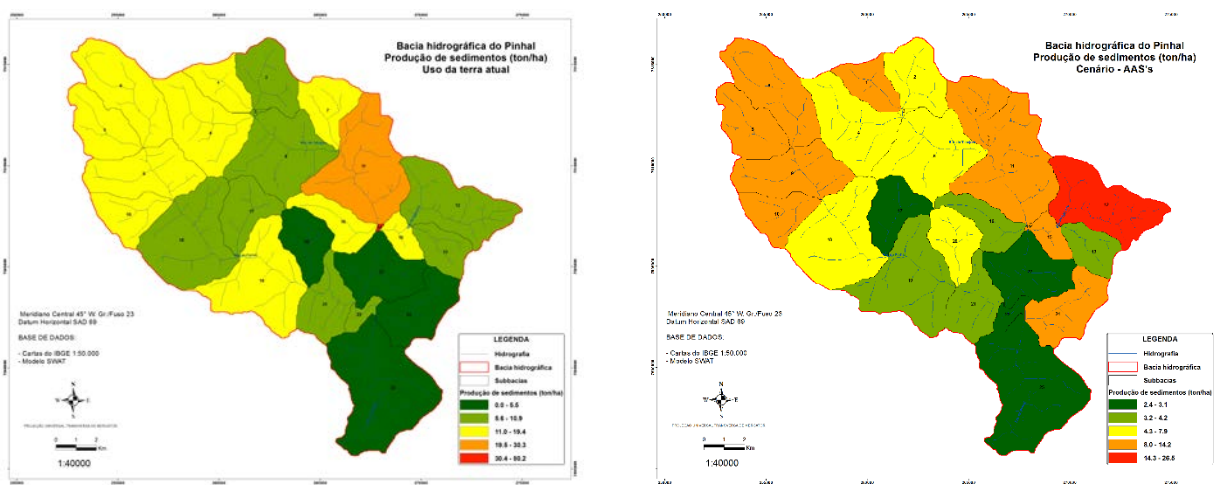
3. RESULTS AND DISCUTION

Table 2 shows the total area and relative occupancy of each land cover in Ribeirão Pinhal watershed for both scenarios. Changinf the current scenarios to the ESA scenario coverd by native forest vegetation there is a reduction in the area occupied by sugarcane (- 46.3%), citrus (- 18.8%) and pasture (- 44,4%) and an increase in the area occupied by native vegetation (+ 373.8%).

The spatial distribution of the average sediment production for the simulated period (2012-2014) is shown in Figure 7. Comparing Figures 7 (a) and 7 (b) it is possible to observe a decrease and redistribution in the production between the scenarios. There was a greater production of sediments in concentrated locals, mainly due to the types of soil occurring in the region. They are shallow or not deep soils (oxisols and cambisols).

Table 2. Land use and occupation for both scenarios (current and ESAs use) in Ribeirão Pinhal watershed.

Land use	Current use		ESA Scenario	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Sugarcane	12566	42.2	6748	22.7
Citrus	8866	29.8	7199	24.2
Pasture	2341	7.9	1301	4.4
Native vegetation	2662	8.9	12609	42.4
Other uses	3337	11.2	1915	6.4
Total	29772	100.0	29772	100.0



7(a) 7(b)

Figure 7 - Spatial distribution of sediment yield (three years average in Ribeirão Pinhal watershed) – current and ESAs scenarios.

Cambisols in the watershed are situated in undulating relief. They are poorly developed soils with incipient B horizon. A key feature of Cambissolos is being shallow and often covered with gravel. The high content of silt and shallow depth make these soils have very low permeability. However, the greatest problem is the risk of erosion. They have restrictions on agricultural use because of high erodibility, strong risk of degradation and strong limitation to trafficability.

The litholic soil despite occupy about 4% of the total area of the watershed, are situated on slopes greater sites. The position they occupy in the landscape, which is unstable geomorphologically causes the erosion will preclude the further development of these soils. This happens, because they are constantly rejuvenated due to the surface materials removal caused by the erosion (Teramoto, 1995).

On these soils are cultivated large areas with sugarcane with partial absence of riparian vegetation. This confirms a strong technical argument of using occurrence areas and soils almost always busy in relief, only to perennial crops or as Permanent Preservation Areas. The spatial location of agricultural areas in relation to various factors such as relief, soil and climate is fundamental important in controlling erosion in watersheds.

In some sub-watersheds predominated the deposition sediment process instead of transport sediment, thus not all sediment removed by erosion process has been carried by drainage network. This suggests that there is strong deposition of sediments in the middle part of the watershed. According Beuselinck (2000), part of the sediment that is produced during storm periods is partially deposited in the watershed, but a substantial part is conveyed to the output by the drainage system. The sediment transport into the drainage system is complex due to the influence of many processes such as soil erosion, sediment transport and deposition within the watershed (Gburek et al., 2000).

In the lower part there is an increased sediment production in relation to the middle part. The factor that may be more closely linked to this is the intensification of land use in these regions with sugarcane culture on oxisols and cambisols soils. However, the connection between generation, transmission and sediment production is complex due to, the combination of factors listed above and also by temporal variation of the drainage network capacity to carry sediment.

The results of sediment yield in sub-watershwd Nº 25 are the erosive and sedimentological processes occurring throughout Ribeirãp Pinhal watershed during the study period. In this sub-watershed, the erosion acts so mild. The relief is almost flat and most of the sediment prominent in the sub-watershed was deposited in the intermediate sub-watershed.

Comparing the simulation results between scenarios is possible to observe the model decreases the prediction of soil loss in most sub-watershed. In the current use scenario the production of simulated sediments ranged from 0.00 to 80.2 t / ha in the analyzed period, with an average of 15.4 t/ha. In ESAs scenario (with the substitution of native vegetation in environmentally sensitive areas) the average output was 7.6 t/ha per year with a maximum observed value of 26.5 tonnes/ha (Figure 8).

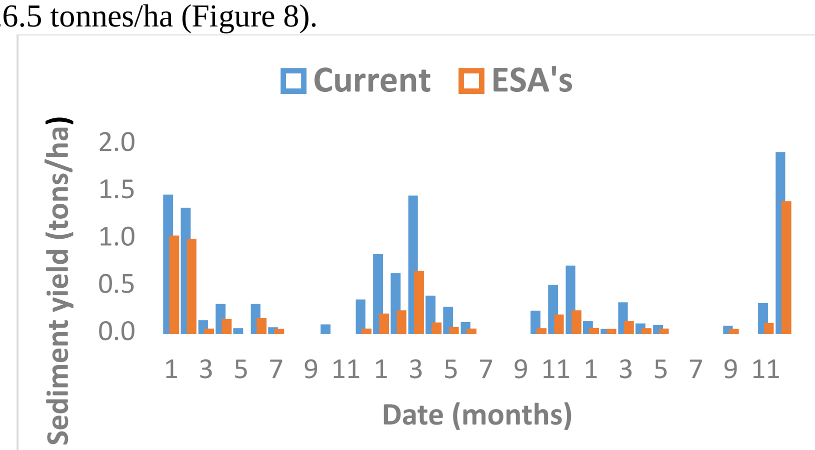


Figure 8 - Comparison of temporal variation in sediment yield between two scenarios in Ribeirão Pinhal watershed. .

In ESAs scenario the reduction was 54% (Dv index) compared to the current usage scenario. This was due to different factor C (USLE) associated with the current type of coverage. In this scenario, medium soil loss was close to the tolerable soil loss for all types of soil and based on Leiz & Leonardos (1977) it is 4.2 tons/ha to litholic soil.

For the water resources of a watershed it is widely reported that the use and change in land cover can affect quantity and quality.

Therefore, knowing the forest influence on various aspects of soil water is important in the assessment of such coverage in the hydrological regime of a watershed. Traditionally, the forest is seen as effective to stabilize and maintain the water flow in rivers, which is one of the reasons revegetation is repeatedly recommended practice in the recovery of watersheds. However, some of the hydrological functions normally assigned to forests, such as increasing the availability of water in the rivers, are questionable and lacking the proper technical-scientific basis. For example, Sahin and Hall, cited by Huang et al. (2003) analyzed empirical data of 145 locations throughout the world and found a decrease of annual runoff resulting from increased plant cover and an increase in the water flow due to the reduction of coverage for deciduous woods.

To check the impact of changes in land use on water regime of the watershed runoff data were analyzed. The monthly average values were then compared between the different scenarios (Figure 09). The result (Dv index = 11.6%) shows that increasing forest coverage areas (scenario ESAs) there was a decrease runoff.

The runoff is a major contribution processes for the water yield of the watershed. The runoff was shown to be decreasing with the change of the current usage scenario for ESAs scenario, especially in dry season. The main cause of decreased runoff was the expansion of forest cover.

The impacts of changing land use on hydrological processes are complex. The production of sediment and runoff showed a downward trend in the scenario of ESAs due to increased forest cover.

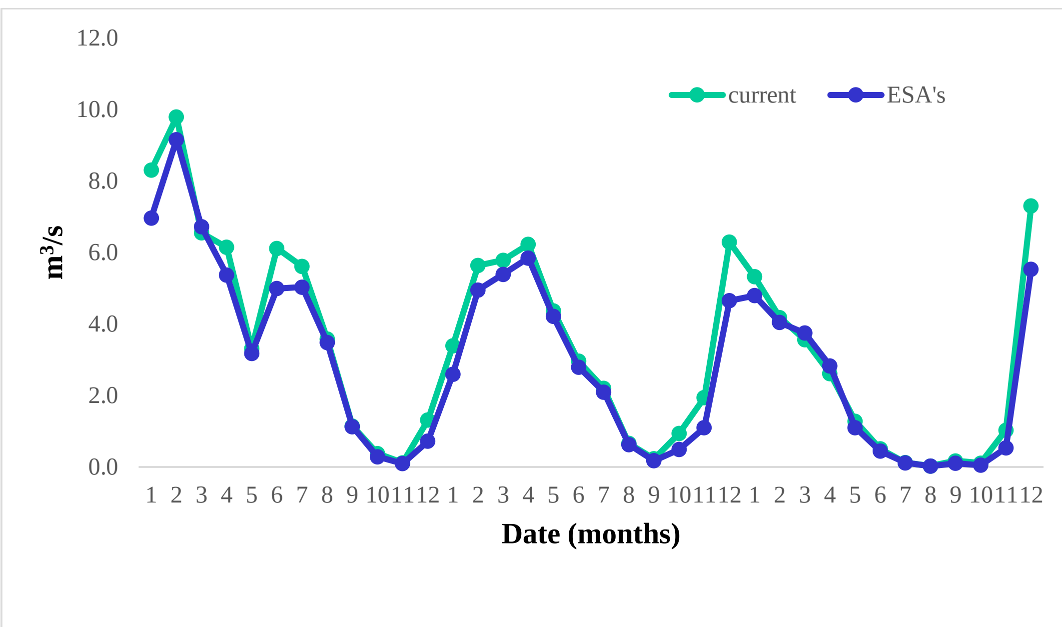


Figura 9 – Impact of land use changes on water flow

4. CONCLUSION

In the scenario of EASs protected by forest cover there was a significant reduction in sediment yield. On the other hand, in this scenario the negative impact on the runoff contributed to the decrease of water flow in the watershed.

Acknowledgements

The authors would like to thank the financial support provided by the funding agencie FAPESP under the number2013/02971-3.

REFERÊNCIAS BIBLIOGRÁFICAS

ADAMI, S. F.; COELHO, R. M.; CHIBA, M. K.; MORAES, J. F. L. Environmental fragility and susceptibility mapping using geographic information systems: applications on Ribeirão do Pinhal watershed (Limeira, State of São Paulo). *Acta Scientiarum.* Technology (Impresso), v. 34, p. 433-440, 2012.

ARNOLD, J.G.; KINIRY, J. R.; SIRIVASAN, R.; WILLIAMS, J.R.; HANEY, E. B.; NEITSCH, S. L. *SWAT2012, Input/output Documentation*. Texas Water Resources Institute, 2012. 650p.

ARNOLD, J. G.; SRINIVASAN, R.; MUTTIAH, R. S.; WILLIAMS, J. R. Large area hydrologic modeling and assessment part I: model development. *Journal of the American Water Resources Association*, v.34, n.1, p.73-89, 1998.

ARNOLD, J.G.; WILLIAMS, J.R.; MAIDMENT, D.R. Continuos-time water ans sediment routing model for large basins. *Journal of Hydraulic Engineering*, v.121, n.2, p.171-183, 1995.

BEUSELINCK, L.; STEEGEN, A.; GOVERS, G; NACHTERGAELE, J.; TAKKEN, I.; POESEN, J. Characteristics of sediment deposits by major rainfall events in small catchments in the Belgian Loam Belt. *Geomorphology*, v.32, p.69-82, 2000.

CHO, S. M.; JENNINGS, G. D.; STALLINGS, C.; DEVINE, H. A. GIS-basead water quality model calibration in the Delaware river basin. *ASAE*, St. Joseph, Michigan, 1995. (ASAE Microfiche, 952404)

DOUGLAS-Mankin, K.; SRINIVASAN, R.; ARNOLD, J. Soil and water assessment tool (swat) model: Current developments and applications. *T. Asabe*, 2010, 53, 1423–1431.

GBUREK, W.J.; SHARPLEY, A.N.; HEATHWAITE, L.; FOLMAR, G.J. Phosphorus management at the watershed scale: A modification of the phosphorus index. *Journal of Environmental Quality*, v.29, p.130-144, 2000.

GOURLAY, D; SLEE,B. Public preferences for landscape features: a case study of two Scottish environmental sensitive areas. *Journal of Rural Studies*, v. 14, n.2, p. 249-263, 1998.

HUANG, M.; ZHANG, L.; GALLICHAND, J. Runoff responses to afforestation in a watershed of the Loess Plateau, China. *Hydrol. Process*. 2003, 17, 2599–2609.

LEINZ, V.; LEONARDOS, O. H. *Glossário geológico*. 2. ed. São Paulo: Companhia Editora Nacional, 1977. 236p.

LESSA, L. G. F.; SILVA, A. F.; ZIMBACK, C. R. L. MACHADO, R.E.; LIMA, S. L. Spatial distribution of sediment and water yield, applying geostatistical tools. *Journal of Environmental Science and Water Resources*, Vol. 3(3), p. 032 - 039, 2014.

MACHADO, R.E; VETTORAZZI, C.A.; CRUCIANI, D.E. Simulação de Escoamento em uma Microbacia Hidrográfica Utilizando Técnicas de Modelagem e Geoprocessamento. *Revista Brasileira de Recursos Hídricos*, Volume 8 n.1, p. 147–155, 2003a.

MACHADO, R.E; VETTORAZZI, C.A.; XAVIER, A.C. Simulação de Cenários Alternativos de Uso da Terra em uma Microbacia Utilizando Técnicas de Modelagem e Geoprocessamento. *Revista Brasileira de Ciência do Solo*, 27:727-733, 2003b.

MACHADO, R.E; VETTORAZZI, C.A. Simulação da Produção de Sedimentos para a Microbacia Hidrográfica do Ribeirão dos Marins, SP. *Revista Brasileira de Ciência do Solo*, 27:735-741, 2003.

MEIJERINK A.M.J., DE BROUWER H.A.M., MANNAERTS C.M AND VALENZUELA, C., 1994. *Introduction to the use of geographic information systems for practical hydrology*. UNESCO, Div. of Water Sciences. ITC Publ. no.23, 243 pp.

NDUBISI, F.; DE MEO T.; DITTO, N.D. Environmentally sensitive area: a template for developing greenway corridors. *Landscape Urban Planning*, v.33, p.159-177, 1995.

PESSOA, M. C. P. Y.; LUCHIARI, A. J.; FERNANDES, E. N. & LIMA, M. A. *Principais modelos matemáticos e simuladores utilizados para análise de impactos ambientais das atividades agrícolas*. Jaguariúna, EMBRAPA/CNPMA, 1997. 83p. (EMBRAPA. CNPMA. Documentos, 8).

PETERSON, J. R.; HAMLETT, J. M. Hydrologic calibration of the SWAT model in a watershed containing fragipan soils. *Journal of the American Water Resources Association*, v.34, n.3, p.531-544, 1998.

RIBAUDO, M. O. Lessons learned about the performance of USDA agricultural nonpoint source pollution programs. *Journal of Soil and Water Conservation*, v. 58, n. 3. p. 13-17, 1998.

ROSENTHAL, W. D.; SRINIVASAN R.; ARNOLD, J. G. Alternative River Management Using a Linked GIG-Hydrology Model. *Transactions of the ASAE*, v.38, n.3, p.783-790, 1995.

RUBIO, J.L. Desertification: evolution of a concept. In: FANTECHI, R.; PETER, D.; BALABANIS, P.; RUBIO, J.L. (Eds.) EUR 15415 *Desertification in a European Physical and Socio-economic Aspects*, Brussels, Luxembourg. Office Publications of the Europen Communities, p.5-13, 1995.

SRINIVASAN, R.; ARNOLD J. G. Integration of a basin-scale water quality model with GIS. *Water Resources Bulletin*, v.30, n.3, p.453-462, 1994.

STEINER, F.; BLAIR, J.; McSHERRY, L.; GUHATHAKURTA, J.M.; HOLM, M. A watershed at a watershed: the potential for environmentally sensitive areas protection in the San Pedro Drainage Basin (Mexico and USA). *Landscape and Urban Planning*, v.49, p. 129-148, 2000.

TERAMOTO, E.R. *Relações solo, substrato geológico e superfícies geomórficas na microbacia do ribeirão Marins*. Piracicaba, 1995. 93p. Dissertação (Mestrado) – Escola Superior de Agricultura “Luiz de Queiroz”, Universidade de São Paulo.

TIM, U. S. Emerging Technologies for Hydrologic and Water Quality Modeling Research. *Transactions of the ASAE*, v.39, n.20, p.465-476, 1996.

Evaluation and focusing of soil and water conservation measures using SWAT model in Krishnagiri reservoir catchment area, south India

Arunbabu Elangovan*
Assistant Professor, Centre for Water Resources, Anna University, Chennai, India,
(*Corresponding author email*: e_arunbabu@yahoo.co.in)

Ravichandran Seetharaman
Professor, Centre for Water Resources, Anna University, Chennai, India

Abstract

The present study evaluated the effectiveness of Soil and Water Conservation (SWC) measures implemented in the catchment area of Krishnagiri Reservoir that has lost 52 % of its capacity in a span of 55 years supporting 3462 ha of irrigated agriculture in the drought prone area of eastern Tamil Nadu, South India. SWAT model was applied to the catchment area calibrated and validated using 13 years stream flow and sediment yield data from 1998 to 2012. Nash-Sutcliffe model fit for monthly stream flow was 0.89 for calibration and 0.83 for validation period. Similarly 0.73 for calibration and 0.76 for validation was obtained for sediment simulation indicating satisfactory model application. SWAT indicated an area of 34.76 km^2 as severe eroding zones of which 32.96 km^2 was covered by the present SWC measures leaving an area of 8.8 km^2 to be covered. Further 20.2 km^2 area of the present program was not classified as severe erosion class by the SWAT model. Focussing the efforts in the severe erosion area identified by the model can improve reduction in sediment yield by 36 %. SWAT also simulated other suitable SWC measures on sediment yield from the catchment. Among them mulching followed by bio-fencing and minimum tillage will greatly improve efficiency of the sediment reduction when implemented. The scrub land in the catchment area contributes higher sediment yield than agricultural lands. Scrub lands constitute 12.35% area of the catchment, but generate 48.5 % of total sediment which is more than 14.5 % of agricultural lands. Simulation results shows that covering the scrub land with plant residue (mulching) can significantly reduce sediment yield upto 1.72t/y from 8.61 t/y. Therefore the present study suggests Bio-fencing which is a cost effective measure in scrub lands can reduce 1.72t/y and more attention is required here.

Keywords: Soil and Water conservation, sediment yield, SWAT

.

Introduction

Man continuously interferes or disturbs the environment for his economic development and other requirements. These activities include deforestation, urbanisation, industrialisation and agricultural development. All these activities promote the erodibility of soil. Soil erosion in the catchment area and the sediment yield of the watershed are major concerns of surface water bodies in terms of sedimentation and loss of storage, while the sediment load also carries nutrients and pollutants that threaten water quality. The consequences of the sedimentation of the water bodies are therefore important for the continued beneficial uses of water by the society. Nature of watershed processes and land cover land use activities are important in the generation of sediment, its quality and transport. Therefore, managing the water quality of lakes and reservoirs primarily needs understanding of the sediment yield and its characteristics, besides the sedimentation and its impacts. The present state of water resources development, increasing demand for water, managing the reservoirs built already demand more understanding to insure their continued beneficial uses. Therefore, these hydrological and water quality processes taking place in watersheds will be the focus of the present study.

Many authors have used successfully SWAT for prediction of flow and sediment yield from the watershed (Rostamian 2008, Lin et al 2010, Pisinaras et al 2010, Nasrin et al 2013). In addition to simulation of flow and or sediment, the efficiency of the model was tested for adaptation to field conditions and specific effects. For example, role of resolution of DEM, tested in a study (Lin et al 2010) in China showed decreasing sensitivity with coarser resolution while the efficiency of sub division of watershed on flow, sediment and nutrient (Jha et al 2004) concentration indicated a threshold value of 5%. In a long term study of Thur watershed in Switzerland (Abbaspour et al 2007), SWAT provided a good flow and transport simulator for nitrogen compounds.In addition to prediction of impacts, evaluation of BMPs in agriculture and specifically the SWC practices adopted in watersheds have been successfully done. In Lam-Southi watershed, Central Thailand (Phomcha et al 2012) SWAT identified 40% of watershed area as erosion prone and further simulations recommend reforestation and mulching as most effective treatment measures to reduce sediment yield.

The foregoing review indicates that SWAT is applied in many watersheds around the world and has many applications in the area of watershed modeling, sediment generation and its delivery, evaluation of BMP's and SWC measures. Further, SWAT was also successful with data scarce situations and recommended for ungauged watersheds by many investigators. SWAT can therefore be considered for use in developing countries where strong monitoring networks or comprehensive natural resources data bases are not yet available for modeling purposes.

Study area

Krishnagiri Reservoir is the first dam constructed across the upper Ponnaiyar River in Tamil Nadu in 1957 to stabilize irrigation in the drought prone Dharmapuri district in northwestern part of Tamil Nadu, India. The catchment area of the reservoir (Fig 1) has eight sub-watersheds with an area of 2500 km^2 which is influenced by south west and north east monsoon rainfall seasons. Tropical hot climate prevails with a maximum temperature range of 34°C to 37°C and minimum temperature range of 22°C to 24°C. This reservoir and its catchment area was the subject of a series of environmental investigations during the last decade. A short term pilot study on the eutrophication of the Krishnagiri reservoir (Ravichandran & Kaarmegam 2004) in Ponnaiyar river basin provided basic information for a detailed study to be taken up. This reservoir in its lifespan of about 50 years has lost 37% of its capacity, with a permanent bloom of algae and declining water quality (Karunakaran 2004). Jasmine & Ravichandran (2008) made a RUSLE2 study of soil erosion in Vepanapalli, a sub-watershed in the catchment area and estimated the total and spatial soil losses. All these studies emphasis the need for a detailed investigation in the catchment area.

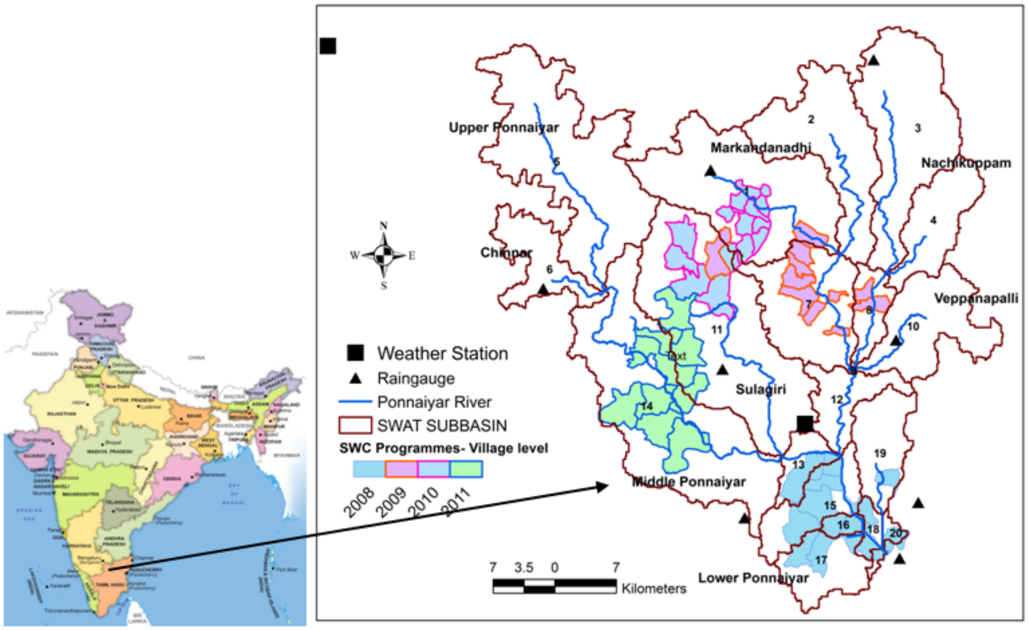


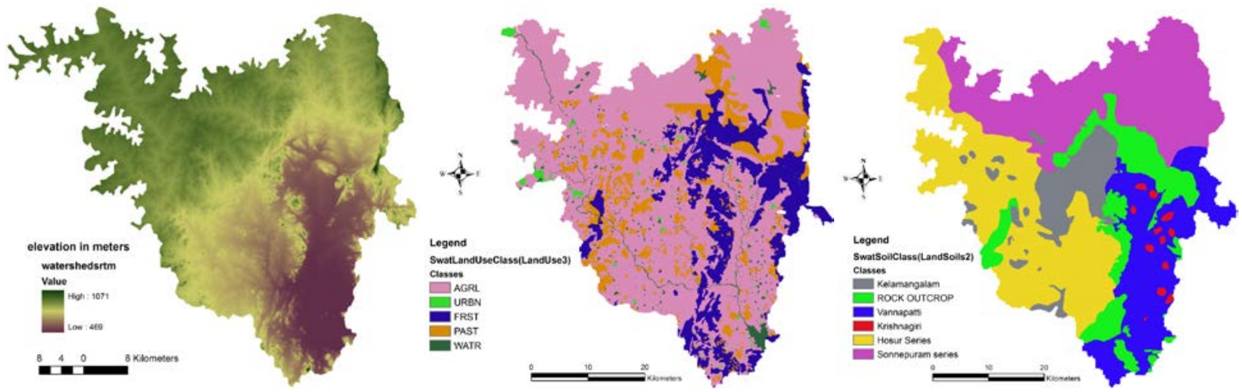
Figure 1 Index map of the Krishnagiri Reservoir Catchment, sub-basins, weather stations, rain gauge stations and SWC programmes in SWAT model

Watershed development programmes

Watershed development refers to conservation, regeneration and judicious use of natural resources like land, water, flora and fauna by human beings. This programme brings the best possible balance between the natural resources and the human beings. To combat the problems encountered by the stakeholders in the watershed, several programmes are being implemented by the Government of Tamil Nadu since 1975. In the year 2002, Government of Tamil Nadu felt the importance of integrated approach at watershed scale, established Tamil Nadu Watershed Development Agency (TAWDEVA) and brought all watershed programmes under Integrated Watershed Management Programme (IWMP). Among several activities much attention was given for the construction of soil and water conservation (SWC) structures in 544 micro watersheds in Tamil Nadu. SWC structures include Field Bunding (FB), Stone Wall (SW), Strip cropping (SC), bio-fencing (BF), check dam and recharge pits. Around 46 villages in the catchment area are being treated with soil and water conservation structures. Hence the present study is focussed in this reservoir for a detailed investigation in the catchment area in quantifying the sediment yield from the catchment area using SWAT model and also to evaluate existing Soil and Water Conservation measures in the catchment area, based on the present study.

Model configuration

The river network for the Krishnagiri reservoir catchment area was extracted from the digital elevation model (DEM) from SRTM data, using standard analytical techniques contained in the ArcSWAT GIS interface. The Krishnagiri catchment area land cover classification codes were converted to the SWAT land cover/plant codes, so a reclassified and aggregated land use data set was prepared for this watershed. There are five different land use classes are assigned. They are 67.37% of agricultural fields belongs to AGRL, 1.04% of residential areas belongs to URBN, 16.91% of forest area belongs to FRST, 12.43 % of wasteland to SCRB land and 2.26% of water bodies belongs to WATR (Figure 2).



(a) **(b)** **(c)**

Figure 2 (a) DEM (b) Land Use classes (c) Soil Classes configured in SWAT Model of the Krishnagiri catchment area

Data on soil attributes were obtained from soil maps provided by the Dharmapuri and Krishnagiri District Soil Atlas and a significant soil profile data from reports of the Tamil Nadu Agricultural University, Coimbatore, India. There are six soil series in the study area. Among which Hosur soil series occupies the major proportion of 30.68% followed by 28.85% of Sonnepuram series, 16.89 % Vannapatti series, 12.97 % of Rock outcrops, 9.75% of Kelamangalam series and 0.87% of Krishnagiri series (Figure 2). Soil profile information for each sub-basin contain percentage clay, silt, sand, as well as percent of organic matter that was estimated for up to three soil layers. This data were provided in the inputs for the soil data base. A hydrologic soil series category (A to D) was assigned to each HRU according to USDA-SCS method. All this data were entered to the user Soil Database of ArcSWAT manually in dbf format.

A user weather database was created to bring the weather condition of the Krishnagiri watershed in to the model. A pre-processor, pcpSTAT generated the precipitation statistics for the weather stations Melumalai and Bengaluru using daily precipitation depths from 1998 to 2011. Similarly the average daily dewpoint per month, daily temperature and humidity data were used from Melumali and Bengaluru station. The results of the pre-processor were imported into the SWAT database to reflect the weather of the Krishnagiri Reservoir catchment area.

Krishnagiri Reservoir catchment area was subdivided into 19 sub-basins (Figure 1) and 333 HRUs. Flow and sediment data from the period January 1, 1998 to December 31, 2011 were used as the simulation period for warm-up, calibration and validation at Gummanoor a gauging site located at the outlet of the catchment area.

Model Evaluation Statistics

Nash-Sutcliffe Efficiency (NSE)

Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (“information”). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in Equation 1.

$$\text{NSE} = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right] \quad (1)$$

where Y_i *obs* is the i_{th} observation for the constituent being evaluated, Y_i *sim* is the i_{th} simulated value for the constituent being evaluated, Y_{mean} is the mean of observed data for the constituent being evaluated, and *n* is the total number of observations. NSE ranges between -∞ and 1.0 (1 inclusive), with NSE=1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance**.**

Percent bias (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. PBIAS is calculated with Equation 2.

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)*(100)}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right] \quad (2)$$

where PBIAS is the deviation of data being evaluated, expressed as a percentage.

Results and discussion

The average annual precipitation of the Krishnagiri reservoir catchment was 864 mm during the period of analysis 1998 to 2011. The water balance of the SWAT model is tested using a standalone screening tool called SWATcheck for potential problems of the SWAT output. The hydrological component ET is verified for every simulation as it emerged the most sensitive parameter that determines the surface runoff and other water balance components. Soil evaporation compensation factor, method of estimating ET and LAI are the vital parameters for the loss of water through Evapotranspiration. Soil evaporation compensation factor was adjusted to fine tune the water balance of the Krishnagiri reservoir catchment area. The model predicted that mean annual rainfall for the total simulation period over the catchment area (864 mm) is mainly removed through evapotranspiration (ET) from the basin (69.7%), percolation/ groundwater recharge accounted 16.7%, yielding a surface runoff of 13%. There were no warnings from the calibration phase. The computed water balance components indicated a good correlation with the observed runoff.

Sensitivity Analysis

Flow

Sensitivity analysis was performed to identify the key parameters in the calibration phase of the model development. The catchment hydrology components of SWAT involve a large number of parameters. In the sensitivity analysis, 20 parameters related to stream flow were initially selected. After the first iteration, 9 parameters such as Curve number (CN2), Manning's 'n' value for main channel (CH_N2), Available water capacity (SOL_AWC (1)), Channel effective hydraulic conductivity (CH_K2), Soil evaporation compensation factor (ESCO), Ground water revap co-efficient (GW_REVAP), Threshold water depth in the shallow aquifer (GWQMN), Groundwater delay time (GW_DELAY) and Base flow alpha factor (ALPHA_BF) were found more sensitive. A *t*-test is then used to identify the relative significance among these 9 parameters. Table 1 shows the results of the t-test and P-value for the parameters chosen. T-stat provides a measure of sensitivity (larger in absolute values are more sensitive) where as p-values determined the significance of the sensitivity (SWATCUP Manual). A value close to zero has more significance. Curve number of the watershed has a larger absolute value for t-stat and hence it is the most sensitive parameter for stream flow followed by Threshold water depth in the shallow aquifer (GWQMN) and Ground water revap co-efficient (GW_REVAP). The fitted value for the flow parameters with its ranges used for calibration is shown in Table 1

Sediment

SWAT uses MUSLE for prediction of sediment concentration and those parameters which are sensitive to sediment only were chosen for sensitivity analysis. After first iteration, 7 parameters were found more sensitive (Table 1. They are Average Slope length (SLSUBBSN), USLE support practice factor (USLE_P), Channel erodibility factor (CH_EROD), Exponent of re-entrainment parameter for channel sediment routing (SPEXP), Linear re-entrainment parameter for channel sediment routing (SPCON), Channel cover factor (CH_COV) and Residue decomposition coefficient (RSDCO). A *t*-test is then used to identify the relative significance among these 7 parameters. Table 1 shows the results of t-test and P-stat values. Average slope length of the basin is found to be the most sensitive followed by USLE support practice factor and Channel erodibility factor. The fitted value for the sediment parameters with its ranges used for calibration is shown in Table 1.

Table 1 SWAT sensitive parameters and fitted values

Variable	Parameter Name	Description	t-Stat	P Value	Fitted Value	Minimum Value	Maximum Value
Flow	r__CN2.mgt	Curve number	-13.386	0.000	-0.102	-0.200	0.200
	v__GWQMN.gw	Threshold water depth in the shallow aquifer	9.954	0.000	167.00	0.000	200.00
	v__GW_REVAP.gw	Ground water revap co-efficient	8.206	0.000	0.178	0.020	0.200
	v__ESCO.hru	Soil evaporation compensation factor	-5.314	0.000	0.630	0.500	0.900
	v__GW_DELAY.gw	Groundwater delay time	5.090	0.000	28.789	5.000	31.000
	v__ALPHA_BF.gw	Baseflow alpha factor	-2.799	0.006	0.745	0.000	1.000
	v__CH_N2.rte	Manning's 'n' value for main channel	1.468	0.146	0.093	0.014	0.300
	r__SOL_AWC(1).sol	Available water capacity	-0.847	0.399	-0.009	-0.020	0.020
	v__CH_K2.rte	Channel effective hydraulic conductivity	-0.046	0.964	6.250	0.000	10.00
Sediment	v__SLSUBBSN.hru	Average Slope length	-13.743	0.005	45.000	10.000	150.00
	v__USLE_P.mgt	USLE support practice factor	-9.175	0.012	0.325	0.100	1.000
	r__CH_EROD.rte	Channel erodibility factor	7.824	0.016	0.030	0.000	0.600
	v__SPEXP.bsn	Exponent of re-entrainment parameter for channel sediment routing	-5.128	0.036	1.225	1.000	1.500
	v__SPCON.bsn	Linear re-entrainment parameter for channel sediment routing	-4.811	0.041	0.006	0.001	0.010
	r__CH_COV.rte	Channel cover factor	-3.515	0.072	0.050	0.000	1.000
	r_RSDCO.bsn	Residue decomposition coefficient	0.835	0.492	0.032	0.020	0.100

Model Performance

Graphical results during calibration and validation indicate a good match between the observed flow and simulated flow. The calibration results showed a better match than validation results. Nash-Sutcliffe Efficiency (NSE) values for the monthly stream flow during calibration process was 0.89 and during validation period 0.83 (Table 2). The percentage bias (PBIAS) for stream flow during calibration was -7.2% and during validation it was -14.0%. Many researchers have (Moriasi et al 2007, Shanthi et al 2001) suggested that model simulation can be judged as 'satisfactory' if NSE > 0.60 and if PBIAS $\pm$ 25 for stream flow. The model performance in the present study for monthly stream flow based on NSE for both calibration and validation period can be rated as 'very good' (Moriasi et al 2007) and based on PBIAS the model can be rated as 'Very good' for calibration and 'Good' for Validation. PBIAS for stream flow shows a negative value for both calibration and validation period indicating the model has overestimation bias.

Similarly the statistical comparison between the measured and simulated sediment concentration and best result from SUFI 2 algorithm showed a good agreement. The results of the model evaluation statistics for monthly sediment concentration are shown in Table 2. The NSE value for sediment simulations are 0.73 and 0.76 during the calibration and validation period respectively.

Table 2 Performance ratings for the model in monthly time step

Station	Variable	Model	NSE	R^2	PBIAS (%)
Gummanur	Flow	Calibration	0.89	0.90	-7.2
		Validation	0.83	0.91	-14.0
	Sediment	Calibration	0.73	0.74	6.6
		Validation	0.76	0.81	23.4

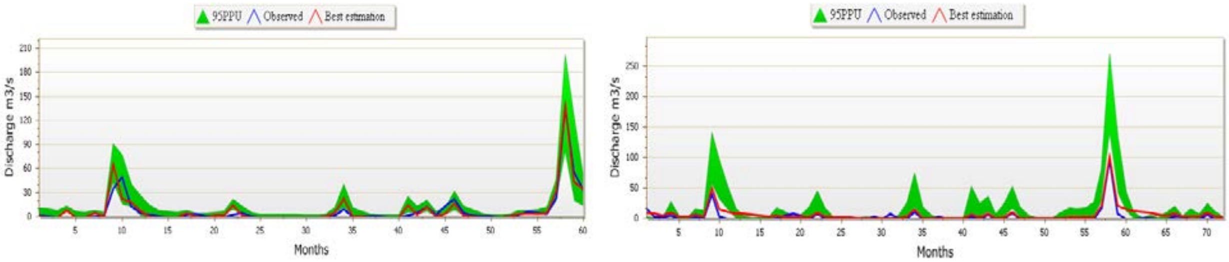
The PBIAS for sediment shows a positive value for both calibration and validation period indicating the model underestimation bias. Model simulation for monthly sediment concentration based on NSE for both calibration and validation period can be rated as 'good' and based on PBIAS the model can be rated as 'Very good' for calibration and 'Good' for Validation. The PBIAS shows a positive value of 6.6 % during calibration and 23.4 % during validation indicating the model underestimation bias.

Calibration and Validation of the Model

Flow

The stream flow at Gummanur gauging station from January 1998 to December 2000 was used as warm-up period to initialise the variables for the model. The calibration was carried out at monthly time steps using stream flow for the hydrological years from January 2001 to December 2005. The capability of a hydrological model to adequately simulate stream flow and sediment concentration typically depends on the accurate calibration of parameters (Xu et al 2009). In this study, the calibration was done using SUFI2 based on sensitive parameters and calibration techniques from the SWAT CUP user manual. After calibration of flow, calibration of sediment was carried out for the same time period used for flow calibration.

The simulated discharge generally followed the trend to observed discharge from January 2001 to December 2005 (Figure 3). A critical evaluation of the hydrographs shows that the flow peaks are simulated slightly higher in the month of October 2001 whereas the highest flow peak in October 2005 with average discharge of 142.3 m^3/s was simulated (145.2 m^3/s) accurately by the model. However low flows during the non-monsoon periods were not matched well (Figure 3). This may be due to the fact that there is a reduction in the flow velocity by the weir located in the upstream of the Gummanur gauging point.

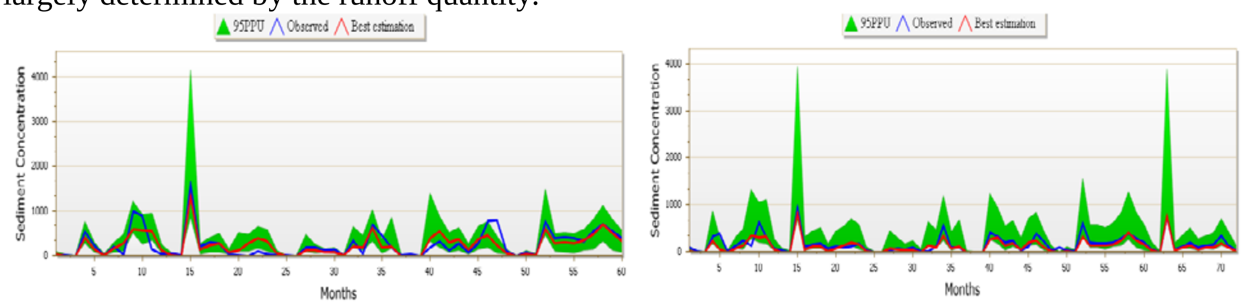


Calibration **Validation**

Figure 3 Monthly discharge calibration and validation for Krishnagiri reservoir catchment at Gummanur gauging station (Sub-basin outlet 19)

Sediment

A comparison of observed and simulated suspended sediment concentration (Figures 4) shows that simulated sediment concentration also followed generally the observed trend during both calibration and validation periods. Although, model predicted peak values were found higher than the observed values at different times in the watersheds, the difference was within reasonable limits. The difference in simulated and observed values could occur due to the high-intensity and short duration rainfall that can generate more sediment than simulated by the model on the basis of daily rainfall (Xu et al 2009). The obvious reason for higher sediment simulation is that the sediment response follows the simulated runoff rate as the sediment generation is largely determined by the runoff quantity.



Calibration **Validation**

Figure 4 Monthly sediment calibration and validation for Krishnagiri reservoir catchment at Gummanur gauging station (Sub-basin outlet 19)

The average sediment yield from the sub-watersheds are given in Table 3. Among the eight sub watersheds, Lower Ponnaiyar shows highest sediment yield of 60523 t/yr where as Veppanapalli sub watershed yields only 906.53 t/yr. The sediment yield from a catchment depends on the land use, soils and slope of the area. Veppanapalli sub watershed comprises of forest land of 60.4 km^2 out of 91.3 km^2. In general, the erosion hazard was found to be low under natural vegetation cover and these are mostly mountainous forests and distributed in the upper part of Veppanapalli and hence may show lesser sediment yield. In contrast high sediment yield is seen in the outlets of Lower Ponnaiyar, Middle Ponnaiyar and Sulagiri subwatersheds. These subwatersheds have high agricultural activity with some steep slopes. This may be one significant reason for high sediment yield from these subwatersheds. Other sub watersheds namely Markandhanadi and upper Ponnaiyar has moderate sediment yield in comparison with other subwatersheds.

Simulation of Conservation Practices

The effect of Soil and Water Conservation practices on sediment yield was obtained by varying the USLE_P factor in the SWAT model at Sub-basins or HRUs. Though several measures are implemented for soil and water conservation in watersheds, only those methods which are feasible, labour saving and economical in the study area are considered for the simulation. Stone wall (SW) and Field Bunding (FB) are the conservation structures implemented by Government of Tamil Nadu in the Krishnagiri catchment (TAWDEVA 2002) and hence the effect of these measures on sediment yield was simulated. In addition, the impact of vegetative methods such as Mulching and Bio fencing over mechanical methods was also evaluated as these may be cost effective and local materials may be favourable. Another possible way of reducing soil erosion and sediment yield from the agricultural fields is by adopting minimum tillage operation where the disturbance to the soil is minimised.

Results of the simulation on sediment yield under different conservation practices in the catchment area are given in Table 3. The outputs showed that Mulching generated lowest value of sediment yield (29642.64 t/yr), then Bio-fencing (56413.75 t/y) followed by Minimum Tillage (72836.15 t/y), Field bunding (91335.73 t/y) and stone walls (103241.11 t/y). Simulation results revealed that soil conservation practices used in simulation could significantly reduce the annual sediment yield into the Reservoir. Stone walls installed along the perimeter of the fields can reduce sediment and nutrients in surface runoff as it passes through the edge-of-the-field. This method can reduce the sediment yield by 30 % from the base value of sediment yield with no conservation practices. Field bunding was similar to the stone walls except that these bunds are made with the local soil along the edge of an agricultural field. Therefore, sediment from the agricultural area that drains into the channel segment is trapped in the field itself.

Table 3 Sediment yield from subwatersheds of Krishnagiri Reservoir catchment under different SWC measures simulated in SWAT

Subwatersheds	SWAT Sub-basin Number	Sediment Load (t/y) No Conservation	Stone Wall	Field Bunding	Minimum Tillage	Bio-fencing	Mulching
Upper Ponnaiyar	5	10259.43	6787.03	6125.37	4787.90	3738.44	1863.90
Chinnar	6	3165.69	2188.22	1953.68	1504.04	1156.29	574.11
Sulagiri	11	23065.04	16431.20	14412.22	12260.15	8804.90	4524.42
Markandanadhi	1,2,7,9,12,18	16211.43	11019.98	9706.08	7653.07	5996.57	3170.09
Middle Ponnaiyar	14	28946.26	20131.86	17898.97	14107.05	11127.35	5877.31
Nachikuppam	3,4,8	5813.19	4016.79	3531.38	2774.53	2149.23	1121.45
Veppanapalli	10	906.53	623.53	547.96	429.41	334.81	173.20
Lower Ponnaiyar	13,15,16,17,19	60523.27	42042.50	37160.07	29320.00	23106.16	12338.16
Total		148890.84	103241.11	91335.73	72836.15	56413.75	29642.64

The simulation results also show that 38.65 % reduction in the sediment yield can be achieved through this practice. Vegetative practices like mulching and bio-fencing are the best methods among the selected SWC measures since the reduction in sediment yield is 71 % in the case of mulching operation and 62.1% in the case of bio-fencing.

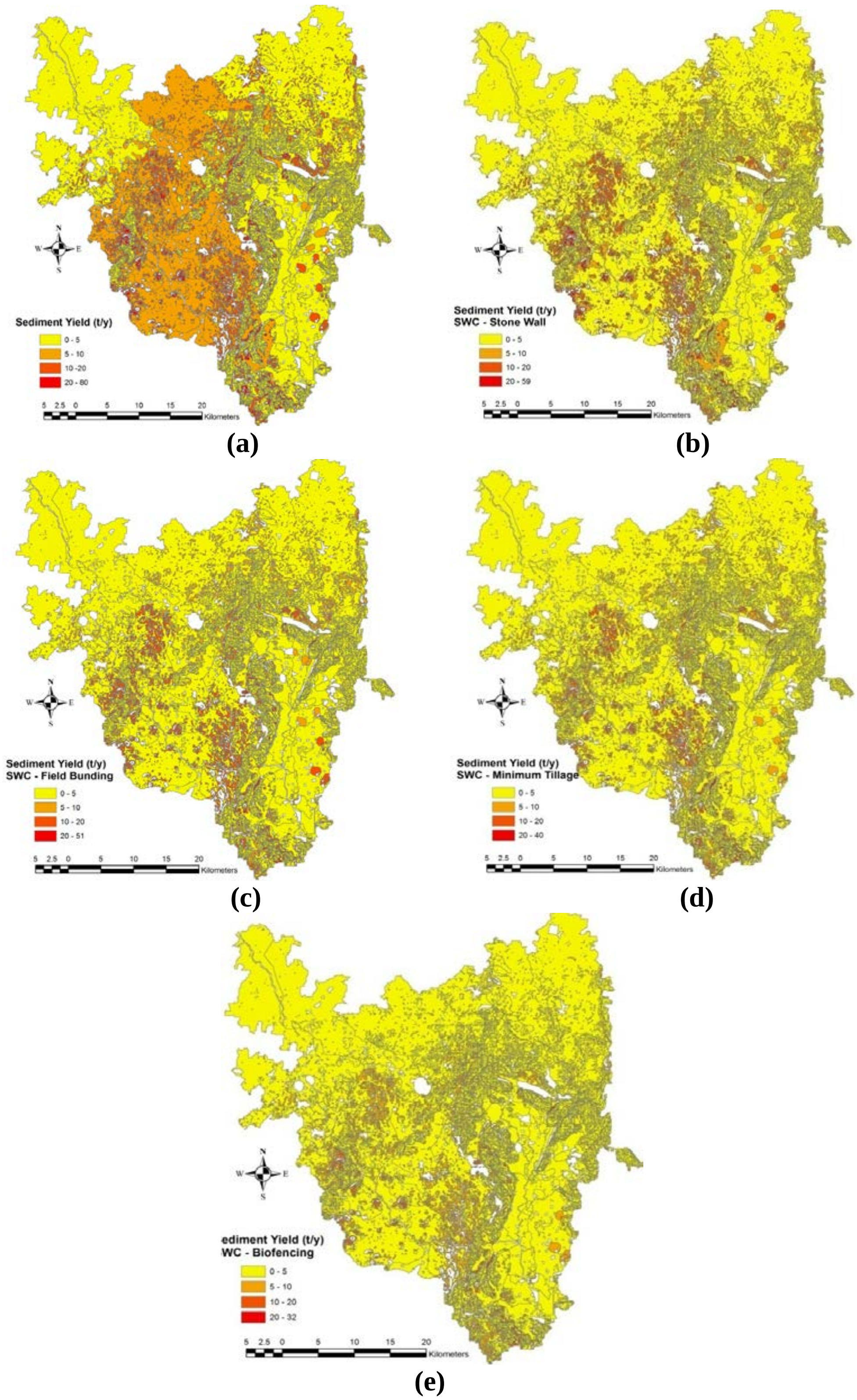


Figure 5 Sediment yield from the Krishnagiri Reservoir Catchment area (a) potential sediment yield (b) Stone Wall (c) Field Bunding (d) Minimum Tillage (e) Biofencing

Average sediment yield reduction under these measures are simulated and shown in Figure 5.38. Sediment yield from different land use categories (Figure 4) show scrub land contribute more sediment load and combined with Agricultural lands, it is more than 80% of the total load from the catchment area. Average sediment yield from agricultural land was 5.97 t/y without any land treatment. Simulation results shows that the average sediment yield can be reduced upto 0.2 t/y when all the agricultural fields are mulched with plant residues before and after harvest. Even though Bio-fencing and Minimum tillage reduce sediment yield to 2.35mt/y and 3.01 t/y respectively, the possibility of minimum tillage operation in all the field are very less. The current practice of stone wall and field bunding in the agricultural lands reduces sediment yield upto 26% (4.36 t/y) and 35% (3.84 t/y) respectively. Maximum reduction in the sediment yield feasible in the catchment was 90% in the case of Mulching and 61% in the case of Bio-fencing while all other measures the reduction achieved was less than 50%.

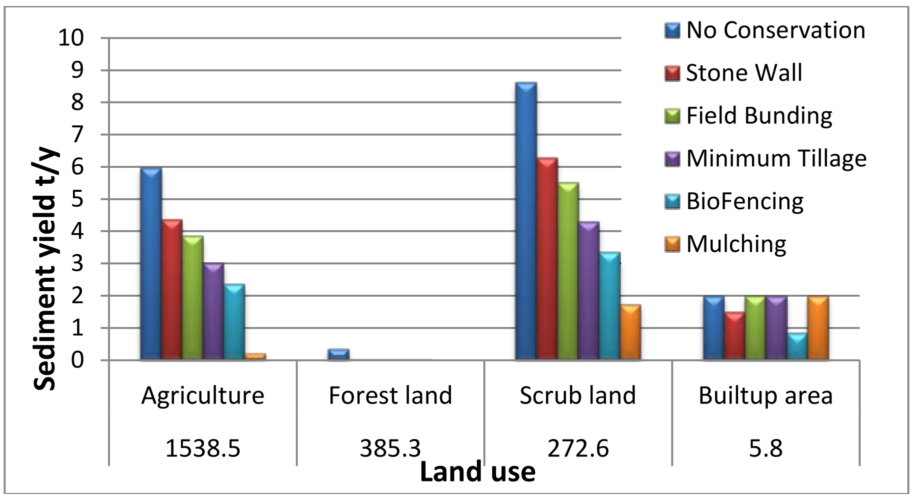


Figure 6 Average Sediment yield from different Land uses categories in Krishnagiri Reservoir Catchment area

The scrub land in the catchment area contributes higher sediment yield than agricultural lands. Simulation results shows that covering the scrub land with plant residue (mulching) can significantly reduce sediment yield upto 1.72 t/y from 8.61 t/y. Among all practices mulching and bio-fencing are found to be more effective and feasible in the catchment area. Therefore the results of the simulation study suggest that Mulching and Bio-fencing can be effective in reducing sediment yield from the catchment area of the Krishnagiri Reservoir and may be considered for implementation. This has to be taken into consideration in devising the type of conservation program suitable for this catchment.

Conclusion

The findings of the present study can be used to prepare an action plan with additional SWC measures that may be cost effective as well as require less maintenance, especially in the scrub lands of the watershed. The usefulness of such a proposed action plan can also be monitored for its performance, as the flow and sediment yield of the catchment area has now been modelled successfully in SWAT environment. More attention towards soil conservation should be focused in the lower part of the watershed especially in the scrub lands with more SWC measures recommended in the present study, if further reduction of sediment generation is desired

References

Abbaspour, KC, Yang, J, Maximov, I, Siber, R, Bogner, K, Mieleitner, J, Zobrist, J & Srinivasan R 2007, 'Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT', Journal of Hydrology, vol. 333, pp. 413-430.

Jasmine, I & Ravichandran, S 2008, 'RUSLE2 Model application for soil erosion assessment using Remote sensing and GIS', Water Resources Management, vol.22, pp. 83-102.

Jha, M, Gassman, PW, Secchi, S, Gu, R & Arnold, J 2004, 'Effect of Watershed Subdivision on SWAT Flow, Sediment, and Nutrient Predictions', Journal of the American Water Resources Association, vol. 40, no. 3, pp. 811-825.

Karunakaran, N 2004, Eutrophication of Krishnagiri Reservoir causes and Environmental Impacts. Ph.D. thesis, Anna University, Chennai

Lin, S, Jing, C, Chaplot, V, Yu, X, Zhang, Z, Moore, N & Wu, J 2010, 'Effect of DEM resolution on SWAT outputs of runoff, sediment and nutrients', Hydrology and Earth System Sciences, Discussion, vol. 7, pp. 4411-4435.

Moriasi, DN, Arnold, JG, Van Liew, MW, Binger, RL, Harmel, RD & Veith, TL 2007, 'Model evaluation guidelines for systematic quantification of accuracy in watershed simulations', American Society of Agricultural and Biological Engineers, vol. 50, no. 3, pp. 885-900.

Nasrin, Z, Gholamabbas, S & Ebrahim, HS 2013, 'Hydrological and Sediment Transport Modeling in Maroon Dam Catchment Using Soil and Water Assessment Tool (SWAT)', International Journal of Agronomy and Plant Production, vol. 4, no. 10, pp. 2791-2795.

Phomcha, P, Wirojanagud, P, Vangpaisal, T & Thaveevouthti, T 2012, 'Modeling the impacts of alternative soil conservation practices for an agricultural watershed with the SWAT model', Procedia Engineering, vol. 32, pp. 1205-1213.

Pisinaras, V, Petalas, C, Gikas, GD, Gemitzi, A & Tsihrintzis, VA 2010, 'Hydrological and water quality modeling in a medium- sized basin using the Soil and Water Assessment Tool (SWAT)', Desalination, vol. 250, pp. 274-286.

Ravichandran, S & Kaarmegam, M 2004, 'Soil erosion and nutrient transport from Krishnagiri Reservoir Catchment area', Report submitted to the Environment Cell Division, WRD, PWD, Chennai.

Rostamian, R 2008, Application of a SWAT model for estimating runoff and sediment in two mountainous basins in central Iran. Hydrological Sciences Journal, vol. 53, no. 5, pp. 977–988.

Shanthi, C, Arnold, JG, Williams, JR, Hauck, LM & Dugas, WA 2001, 'Application of a Watershed model to evaluate management effects on point and nonpoint source pollution', Transactions of the ASAE, vol. 44, no. 6, pp. 1559-1570.

Tamil Nadu Watershed Development Agency (TAWDEVA) 2002, Watershed development programmes. Available from: <http:// www.tawdeva.gov .in>. [19 August 2011].

Xu, ZX, Pang, JP, Liu, CM & Li, JY 2009, 'Assessment of runoff and sediment yield in the Miyun Reservoir catchment by using SWAT model', Hydrological Processes, vol. 23, pp. 3619-3630.

swat.tamu.edu/conferences/2015

We would like to thank the following conference sponsors:

CRS4 IDEAS BECOME LIFE

SARDEGNA RICERCHE

European Commission

enterprise europe network

L'Europa alla portata della vostra impresa.

Facoltà di Ingegneria e Architettura

IRSA CNR

REGIONE AUTÒNOMA DE SARDIGNA
REGIONE AUTONOMA DELLA SARDEGNA

EUROMED MAPPING

TEXAS A&M AGRILIFE RESEARCH

USDA ARS Agricultural Research Service