Application and Validation of SWAT Model to an Alpine Catchment in the Central Spanish Pyrenees

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Abstract

Modeling runoff and sediment transport at catchment scale are key tools for predicting water and sediment yields with the purpose of preserving soil and water resources. This study aims to validate the SWAT model for its use in an alpine catchment as a simulator of processes related to water quantity and soil erosion in order to minimize indirect impacts such as reservoir siltation and loss of water quality. The newest version of Soil and Water Assessment Tool (SWAT2009), coupled with a GIS interface (ArcSWAT), was applied to the Barasona Reservoir catchment located in the central Spanish Pyrenees. The 1,509 km^2 catchment presents an altitudinal range close to 3000 meters and a precipitation variation of 1000 mm/km. The high mountainous characteristics of the catchment required specific definitions for some parameters. The snowmelt is a significant process in the hydrologic regime of the drainage area of the reservoir. The snowmelt was defined with the temperature-index plus elevation bands algorithm. The model was calibrated and validated using continuous streamflow data from gauge stations. Calibration and validation results showed good agreement between simulated and measured data. Model performance was evaluated using several statistical parameters, such as the Nash–Sutcliffe coefficient. The information gained with this research will be of interest to identify sediment sources and areas of high sediment yield risk, and to identify erosion and sediment transport patterns in the catchment.

Keywords: SWAT, mountainous catchment, snowmelt, streamflow, alpine catchment

1. Introduction

In the last century, topographical and hydrological characteristics of the Spanish Pyrenees were considered to be appropriate for constructing reservoirs. Many Pyrenean rivers have been dammed to provide electricity and irrigation water to the lowland areas. The rugged topography, the regime of the rivers with frequent floods, and the changes in land use which have occurred during the past few decades have triggered soil erosion and consequently siltation and reservoir management problems (Valero-Garcés et al., 1999; Navas et al., 2009). In this paper we investigate the drainage area of the Barasona Reservoir which is located in the Central Spanish Pyrenees.

Since it is difficult to obtain continuous direct measurements with sufficient spatial coverage in mountain ecosystems, a robust computational hydrologic model that simulates fluxes of energy and water between the atmosphere and the land surface can be an effective means of studying land-surface dynamics (Stratton et al., 2009). The need to better understand the hydrologic characteristics of a snow-dominated catchment at the regional scale of a reservoir basin is highlighted by problems related to preserving soil and water resources.

Snow-dominated mountain catchments present considerable challenges for spatially distributed modeling due to highly heterogeneous climate drivers, complex topography, and environmental gradients (Stratton et al., 2009). Because of the limited climatic data in these areas, extrapolation of temperature and precipitation is required with the difficulty that this implies through mountainous terrain. Therefore, both precipitation and temperature lapse rates computed for this data-limited region can only be an approximation and they can restrict the ability of the model to capture the catchment processes. Complex topography introduces diverse snowmelt patterns, and large elevation gradients can produce complicated precipitation distributions.

A review of the historical development and applications of SWAT was conducted by Gassman et al. (2007). SWAT has been implemented to adequately estimate streamflow volumes and timing from mountainous catchments. Fontaine et al. (2002) first applied SWAT to the Upper Wind River basin of Wyoming by adding elevation bands, an areal depletion curve, and snowpack temperature and meltwater production routines, which significantly improved SWAT′s runoff simulation capability. Lemmonds and McCray (2007), Ahl et al. (2008) and Stratton et al. (2009) have since applied these hydrologic changes within SWAT to experimental watersheds in Montana and Idaho with reasonable success. Eckhardt et al. (2002) and Govender and Everson (2005) all describe additional hydrologic applications worldwide (Germany and Africa). Zang et al. (2008) compared snowmelt algorithms incorporated into SWAT in the headwaters of the Yellow River and concluded that utilization of temperature index plus elevation bands gave satisfactory results. However, fewer studies have been conducted to evaluate sediment production with SWAT in mountainous topography. For example, Gikas et al. (2005) found acceptable agreement of predicted sediment yields for the Vistonis Lagoon watershed, a low-gradient, mountainous agricultural catchment in northern Greece. Abbaspour et al. (2007) report very good agreement between simulated and observed sediment on the Thur River, a predominantly agricultural, 1,700 km^2 pre-alpine watershed in northern Switzerland. Finally, Rostamian et al. (2008) and Van Liew et al. (2007) describe work in western Iran and Northern Montana, respectively, in which limited availability of suspended sediment data precluded making any robust conclusions about the predictive ability of the model.

The work of this study aims at the calibration and validation of a mountainous catchment with limited climatic data, important snowmelt-induced streamflow and a main dammed river.

2. Materials and Methods

2.1. Study area

The catchment studied corresponds to the drainage basin of the Barasona Reservoir in the Central Spanish Pyrenees (Figure 1). The Barasona Reservoir was built in 1932 for irrigation purposes and power generation. The initial water capacity was 71 hm^3 and was increased in 1972 to a maximum water storage capacity of 92 hm^3. Today, the surface of the reservoir is 692 ha. The Aragón and Cataluña canals that originate in the reservoir provide irrigation water to 104,850 ha. The irrigation season extends from March to October, with a maximum demand in May, July and August. The Barasona Reservoir supplies an agroforestry catchment of about 1,509 km^2.

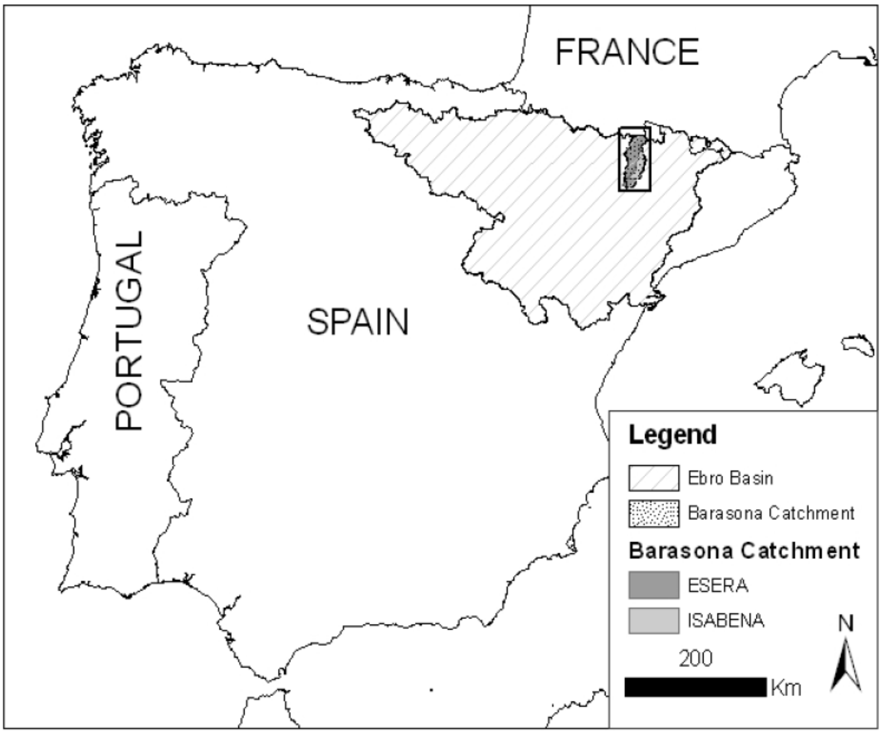

Figure 1. *Location of the Barasona Catchment*

The study area is characterized by a heterogeneous topography and lithology composed of four principal Pyrenees Structural Units (WNW–ESE trending geologic units) disposed from north to south as follows: the Axial Pyrenees composed of Paleozoic rocks (quartzites, limestone, shales) and granodiorites with peaks above 3000 m.a.s.l.; the Internal Ranges composed of Cretaceous and Paleogene sediments with several Internal Depressions formed upon more erodible materials (Eocene marls); The Intermediate Depression, a relatively lowland area composed of Miocene continental sediment; and the External Ranges that bound the basin to the south and are composed mainly of Tertiary materials

The catchment presents an altitudinal range of 3000 m, from 424 m at the basin outlet to 3,404 m (Aneto Peak) at the headwater of the basin, and a mean elevation of 1,313 m above sea level (m.a.s.l.). The average catchment slope is 39%.

The climate is defined as the mountainous type that is wet and cold with both Atlantic and Mediterranean influences (García-Ruiz et al., 1985). Temperature and precipitation gradients are observed for both north–south and west–east regions according to the relief along with the influences of the Atlantic Ocean and Mediterranean Sea. As a result, mean annual precipitation and temperature range from 500 mm/yr and 12ºC at the reservoir to more than 2000 mm/yr and less than 4ºC at the areas above 2000 m.a.s.l. The 0ºC isotherm was around 1600–1700 m.a.s.l. between November and April (García-Ruiz et al., 1986), representing the level above which snow accumulation occurs for a long period.

The drainage network is composed of two main rivers: the Ésera River and its main tributary the Isábena River, which run from north to south dividing the catchment in two main subcatchments (Figure 3).

In contrast to the Isábena River, the Ésera River is regulated by small reservoirs and dams. These rivers have different spatial developments (Figure 3) that bring different hydrological characteristics. The hydrologic regime is transitional pluvial–nival characterized by two maxima (García-Ruiz et al., 1985) (Figure 2), the late autumn maximum (October – November) and the spring maximum (April - June) which relates to the snowmelt. The streamflow related to snowmelt lasts until late April or early May.

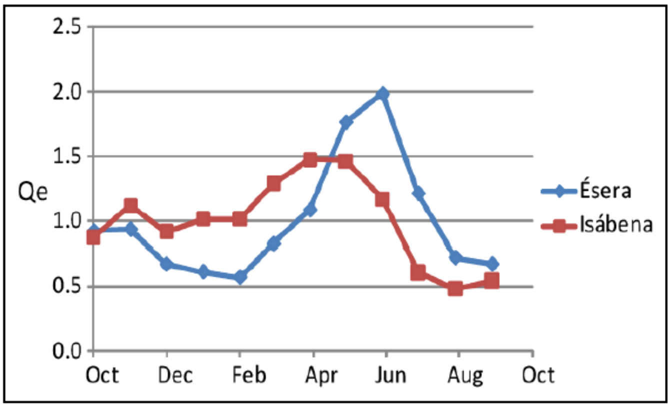

Figure 2. *Hydrologic regimes of the main rivers. Qe: specific streamflow ($m^3/s\ km^2$)*

High slopes in the headwaters and the presence of deep, narrow gorges favors rapid runoff and large floods. The floods are mainly caused by three different mechanisms: late spring–early summer snow melt and heavy rains, summer thunderstorms, and late autumn heavy rains.

In general, the soils of the catchment are stony and alkaline soils overlying fractured bedrock with textures from loam to sandy loam. These are shallow (< 1 m) and (apart from forest soils) have low organic matter contents (< 3-4 %). They are generally well drained soils with limited average water content and moderate to low structural stability.

The distribution of land uses also varies from north to south. Predominating land uses are grassland in the Axial Pyrenees, forest in the Internal Ranges and cultivated land in the more gentle southern areas of the Intermediate Depression.

2.2. SWAT model

The Soil and Water Assessment Tool (SWAT) is a physical based and continuous, long-term, distributed-parameter model designed to predict the effects of land management practices on the hydrology, sediment and contaminant transport in agricultural watersheds with varying soils, land use, and management conditions (Arnold et al., 1998). SWAT is based on the concept of hydrologic response units (HRUs) which are portions of a subcatchment that possess unique land use/management/soil attributes. The runoff, sediment, and nutrient loadings from each HRU are calculated separately using input data about weather, soil properties, topography, vegetation, and land management practices. This data is ultimately used to determine the total loadings from the subcatchment.

The most current version of the model, SWAT2009, was used in this work as an extension within the Environmental Systems Research Institute (ESRI) GIS software package ArcMAP (9.3). Fundamental spatially distributed input data required for ArcSWAT include topography, land use, soils and climate.

Estimation of key parameters pertaining to soil (e.g., available water content and saturated hydraulic conductivity), snow (e.g., lapse rates, melting) and vegetation (e.g., leaf area index and maximum canopy index) by using additional field observations in the catchment is critical for better prediction. These characteristics make it a good tool for studying the hydrologic cycle at basin scale.

2.3. Catchment configuration

A digital elevation model (DEM) obtained from the Aragón Territorial Information System (SITAR, 2010) with a spatial resolution of 20 m was used to delineate the catchment. Different subdivisions of the catchment were assessed to improve the results of the simulation. The limited daily climatic data for high altitudes caused problems which restricted the subdivision of the basin in the first simulations. The highest one is at Serraduy (1402 m.a.s.l.). Finally, the catchment was subdivided into four subbasins and 290 HRUs. The gauge stations of the catchment were used to define the subbasins in the final best project.

2.4. Soil property inputs

The soil map and parameterization was derived from the digital Soil Map of Aragón and the Harmonized World Soil Database (HWSD, 2008). The soil map includes 19 types of soil at a scale of 1:500,000 (Soil Map of Aragón, Machín J, awaiting publication). A user soil database was developed with the information of the HWSD and input into the SWAT2009 database to supplement the information of the soils. Soil parameters were defined based on FAO (2007) soil type map and field observations.

2.5. Land use

The land use map was obtained from the European Project Corine Land Cover (1990) with a resolution of 100 m and 44 classifications of land use. The land cover of the catchment is mostly classified as forest (> 50 %, table 1). Each Corine Land Cover Classification has been given an equivalent in the SWAT2009 database.

Table 1. *Simplified land cover in the 1508 km^2 Barasona Catchment (a)*

Land cover Type	Area (%)
Urban	0.1
Water	0.5
Range, grass	7.9
Bare rock, perennial ice and snow	8.5
Range, brush	11.2
Forest, deciduous	13.3
Forest, transitional and mixed	13.3
Agricultural land	16.5
Forest, evergreen	28.6

(a) Source Corine Land Cover (CLC1990) (European Environment Agency)

2.6. Climate data

Climate inputs available and utilized in this SWAT application were daily minimum and maximum temperature and rainfall. All of these inputs were based on measured data within or close to the region for the period 1987-1996. Data sources were obtained from the Governmental Meteorological Agency (AEMET Agencia Estatal de Meteorología). The increase in precipitation and decrease in temperature have been well documented. There are no climatic continuous data in the upper part of the catchment (above 1,402 m.a.s.l.) to feed into the model, so results of the model are not as satisfactory as would have been expected.

Table 2. *Meteorological stations*

Rainfall stations	Elevation (m)	Temperature station	Elevation (m)
(9829) Mediano	483	(9756) Benabarre	734
(9840) Eriste	1078	(9828) Tierrantona	635
(9841) Sesue	943	(9829D) Trillo	597
(9853) Serraduy	905	(9851) Las Paules	1402

2.7. Hydrological data

Three gauge stations were used in the model. Two gauge stations are situated in the main rivers near the end of the Barasona Reservoir (Graus and Capella) and the other one is situated at the headwater of the Ésera River (Eriste) (Figure 2). Linsoles Reservoir, situated in the Ésera River, was configured in the model in the gauge station named Eriste. The streamflow data information was provided by the Ebro River Hydrographic Administration (CHE: Confederación Hidrográfica del Ebro).

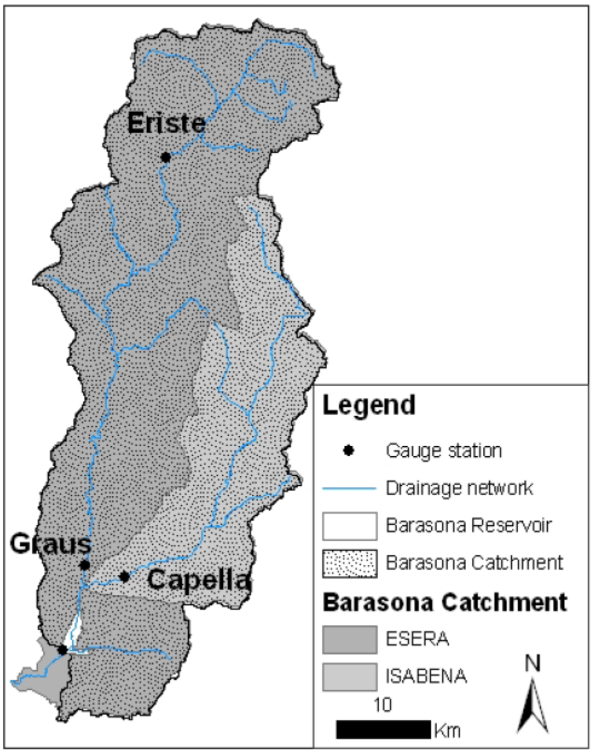

Figure 2. *Distributions of the subcatchments and locations of the gauge stations*

2.8. Model parameterization

Before applying auto-calibration, a rigorous manual parameterization exercise was performed for a better characterization of the catchment.

To alleviate the problems associated with the nonexistence of climatic data in high altitude elevations bands, temperature lapse rates and precipitation lapse rates were defined. The elevation bands were 300 m in width. A total of ten elevation bands were established for each subcatchment. The calculated precipitation lapse rate (PLAPS) was 1000 mm/km and temperature lapse rate (TLAPS) was -5 ºC/km. These values were used for the whole catchment.

As a result of the nonexistence of data corresponding to the snow routine in SWAT, a process of trial and error was used to increase the quality of the snowmelt parameterization. The initial values of the parameters of the snow routine were defined in a way to obtain resultant snowfall and snowmelt values in good agreement with those expected in the region (Table 3).

Table 3. *Defined parameters relating to the snow routine:*

Parameter	**Value**
Snow fall temperature, SFTMP (ºC)	2
Snowmelt temperature, SMTMP (ºC)	1.5
Maximum melt rate of snow during a year, SMFMX (mm/ºC/ day)	3.5
Minimum melt rate of snow during a year, SMFMN (mm/ºC/ day)	0.1
Snow pack temperature lag factor (TIMP)	0.1
Minimum snow water content at 100% snow cover, SNOCOVMX (mm)	200
Snow water equivalent at 50% snow cover, SNO50COV	0.1

3. Model Calibration and Validation

Calibration efforts focused on improving model streamflow predictions at the two gauge stations (Graus and Capella) which are close to the reservoir. Prior to the auto-calibration of the parameters, the Nash–Suttcliffe coefficient (NSE, Nash and Suttcliffe, 1970) and the deviation in total volume (Dv, ASCE, 1993) were used to quantitatively assess the ability of the model to replicate monthly temporal trends in measured data.

Because of the dammed characteristics of the Ésera River, only the data of the gauge station of the Isábena River (Capella gauge station) were used like observed data in the auto-calibration process. For this purpose, the SUFI-2 (Abbaspour et al., 2007) algorithm of SWAT-CUP (Abbaspour et al., 2010) was used, choosing the Nash-Sutcliffe efficiency (NSE) as the objective function. Among parameters, thirteen parameters were used in the calibration. The first six parameters were ranked high in the sensitivity analysis and others were related to the snow routine (Table 4). The model was calibrated only for flow. The calibration period corresponded to 1987-1991 and the validation period to 1992-1996.

4. Results and Discussion

NSE values for calibration of the model varied. Initial NSE values of 0.64 and 0.51 were found for the Capella and Graus gauge stations, respectively, while NSE values obtained after calibration were 0.65 and 0.40 for the Capella and Graus gauge stations, respectively. The Dv achieved values from -3.91% and -0.68% to 0.41% and 0.11% calibrated values, respectively to Capella and Graus gauge stations.

Calibration slightly improved the NSE of the Capella gauge station but did not improve the NSE of the Graus gauge station. This produced an increment of the available water in the catchment.

Table 4. *Calibrated parameters results*

Parameter	Fitted Value
r__CN2.mgt	0.08075
v__ALPHA_BF.gw	0.0215
v__GW_DELAY.gw	25.32625
v__CH_N2.rte	0.00885
v__CH_K2.rte	2.61225
v__ALPHA_BNK.rte	0.60485
v__SFTMP.bsn	1.33603
v__SMTMP.bsn	4.3
v__SMFMX.bsn	1.375
V__SMFMN.bsn	0.375
V__TIMP.bsn	0.09775
V__SNOCOVMX.bsn	462.5
v__SNO50COV.bsn	0.25475

r: multiply by (1+x) value; v:replace by value

Simulation improvement after calibration was less than expected but within the range of acceptable error (Figure 3). The error of streamflow in the high flows occurred in the summer (Figure 3); this might be caused by uncertainties in observed precipitation data related to local thunderstorm events. This, coupled with limited climatic data in altitude and the inferred snow routine, may explain the rest of the error.

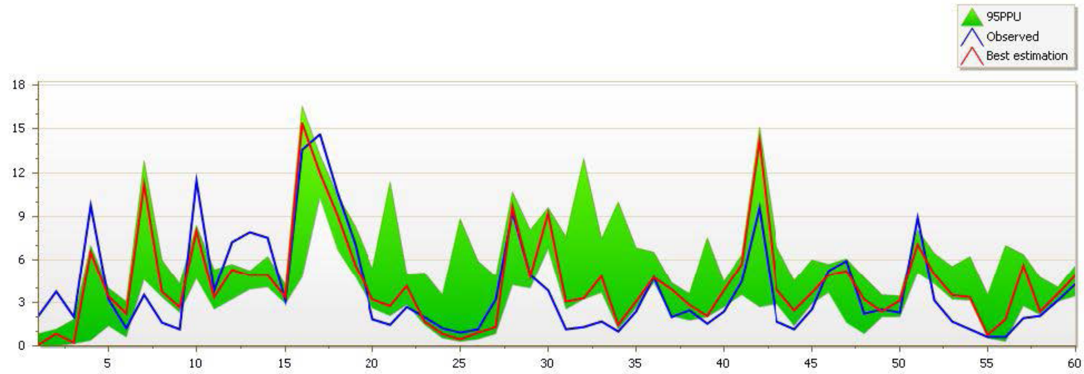

Figure 3. *Observed and calibrated streamflow at Capella gauge station*

Model validation for the period 1992-1996 produced an acceptable simulation for the Capella gauge station with an NSE of 0.46 and a Dv of 0.30%. For the Graus gauge station, the simulation had an insufficient NSE of -0.12 and a Dv of 0.08 %.

5. Conclusions

Rugged topography and lack of meteorological data at headwaters are limitations to SWAT simulation in this alpine catchment. As a consequence, simulation of snow, snowmelt and streamflow presents some inconsistencies. Therefore, an improved definition of the climatic data for the catchment is necessary in order to produce more adjusted simulations. The dammed characteristics of the Ésera River may also affect the simulation results of the Esera subcatchment and a more detailed adjustment of inflow-outflow data for the Linsoles reservoir might also contribute to an improved calibration for the Esera subcatchment.

Acknowledgments

This research was supported by the MEDEROCAR project (CGL2008-00831/BTE).

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