Hydrological modelling and forestation scenarios – predicting how forests will contribute to the provision of hydrological services in a small watershed using SWAT

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ABSTRACT

Forests are among the most important ecosystems for the provision of hydrological services. These include: water supply and water damage mitigation. Because forests may play different hydrological roles according to the environmental characteristics of each region, it is important to model how forests will contribute to the provision of hydrological services. Distributed and physically based hydrological models, such as SWAT, can help to predict the impact of land-use changes and management involving forests and other land uses, on water resources. In this context, the objective of this paper is to apply SWAT hydrological model to Vez watershed, in Northwest Portugal, and to analyse the hydrological consequences of different land cover scenarios.

SWAT was applied in Vez watershed with climatic daily records for a period of 10 years (1999-2008), and calibrated with observed discharge and sediment records. SWAT provided data about water yield, amount of sediments, evapotranspiration and water balance. Those variables were used to forecast the hydrological effects of three scenarios of forestation: conservation, production and degradation.

Expected results will be the change of water yield after increase of forest cover. Water supply services quantity will probably be affected mainly in dry years, but timing will improve under forest cover. The benefits of having forests will be more important for water damage mitigation services, including the decrease of soil erosion and reduction of peak flows due to increased infiltration.

The outcomes of the modelling exercise may be useful to improve options for forest planning and water management under an ecosystem service framework.

KEY WORDS: *Hydrological services, Forests, SWAT, forestation scenarios, Northwest Portugal.*

INTRODUCTION

Water plays an essential role in the functioning of ecosystems (ChapinIII *et al*., 2002). In addition, humans and society rely on ecosystems to provide hydrological services and their resulting benefits (MA, 2003; Brauman *et al*., 2007). These include: water supply in terms of quantity, quality and timing (for household, agriculture, industry, hydropower generation, transportation, recreational and spiritual benefits); and water damage mitigation (reduction in the number and severity of floods, decrease in soil erosion and mitigation of landslides).

Forests are among the most important ecosystems for the provision of hydrological services (Calder, 2002; Carvalho-Santos et al., 2013). Forests promote infiltration, increasing soil moisture content, groundwater recharge and the gradual release of water throughout the year (Bruijnzeel, 2004; van Dijk & Keenan, 2007). In addition, surface runoff is lowered, maintaining soil stability (Ilstedt *et al*., 2007). Furthermore, there is evidence that the existence of forests contributes to moderate water-related hazards, such as floods and landslides (Calder & Aylward, 2006; Bredemeier, 2011). Conversely, forests may reduce the annual water yield through increased loss by evapotranspiration, and consequently limit the amount of water available in the watershed (Bosch & Hewlett, 1982; Sahin & Hall, 1996; Brown *et al*., 2005; *Farley et al*., 2005)

Because forests may play different hydrological roles according to the environmental characteristics of each region, it is important to model how forests will contribute to the provision of hydrological services in order to improve land management options for forest planning. SWAT (Soil and Water Assessment Tool) is a widely used hydrological model developed in the early 1990s by the Agriculture Research Service (USDA), USA (Arnold *et al*., 1998). SWAT was developed to predict the impact of land management on water resources, performing routines of simulated discharge on monthly or daily time steps (Arnold & Fohrer, 2005). SWAT has been successfully applied around the world, including in the Mediterranean watersheds of Portugal (Nunes *et al*., 2008). However, it has not been applied yet to the Northwest mountains in Portugal, where annual precipitation can reach more than 3 000 mm/year.

In this context, the objective of this paper is to apply the SWAT hydrological model to the Vez watershed, in Northwest Portugal. We intend to spatially analyze the role of forests in the provision of hydrological services in a mountainous region with high (though seasonal) precipitation rates, and to analyze scenarios of forestation regarding the provision of hydrological services.

METHODS and PLELIMINARY RESULTS

Study area

The river Vez has a small watershed (252 Km^2) located in the Soajo and Peneda mountains, Northwest Portugal (Figure 1). Annual precipitation varies from 1 000 mm/year up to 3 000 mm/year in wet years, mainly concentrated in the autumn and winter months (Figure 2 a). Average precipitation for the study period (1999-2008) was 1 500 mm/yr, and average temperature was 13.8 ºC/yr. Average observed discharge (2003-2008) in Pontilhão de Celeiros hydrometric station was 1 040 mm/yr. Topography is complex with elevation ranging from 30 m to 1 400 m. Slopes are steep with 58% of the watershed above 25% slope. Granites and some schist characterize geology. There are five major soil types in the watershed (Figure 2 d): in highlands prevails Humic Regosols (67%) and Leptosols (9%); in lowlands Dystric Antrosols (22%), Fluvisols (1%) and Urban (0.56%). In terms of land use (Figure 2 c), open areas of bare rock and heath, with shrubland (broom) and transitional forest occupy the highlands, whereas agricultural and forest areas (common oak, maritime pine and eucalypts) are common in lowlands (Table 1).

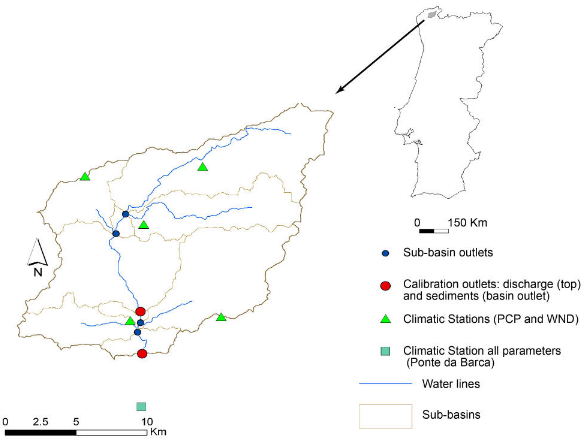

Figure 1. Study area (Vez watershed).

Table 1. Land-use in Vez watershed. Correspondence between COS'00 classes (reclassified) and SWAT.

COS'00	Identification	% area	SWAT code	Parameters sources
1	Urban areas	3.76	URLD	ArcSWAT
2	Arable land	18.20	AGRL*	ArcSWAT
3	Permanent crops	0.24	VINE	Nunes, 2007
4	Pine	6.93	PINE	ArcSWAT
5	Oak	6.95	OAK	ArcSWAT
6	Broad-leaved forest	2.01	FRSD	ArcSWAT
7	Eucalyptus	0.69	EUCL	Nunes, 2007
8	Bare rock and sparsely vegetated areas	8.87	BSVQ (Baren sparsely vegetated)	MWSWAT
9	Natural grassland, moors and heathland	37.49	MIGS (mixture grassland/shrubland)	MWSWAT
10	Transitional forest and shrub	14.72	MISF (misture shrubland/forest)	Adapted from SHRM (Nunes, 2007)
11	Water	0.15	WATR	ArcSWAT

* Corn (60%) and Winter Pasture (40%)

Data

Data for SWAT set up was collected and prepared using Excel 2010 and ArcGis 9.3.1 (ESRI).

Topographic data used in the watershed delineation and parameterization process came from Digital Elevation Model (DEM) 25 m resolution from IGeoE (Instituto Geográfico do Exército, Portugal).

Land cover dataset came from Land Cover map from the Northwest Portugal and Galicia 2000 (COS'00), 1:25 000 scale resolution (SIGN II, 2008). This map was elaborated under the project SIGN II and respects the requisites of COS'90. Classes from this map were aggregated into 11 groups, in order to represent the major types of land-use for SWAT parameterization (Table 1). Soil dataset was based on Soil Map for Entre-Douro e Minho, 1:100 000 (Agroconsultores/Geometral, 2002). Classes were grouped into five major soil types (Humic Regosols and Leptosols, Urban, Dystric Fluvisols and Antrosols).

Climatic parameters were obtained from SNIRH for the period 1999-2008 (SNIRH, 2012). From 1999 until 2003, daily records were collected. After this period, hourly precipitation and wind speed records were collected for 7 climatic stations (Figure 1). Hourly solar radiation, relative humidity and minimum and maximum temperature were available for station Ponte de Barca. All hourly were turned into daily records. Days with less than 20 hourly records were considered as gap value. To fill the gap value days for precipitation, a regression analysis was made considering the correlation between more 10 udometric stations around

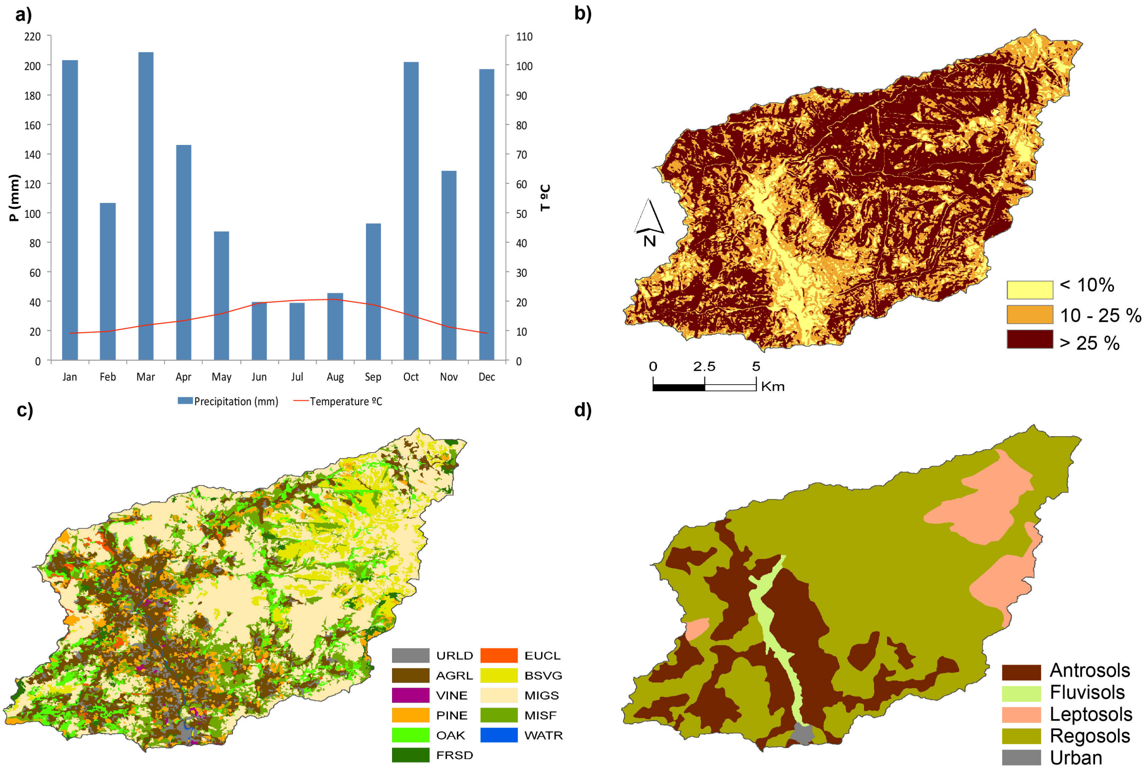

Figure 2. SWAT setup for Vez watershed: a) Climate graph for the study period (1999-2008) - average precipitation from 5 climatic stations in Vez basin (PCP stations - figure 1) and temperature from Ponte da Barca; b) Slope (from DEM - IGeoE); c) Land use map (COS'00); d) Soil map (Agroconsultores and Geometral, 1995)

the watershed. For the other climatic parameters the same procedure was made using 4 climatic stations inside a buffer of 50 km distance.

Climatic data to create the weather generator table came from NCDC for the station Vigo, Spain, with a dataset of 20 years (NCDC, 2012). Solar radiation was calculated using Hargreaves-Samani equation.

Daily-observed discharge records for hydrometric station Pontilhão de Celeiros were collected and calculated without gaps for the period 2003-2008 (SNIRH, 2012). Monthly sediment load records were collected from Valeta station (Figure 1 basin outlet) for the period 1999-2008 (SNIRH, 2012).

SWAT setup, calibration and validation

SWAT is a physically based distributed model with daily and monthly calculations of hydrological balance parameters in the watershed (Neitsch et al., 2011). The watershed is divided into homogeneous simulations units, Hydrologic Response Units (HRU's) based on land use, soil and slope (Gassman et al., 2007). We applied SWAT (2009 version) using ArcSWAT interface in ArcGIS 9.3.1 (Winchell et al., 2010). We established a period of simulation between 1999-2008, which has daily records of climatic parameters.

The Vez watershed was delineated into 10 sub-basins using DEM (Figure 1). Land cover, soil and slope data were used to parameterize the model and create HRU's (Figure 2). COS'00 land use classes were converted in SWAT compatible classes (Table 1). We used classes from ArcSWAT, from MWSWAT and from the Ph.D thesis of Nunes (2007). We created a new class, MISF (Table 1), which parameters were adapted from SHRM (Nunes, 2007) considering the different vegetation types in the Atlantic context. Soil classes' parameters were based on (Nunes, 2007). We divided slope in 3 classes: 0-10%; 10-25%; > 25% (Figure 2). To reduce the number of insignificant combinations of these 3 parameters, we used 50 ha threshold. Therefore, class 3 (VINE) and class 11 (WATR) were dissolved. SWAT defined 166 HRU's representatives of environmental conditions of the region.

Finally, the model was forced using daily rainfall and wind speed from five climatic stations. To improve the model performance we establish 10 elevation bands for precipitation with a lapse of 1 000 m/Km calculated from collected data. The model was not sensitive to this input, which we believe is because precipitation was already representative of the basin.

To calibrate the model, some sensitive parameters were changed manually against observed discharge and sediment records, in a trial error method. Daily discharge measurements for the period 2003-2005 were used to calibrate the model in the area upstream the discharge outlet (Pontilhão de Celeiros). The period 2007-2008 was used to validate the model. Calibrated parameters were then applied to the entire basin. Monthly sediment records (basin outlet) for the period 1999-2008 were used to calibrate the model for the entire basin.

Forestation scenarios

SWAT has routines that allow for simulation of forest growth from seedling to mature stands, considering plant phenological development, leaf area, radiation interception and biomass (Gassman et al., 2007; Neitsch et al., 2011). Scenarios of land cover change, namely increase in forest cover, may influence evapotranspiration, water yield and sedimentation values. We consider 3 different forestation scenarios to run in SWAT, considering the current simulation as a reference scenario: i) conservation/protection, using autochthones tree species, namely common oak (*Quercus robur*) and in areas with shallow soils with less forest capability, maritime pine (*Pinus pinaster*); ii) production/invasion using fast-growing tree species, such as eucalypts (*Eucalyptus globulus*) and increase areas of invasive species, such as silver wattle (*Acacia dealbata*); and iii) degradation, constant shrubland due to fire disturbance. A special class for silver wattle was parameterized based on literature review and expert knowledge. Forests of oak, pine, other deciduous and eucalypts occupy about 16% of Vez basin (COS'00). In 1990 (COS'90) forests occupied about 30% of the area with prevalence of pines and common oaks. Fires in the watershed (1993, 1995 and 1998) were one of the causes for forest area decrease. We want to increase forest occupation to 60% (with exception for urban areas, agricultural areas and areas with null capability for forest (BSVQ)). According to the capability for forest map, half of the region has reduced capability for forests growth (SIGN II, 2008). However, this characteristic is important for the creation of forest with protection function, in which pine is commonly used due to its capacity to growth in shallow poor soils.

Preliminary results

SWAT simulations and parameterization processes are still going on at the time of paper submission. Therefore, we only present the methods and the setup of SWAT to better guide the reader at the time of oral presentation.

However, expected results will be that an increase of forests will affect the total water yield. Only under the degradation scenario water discharge would increase, due to lower evapotranspiration, however the amount of sediments from soil erosion would increase. We expect that forestation scenarios would not affect water supply services in terms of quantity, taking into account the annual precipitation rates, comparing for instance with Mediterranean watersheds. In turn, the benefits related to water supply timing would improve significantly under the conservation scenario. The benefits of having forest will be more important on water damage mitigation services, mainly in the decrease of soil erosion. Under the production/invasion scenario, the negative effects of water loss by forests should be balanced with the positive effects of soil erosion control.

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