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Field data to enhance SWAT model performance. The case of a small forested watershed.

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Abstract

The Soil and Water Assessment Tool (SWAT) model has been applied widely in many types of environment with different aims. The purpose of this paper is to assess the ability of SWAT to simulate hydrological processes in the Aixola watershed. Electrical conductivity (EC) was used to estimate water contribution from the two main sub-watersheds. Streamflow contribution from the sub-watersheds varies throughout the year; the largest of the two contributes greater flow in wetter seasons, while the smaller one has more regulation capacity and contributes more in summer. The data obtained from EC were compared with results from the model, simulating this variability satisfactorily, and even better when the model was forced during calibration. Additionally, EC measured at the outlet of the watershed was used to make a decomposition of the hydrograph (surface runoff - base flow), comparing the data obtained with those simulated by SWAT. The results showed that the model performed well and identified the source of uncertainties in modelling this watershed. Using field data made it possible to obtain a more realistic hydrological simulation of the Aixola watershed.

Key words: SWAT model; sub-watershed contribution; soil regulation; electrical conductivity; forced simulation.

1. INTRODUCTION

Understanding runoff generation processes is essential for predicting water quantity and quality (Ladouche et al., 2001; Uhlenbrook, 2006). Consideration of these processes becomes necessary when climate and land use conditions change (Naef et al., 2002; Negley and Eshleman, 2006; Stewart and Fahey, 2010) or when management decisions have to be taken. The most widely tool used by managers when handling these changes at watershed scale is modelling. In the present study, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) was applied and tested to evaluate its ability to reproduce these processes in a small watershed (Aixola). This is a hydrological model incorporating water quantity and quality which is used in watershed management applications. SWAT has been applied in many studies targeting watershed management (e.g. Santhi et al., 2001; Tuppad et al., 2010), modelling of agricultural activities (e.g. Van Liew et al., 2003; Srinivasan et al., 2010) and even in small and/or forested watersheds (e.g. Veith et al., 2005; Bracmort et al., 2006; Behera and Panda, 2006; Parajuli, 2010; Zhou et al., 2011).

In the Basque Country, SWAT has been used in several watersheds for different purposes. The model was employed in the Alegria watershed to study the transport of pollutants in an agricultural area (Cerro et al., 2014) and in Aixola to explore the potential impact of climate change on runoff and suspended sediment yield (Zabaleta et al., 2014). Some authors have noted that SWAT needs some improvements in small (Qiu et al., 2012) and forested (Arnold and Fohrer, 2005) watersheds. Nonetheless, for the Aixola watershed, which is both small (4.6 km^2) and forested, the model calibration (1/1/2007–31/12/2010) and validation (1/1/2005–31/12/2006) results in the outlet were rated as satisfactory (Zabaleta et al., 2014). However, no evaluation was made of the processes simulated by the model.

In most cases, models are applied with little knowledge of the hydrological processes occurring in the studied area. However, as Beven (2007) suggests, neglecting processes because of a lack of understanding of how the systems work ultimately influences how well the system can be predicted by a model. In this regard, Yu and Schwartz (1999) noted that the performance of the numerical models would be enhanced by analysing and taking into account the runoff generation processes in the watershed under study when modelling. These authors showed that separation of the hydrograph can provide data that can be used to calibrate numerical models.

Bearing all this in mind, many studies have used electrical conductivity (EC) as an environmental indicator for hydrograph separation (Pilgrim et al., 1979; Matsubayashy et al., 1993; Caissie et al., 1996; Cey et al., 1998; Stewart et al., 2007), applying a mass balance approach. EC was also applied in the Aixola watershed (Zabaleta and Antigüedad, 2013) to make a preliminary approximation of the base flow/surface runoff contribution in storm events. In this study, newly obtained field data (continuous series of electrical conductivity in the main tributaries and the outlet of the watershed) have made it possible to perform a new application of the model in the Aixola watershed and evaluate it. Indirect data obtained through the electrical conductivity-based mass balance approach have been used to understand better the runoff generation processes throughout the watershed in order to help provide a more realistic simulation. These data have been used to perform a new SWAT project, whose main objectives are: 1) to indicate where and when the greatest uncertainties in the simulation results occur (surface/base flow contribution, spatial and temporal distribution) and 2) to assess whether it is possible to obtain good results in the outlet along with a good approximation of the water contribution from different parts of the watershed.

2. MATERIAL AND METHODS

2.1. Study area

The Aixola watershed is located in the central part of the Basque Country (northern Spain) in the province of Gipuzkoa, at an average latitude of 43° N and an average longitude of 1° W (Fig. 1). It covers an area of 4.6 km^2 and is comprised of two main streams; the watershed can therefore be divided into two main sub-watersheds. The smallest sub-watershed, Txulo, covers 25% of the entire watershed (1.1 km^2) and is located in the north, whilst the largest, Elgeta, covers 75% (3.5 km^2). The two streams converge near the gauging station (40 metres upstream), which was selected as the outlet of the watershed. The Aixola river drains into the Aixola reservoir, which has a capacity of 2.79 hm^3 and is used for drinking water supply. The prevailing climate in the region is humid and temperate. The mean annual precipitation is about 1480 mm, distributed fairly evenly throughout the year; the mean annual temperature is 12 ºC, and the mean annual discharge is 600 mm, around 0.092 m^3 s^{-1}.

The elevation in the watershed ranges from 340 m at the outlet of the watershed to 750 m at the highest peak. Most slopes have less than 30%. The lithology is highly homogeneous with most of the bedrock (94%) consisting of practically impervious Upper Cretaceous Calcareous Flysch (Santonian-Mid Maastrichtian). The main types of soil are cambisols and regosols, with depths ranging from less than 1 m to more than 13 m, and a loam texture (Fig. 1b). The characteristics of these soils are known thanks to the description of the soil cores obtained when drilling for the installation of six piezometers (Fig. 1b) in the watershed in January 2012. The land use is very homogeneous; this is a highly reforested watershed with evergreen stands (pinus radiata); Pinus radiata occupies more than 80% of the area (Fig. 1c).

2.2. Measured data

Precipitation, air temperature and discharge are measured every 10 minutes in the gauging station (Fig. 1a). Additionally, at this point, the specific electrical conductivity (at 25 ºC, hereafter EC; µS cm^{-1}) of water is measured every 20 minutes. For this purpose a CTD-Diver probe (Eijkelkamp) was installed in April 2011. In October 2011 another four probes were installed; three of them along the Elgeta stream (d6, d14 and d15) and one in Txulo stream (d3) (Fig. 1a). Using these conductivity data, a mass balance approach (hereafter CMB) (Stewart et al., 2006) was applied with two aims: 1) to quantify the streamflow contribution of the sub-watersheds and 2) to separate the hydrograph observed at the outlet into two components, base flow (groundwater and subsurface flow) and surface runoff. According to this approach, water from different sources will possess different hydrochemical characteristics and the relative contributions of these sources can be evaluated by measuring both the stream discharge and the chemical quality of the mixed water flowing in the stream.

CMB does not take into account the hydrodynamic dispersion which might affect the degree of mixing between waters from different sources (Jones et al., 2006). For this reason in some cases it has been called into question (Rice and Hornberger, 1998; Jones et al., 2006). However, this approach has been successfully applied in other cases. Martínez-Santos et al. (2014) applied the CMB approach to separate the hydrograph in the Oka river (Bizkaia province, very close to the Aixola river). They considered that the small size of the watershed (31.5 km^2), the steep slopes and the quick response to precipitations led to greater consideration being given to processes driven by hydraulic gradients than those caused by hydrodynamic dispersion. A preliminary EC-based mass balance was also applied in the Aixola watershed (Zabaleta and Antigüedad, 2013) to separate streamflow during storm events. These authors show that an EC based-approach may be suitable to provide insights on the runoff generation processes in certain types of watershed.

2.3. Sub-watershed contribution

As a first step, the discharge of the two main sub-watersheds to the entire watershed (Fig. 1a) was calculated in a daily time step. For this purpose, a daily CMB was conducted for data recorded between 1/10/2011 and 31/12/2012. Points d3 and d6 were established as references for the chemical characteristics of waters from the Txulo and Elgeta sub-watersheds respectively. The CMB was performed using these data and the EC and discharge data in the outlet (d4).

$$Q_{d4}C_{d4}=Q_{d6}C_{d6}+Q_{d3}C_{d3}$$

$$Q_{d4}=Q_{d6}+Q_{d3}$$

where Q is the discharge, C is the EC and the subscripts d4, d6 and d3 are the points in the watershed where the EC was measured.

The results obtained from the CMB approach were used in the SWAT calibration process performed in this work.

2.4. Hydrograph separation

Subsequently, in order better to understand the hydrological processes occurring in the watershed and test the hydrologic simulation, two different methods were used to separate the hydrograph at the outlet of the watershed.

Firstly, a tracer-based method was used to separate the hydrograph into base flow (groundwater + subsurface) and surface runoff. To achieve this, an EC-based CMB was applied. In this case the CMB assumes that: 1) base flow conductivity is equal to streamflow conductivity at lowest flows, 2) surface runoff conductivity is equal to streamflow conductivity at highest flows, and 3) the base flow and surface runoff EC values given in Points 1) and 2) remain constant throughout the period analysed (Stewart et al., 2007). This two-component mixing model and the relationship between EC and discharge can be expressed as:

$Q_tC_t=Q_{BF}C_{BF}+Q_{SR}C_{SR}$

$Q_t=Q_{BF}+Q_{SR}$

where Q is the discharge, C is the EC and the subscripts t, BF and SR are the total, base flow and surface runoff values respectively.

During very intense storm events, in the available data series the electrical conductivity drops to minimum values of around 150 μS cm^{-1}; this value was taken as the EC of surface runoff. The maximum values were recorded before the drop in conductivity caused by storm events at the end of the summer period; highest electrical conductivity was commonly around 380 μS cm^{-1}; this value was taken as the base flow EC. These values were used to apply the CMB approach to the daily EC and discharge data recorded in the gauging station between 13/04/2011 and 31/12/2012, making it possible to decompose the hydrograph into base flow and surface runoff.

Secondly, as proposed in the SWAT model website (http://swat.tamu.edu) an automated digital filter programme (Base Flow Filter Program – BFP) (Arnold et al., 1995) was used to separate the daily discharge into the two components; in this process a low-pass filter is applied separating the “low-frequency” base flow component from the “high-frequency” runoff component (Stewart et al., 2007). In this kind of filter, the operator determines the degree of filtering by adjusting a filter coefficient and selecting the number of passes the filter makes through the discharge data set (Nathan and McMahon, 1990; Mau and Winter, 1997). The BFP passes over the discharge three times (forward, backward and forward). This is a non-tracer-based technique which, although it has only a graphical basis, is objective and reproducible (Arnold and Allen, 1999). The equation for the filter is:

$q_t = \beta\ q_{t-1}+(1+\beta)/2*(Q_t-Q_{t-1})$

where q_t is the filtered surface runoff at the time step t (one day), Q is the original discharge and β is the filter parameter (always 0.925). Base flow, b_t, is calculated using the equation:

$b_t = Q_t-q_t$

The filter method is comparable in accuracy with the manually separated base flow and gives results similar to the automated model of Rutledge (1993) (Arnold et al., 1995). This methodology is described in greater detail by Arnold and Allen (1999) and Arnold et al. (1995).

Data obtained from the hydrograph separation (base flow and surface runoff) using the CMB method and BFP have been compared with that obtained from the model simulation. This was possible because SWAT offers different flow components as output data. In this case only the distinction between surface runoff and base flow was considered for comparison. Decomposition of the hydrograph was only used to test the model performance but not to calibrate the model.

2.5. SWAT model

The SWAT model is a basin-scale continuous time hydrological and environmental model that uses a time step of one day (Arnold et al., 1998). It was developed for the US Department of Agriculture (USDA), Agricultural Research Service, to predict the effect of land management practices on water, sediment and agricultural chemical yields.

In SWAT the watershed is divided into multiple sub-basins which in turn subdivided into Hydrological Response Units (HRUs) with relatively homogeneous land use, slope and soil properties. The model is flexible in watershed discretization; the user can place a control point anywhere in the watershed, which will then be taken as the outlet of that sub-basin. This makes it possible to obtain the results of the simulation relating to water quantity (including the separation of the hydrograph) and quality for any previously selected point. However, there is no possibility of analysing what is happening inside the sub-basins.

SWAT considers the watershed hydrology in two parts. The first part is comprised of the watershed land areas that simulate the water transported to the channel together with sediment, nutrients and pesticides from each HRU. The second part consists of the behaviour of the water in the channels from tributaries to the watershed outlet (Cibin et al., 2012). The surface runoff is predicted for daily rainfall by using the modified SCS curve number (USDA Soil

Conservation Service, 1972). The peak runoff rate is calculated with a modified rational method (Chow et al., 1988). The lateral subsurface flow in the soil profile (0–2 m) is determined in each soil layer with the kinematic storage routing model (Sloan et al., 1983) and is calculated simultaneously with percolation. Groundwater flow contribution to total streamflow is simulated by creating shallow aquifer storage (Arnold and Allen, 1999) and the percolation from the bottom of the root zone is considered as recharge to the shallow aquifer. In the Aixola watershed, as mentioned above, the soil profile is very deep (up to 13 m) and therefore the water storage in the soil might be similar to that represented by SWAT as a shallow aquifer, especially taking into account that the bedrock is impervious. The potential evapotranspiration can be estimated with different methods; in this case, Hargreaves (Hargreaves and Samani, 1985) was selected because the available data were temperature and precipitation. Flow is routed through the channel using the variable storage coefficient method (Williams, 1969).

2.6. Model input

In this study a new SWAT project (SWAT 2012 with an ArcGIS 10 supported interface) was performed in an attempt to improve on that previously applied (Zabaleta et al., 2014). The inputs (topography, soils, land use and meteorology) and their sources are summarized in Table 1.

The main outlet of the watershed was set at the Aixola gauging station. The digital elevation model (DEM) was used to delimit the drainage area of the watershed and taking the topographic parameters into consideration the hydrological model partitioned the watershed into 23 sub-basins (Fig. 1a), each of them corresponding to approximately 4% of total watershed area. This subdivision is consistent with studies that show the impact of the watershed subdivision on watershed modelling processes and the results obtained from the modelling (FitzHugh and Mackay, 2000; Jha et al., 2004; Arabi et al., 2006). Txulo sub-watershed was divided into 5 sub-basins (1, 2, 3, 5 and 8), while the Elgeta sub-watershed was distributed into 18 sub-basins (4, 6, 7, 9-23). The location of the CTD-divers was set as the outlet of the main two sub-watersheds, located in d3 in Txulo and d6 in Elgeta (Fig. 1a).

The different types of land use were parameterized based on the SWAT land use classes (Fig. 1c), and the primary source of the soil types was based on the Basque Government's geographical database (GeoEuskadi, 2012).

Additionally, during drilling (January 2012) of the soil cores (Fig. 1b), soil properties, such as the depth of the soils, their horizons, root depth, the texture for each horizon and in some cases the amount of organic matter were described. In general the soils are deep, with depths ranging from about 1 m in the lower zones (near the river) to 13 m in higher areas. The texture varies from loam to clay loam, and the organic matter in the first horizon is around 1-5%. Taking the Basque Government's Soil Types map as a reference and including these new data, a more specific soil map was created (Fig. 1b).

On the DEM the slopes were classified into four slope ranges 0-5%, 5-35%, 35-50% and >50%. Using the land use map, the soil types and the slope classification, SWAT performed 150 HRUs. The meteorological data used were the daily precipitation and daily maximum and minimum temperatures obtained from the gauging station (Table 1).

2.7. Model calibration, validation and evaluation

The first step (Step 1) before calibration was to evaluate the effect of the new soil map and properties obtained from the analysis of soil cores on the simulation. To do this, a simulation was performed on the new SWAT project with the values of the calibrated parameters described by Zabaleta et al. (2014) (Table 2). The second step (Step 2) was to calibrate the model from 1/1/2009 to 31/12/2012 using the daily discharge ($m^3 s^{-1}$) measured in the gauging station. In addition, for the period between 1/10/2011 and 31/12/2012 the discharge data of the main two sub-watersheds derived from the CMB approach were also taken into consideration. In this way, it was intended to study whether the use of these new data and the consideration of the associated hydrological processes might help improve the results of the simulation.

Calibration was performed manually and also automatically using the SWAT CUP program (Abbaspour et al., 2007). The SWAT CUP program was used for an autocalibration. However the results obtained with this method for the calibrated outlets (Gauging station, Elgeta and Txulo sub-watersheds) were no better than those achieved manually and therefore the results shown refer to a manual calibration. During validation (1/1/2005-31/12/2008), only the discharge in the gauging station (outlet) of the watershed was considered since no records of EC data existed for that period.

Table 2 shows the parameters that were adjusted from the model default values during calibration. These parameters were selected after a thorough sensitivity analysis using the SWAT CUP's one-at-a-time approach. The parameters have been modified separately for each of the sub-watersheds due to their slightly different hydrological behaviour: although both sub-watersheds manifest a swift response to precipitation, Txulo (sub-basins number 1, 2, 3, 5 and 8) has higher regulation capacity than Elgeta (sub-basins 4, 6, 7, 9-23) which is observed during lack of rainfall (Fig. 2). This is the reason why differences in the parameterization of sub-watersheds focus on the key characteristics for runoff distribution. The lateral flow travel time (LAT_TTIME) is considerably higher in the Txulo sub-watershed than Elgeta (Table 2), with the result that the water circulates for longer through the soil profile. Focusing on the soil properties, the available water capacity (SOL_AWC) and the moist bulk density (SOL_BD) of the soil layer in Txulo increased during calibration and therefore the soil of this area of the watershed is able to hold more water. On the other hand, parameters such as Manning’s n value for overland flow (OV_N) and the base flow alpha factor (ALPHA_BF) decreased in Txulo, so that water circulation was lower. Another parameter with a lower value in Txulo is the maximum canopy storage (CANMX); evapotranspiration in this sub-watershed is therefore lower and thus there is more available water. To intensify the flow peaks, the Curve Number for moisture condition II (CN2) was increased by 10% in Txulo. Additionally, elevation bands (ELEVB, ELEV_FR) were used to account for orographic effects on precipitation and temperature of the Aixola watershed.

The values of the parameters of the Elgeta sub-watershed are very similar to those set in the previous SWAT proyect (Zabaleta et al., 2014), in which the values of the parameters were the same throughout the watershed.

In order to evaluate the performance of the model in the Aixola watershed and Txulo and Elgeta sub-watersheds, simulated data were compared with data taken from field measurements using several widely-used model evaluation methods, namely: Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), the coefficient of determination (R2), the percent bias (PBIAS) (Gupta et al., 1999) and the ratio of the root mean square error to the standard deviation of measured data (RSR) (Moriasi et al., 2007). According to the aforementioned authors, model performance is judged as “satisfactory” if the NSE > 0.5, RSR ≤ 0.7, and PBIAS < 25% for flow for a monthly time-step. Since in this case, data are evaluated using daily time-steps it can be stated that at the mentioned statistics (NSE > 0.5, RSR ≤ 0.7, and PBIAS < 25%) the results would be, at least satisfactory. R2 values of over 0.5 are considered “acceptable” for this study based on previous criteria reported by Santhi et al. (2001) and Van Liew et al. (2003).

3. RESULTS AND DISCUSSION

3.1. Contribution from sub-watersheds

As mentioned in the Methodology section, the flow obtained from the CMB approach (1/10/2011-31/12/2012) was used to calibrate and evaluate the model daily discharge in the outlets of Elgeta and Txulo sub-watersheds. Figure 3 shows the results for the discharge for both calibration (1/1/2009-31/12/2012) and validation (1/1/2005-31/12/2008) periods for the gauging station. It can be observed that merely introducing more realistic characteristics of soils (Step 1) improves the simulation, especially in the driest seasons. However in these periods small storm events occur and the model is still unable to simulate these effects (Fig 3., Step 1). Additionally, after the first step the discharge was zero between runoff events during the driest season (summer) in the output of Txulo sub-watershed.

Once calibration has been performed, taking into account the contributions of Elgeta and Txulo sub-watersheds, peaks produced by storm events in the outlet of the watershed are simulated correctly (Fig 3., step 2) obtaining a much more adjusted simulation in high and low flows. After Step 2, simulated discharge in Elgeta sub-watershed fits well with the discharge obtained from field data, showing very good performance of the model (Fig. 2) – even better than in the outlet (Fig. 3), according to NSE, R2, PBIAS and RSR. Therefore, for the discharge in Txulo, and using the recommended statistics, data for the calibration period would show only acceptable levels of agreement (Fig. 2).

During calibration, the parameters relating to the retention capacity of the Txulo sub-watershed were changed as shown in the Model calibration, validation and evaluation section obtaining better results for discharge between runoff events. Nevertheless, these changes led to a decline in the simulation of rainfall events, as runoff response was not as quick and direct as the response observed in data obtained from the CMB. This may be one of the reasons why the simulation of Txulo was not so good. However, other issues should also be considered: the small size of the sub-watershed (1 km^2) may be critical for correct simulation of the SWAT model, or there may be gaps in the knowledge of the physical properties of this sub-watershed. Underestimation of the peak flows in the Txulo sub-watershed has a direct effect on simulation of the discharge in the outlet of Aixola watershed, and therefore the largest errors and uncertainties come from this small area.

Nevertheless, it should be noted that the use of data obtained from the CMB approach was essential in the calibration process because considering that the input data from Txulo and Elgeta are quite similar, if SWAT is not forced it is always going to simulate more water quantity in the larger sub-watershed (Table 3, Step 1). Therefore, use of this methodology revealed the importance of the Txulo sub-watershed (Fig. 2 and Table 3) which, although much smaller than Elgeta, provides a larger quantity of water in the driest seasons (summer). Regarding the temporal (seasonal) distribution of the streamflow contribution of each of the sub-watersheds into Aixola river, the results of the simulation present good results for the calibration. Table 3 shows the percentage of the model simulated in Step 1 and 2, and the streamflow contribution estimated from the CMB for each season and sub-watershed. From this data it may be concluded that the model underestimates the percentage of water contributed to the Aixola river from the Txulo sub-watershed for all seasons. Conversely, it overestimates the percentage of water coming from Elgeta.

Autumn is the only season for which two years of data could be compared. For this season, it is noteworthy that while for 2011 the results fit well there are important differences in 2012. These differences may be related to the fact that a storm event occurred in the area during October 2012 which the model was unable to correctly simulate for the Txulo sub-watershed (Fig. 2).

3.2. Surface runoff/base flow contribution

The simulated surface runoff (Step 1 and 2) and base flow were compared with that obtained applying the CMB and BFP to evaluate the performance of the model. The three methods used to separate the hydrograph (SWAT-model-based separation, tracer-based CMB and non-tracer-based BFP) show the important contribution of base flow (Fig. 4) in the Aixola watershed (13/04/2011-31/12/2012).

Comparing the results of the simulation, for the entire period and seasonally, Step 1 generates a higher amount of base flow. This may occur because, as mentioned in the previous section, during the calibration phase the model does not simulate the discharge peaks caused by small storm events. However it should be borne in mind that the calibration of Step 1 has not yet been completed and the results obtained in Step 2 are therefore the ones that will be compared with the other methods to decompose the hydrograph.

The results obtained from the CMB approach and the results of the simulation (Step 2) are very similar; around 15% surface runoff and 85% base flow in annual terms. The BFP apportioned the observed streamflow of the outlet in 30% surface runoff and 70% base flow. When this distribution is analysed seasonally (Fig. 4), it can be seen that decomposition obtained from the CMB approach and the SWAT simulation (step 2) are usually similar. These methods give base flow contribution values of around 80% for autumn, and around 90% for spring, winter and summer. The BFP gives a similar distribution but with slightly different contribution percentages. In this case, base flow contributes around 60% in autumn, less than 80% in spring and winter and around 90% in summer. Autumn is the season with the greatest differences between the three methods. It can be seen that using BFP which is comparable in accuracy with the manually separated graphical method (Arnold et al., 1995), the base flow is lower than that calculated by CMB and SWAT simulation (Step 2). Research at a watershed located near Aixola with similar physical characteristics (Martínez-Santos et al., 2014) concluded that the graphical methods might underestimate the base flow contribution, and use of this method only becomes viable for storm events where surface runoff is dominant. A previous study (Zabaleta and

Antigüedad, 2013) carried out in Aixola watershed, showed that the amounts of base flow (in storm events) were important and it may therefore be assumed that the BFP is underestimating the base flow contribution. It should also be taken into account that two of the three methods used (CMB and SWAT simulation outputs) show practically the same results (Fig. 4).

The data obtained through the CMB and BFP were not used for the calibration but they were used to evaluate the accuracy of the simulation compared with SWAT outputs. The results differ, depending on the hydrograph separation method. However, in general it can be seen that when SWAT is calibrated taking additional field data into consideration (soil characteristics and sub-watershed contribution) the results are similar to those obtained with BFP and to an even greater extent with CMB, which presents more reliable results, as shown before. Therefore the uncertainty related to the base flow / surface runoff contribution may be considered to be negligible.

Not only have we managed to achieve good simulation for the outlet; we have also managed to simulate quite accurately the runoff distribution taking place in the watershed. In any case, it should be noted that it was necessary to use data derived from field measurements to apply this approach.

4. CONCLUSIONS

Installation of probes in the river to measure the specific electrical conductivity (EC) allowed us to quantify the amount of discharge from the two sub-watersheds in Aixola and showed that the smaller sub-watershed, Txulo, has higher regulation capacity than the larger one, Elgeta. When discharge contributions based on EC data are not taken into account in calibration, SWAT always simulates higher discharge from the Elgeta sub-watershed, due to the apparent homogeneity of the watershed.

According to habitually used statistics good simulation results were obtained for the discharge in the outlets of the Aixola watershed (1/1/2009-31/12/2012 calibration, 1/1/2005-31/12/2008 validation) and Elgeta and Txulo sub-watersheds (1/10/2011-31/12/2012), for daily and seasonal time steps. The Conductivity Mass Balance (CMB) and the Base Flow Filter Program (BFP) were used to separate the discharge observed in the outlet of the watershed (13/4/2011-31/12/2012), into base flow and surface runoff. The results obtained using the CBM method were very similar to the simulation results, showing that the base flow contribution in Aixola is very important (85%). Base flow contribution calculated with the BFP (70%) is usually lower than that calculated with the other methods. Hence, the greatest uncertainties relating to modelling of the Aixola watershed with the SWAT model come from the spatial distribution of streamflow, specifically that from the smallest sub-watershed, Txulo. When this distribution is analysed seasonally good performance is observed, with autumn being the season with most uncertainties. In terms of the base flow / surface runoff relation, the model performs well.

This paper shows the importance of integrating field data related to hydrological processes in the watershed during modelling. Because Aixola is a small watershed (4.6 km^2), it was possible to achieve acceptable performance of the SWAT in the watershed outlet. However, as this paper shows, an acceptable simulation of discharge in the outlet of a watershed does not mean either a good performance of runoff generation processes in the watershed or an acceptable spatial contribution of discharge. It was therefore necessary to use field data that are usually not considered in calibration processes in order to achieve acceptable performance of the hydrological processes taking place in the watershed. Taking these field data into consideration helped make the simulation more realistic.

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***Highlights (for review)**

- Enhanced SWAT hydrological simulation in a very small forested watershed.
- Field data, uncommonly used in model calibration, included in the calibration process.
- Satisfactory simulation of outlet-discharge and sub-watersheds contribution achieved.
- Modeled and field data derived hydrograph separations were coherent.
- The model-field combined approach allowed detecting spatial-temporal uncertainties.

Table 1. Summary of the inputs introduced in the model

Data type	Description / properties	Source
Topography	LIDAR DEM 2008 (5 x 5 m)	Basque Government; Geoeuskadi (www.geoeuskadi.net)
Land use	Land use classification, 2005 (1:10000)	Basque Government; Geoeuskadi (www.geoeuskadi.net)
Soils	Soil types (1:25000)	Basque Government; Geoeuskadi(www.geoeuskadi.net)
Meteorology	Daily precipitation and minimum and maximum temperature	Gipuzkoa Provincial Council (http://www4.gipuzkoa.net/oohh/web/eus/index.asp)

Table 2. SWAT parameters selected for calibration, their description and modifications carried out during calibration for each of the sub-watersheds. Data from Zabaleta *et al.,* 2013 are for the whole watershed.

*v means that the default parameter is replaced by a given value, and r means the existing parameter value is changed relatively.

Change type	**Parameter name**	**Description**	**Flow**		**Zabaleta et al., 2013**
			Txulo	**Elgeta**	
r	CN2.mgt	Curve number for moisture condition II	↑10%	No change	↓10%
v	CH_K2.rte	Main channel conductivity	52	7	100
v	SURLAG.bsn	Surface runoff lag coefficient	1	1	1
v	ALPHA_BF.gw	Baseflow alpha factor	0.005	0.015	0.021
v	ESCO.bsn	Soil evaporation compensation factor	0.9	0.9	0.9
v	GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur	700	700	700
v	CANMX.hru	Maximum canopy storage	5	10	8
v	GW_REVAP.gw	Groundwater “revap” coefficient	0.05	0.15	0.19
	SOL_K.sol	Saturated hydraulic conductivity	No change	No change	↑10%
r	SOL_AWC.sol	Available water capacity of the soil layer	↑22%	No change	↓4%
r	GW_DELAY.gw	Groundwater delay time	450	450	40
r	SOL_BD.sol	Moist bulk density of first soil layer	1.7	No change	No change
r	ELEV. sub	Elevation at the centre of the elevation band	450	19	No change
r	ELEV_FR. sub	Fraction of sub-basin area within the	1	12	No change

		elevation band			
r	SPCON.bsn	Channel sediment routing parameter	0.0001	0.0001	0.0001
v	SPEXP.bsn	Exponent parameter for calculating sediment re-entrained in channel	1.5	1.5	1.5
v	LAT_TTIME.hru	Lateral flow travel time	82	3.57	5
v	OV_N.hru	Manning's *n* value for overland flow	0.1	0.6	0.6
v	SHALLST.gw	Initial depth of water in the shallow aquifer	1000	1000	1000
v	DEEPST.gw	Initial depth of water in the deep aquifer	0	0	0
v	RCHR_DP.gw	Deep aquifer percolation factor	0	0	0

Table 3. Percentage of seasonal streamflow contribution for Elgeta and Txulo sub-watersheds to the Aixola river for the data estimated with the mass balance approach (observed) and the simulated data (simulated Step 1 and 2).

	Observed (indirec data)		**Simulated Step 1**		**Simulated Step 2**	
	TXULO	**ELGETA**	**TXULO**	**ELGETA**	**TXULO**	**ELGETA**
FALL 2011	30	70	28	72	32	68
WINTER 2012	41	59	31	69	36	64
SPRING 2012	45	55	29	71	40	60
SUMMER 2012	92	8	27	73	82	18
FALL 2012	45	55	29	71	35	65

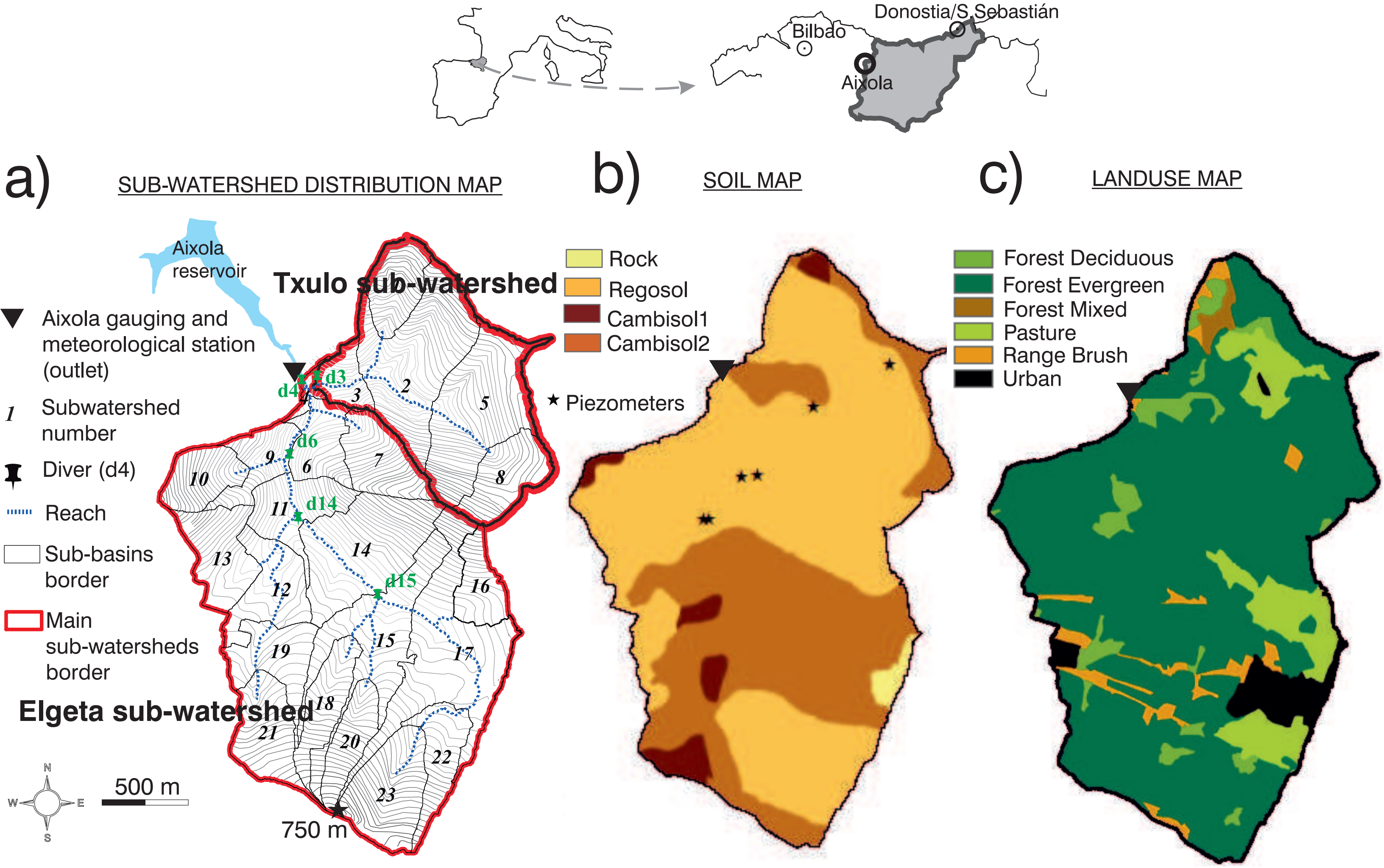
Figure 1. Location of Aixola watershed and a) contour line map, b) land use map and c) soil map. In a) the two main sub-watersheds (Elgeta/Txulo), the location of the electrical conductivity probes and the sub-basin subdivision made using SWAT can be observed. In c) the location of piezometers is shown.

Figure 2. Daily discharge derived from the CMB method and simulated daily discharge. Model evaluation statistics for Txulo y Elgeta sub-watersheds are also shown. Precipitation of the period is included.

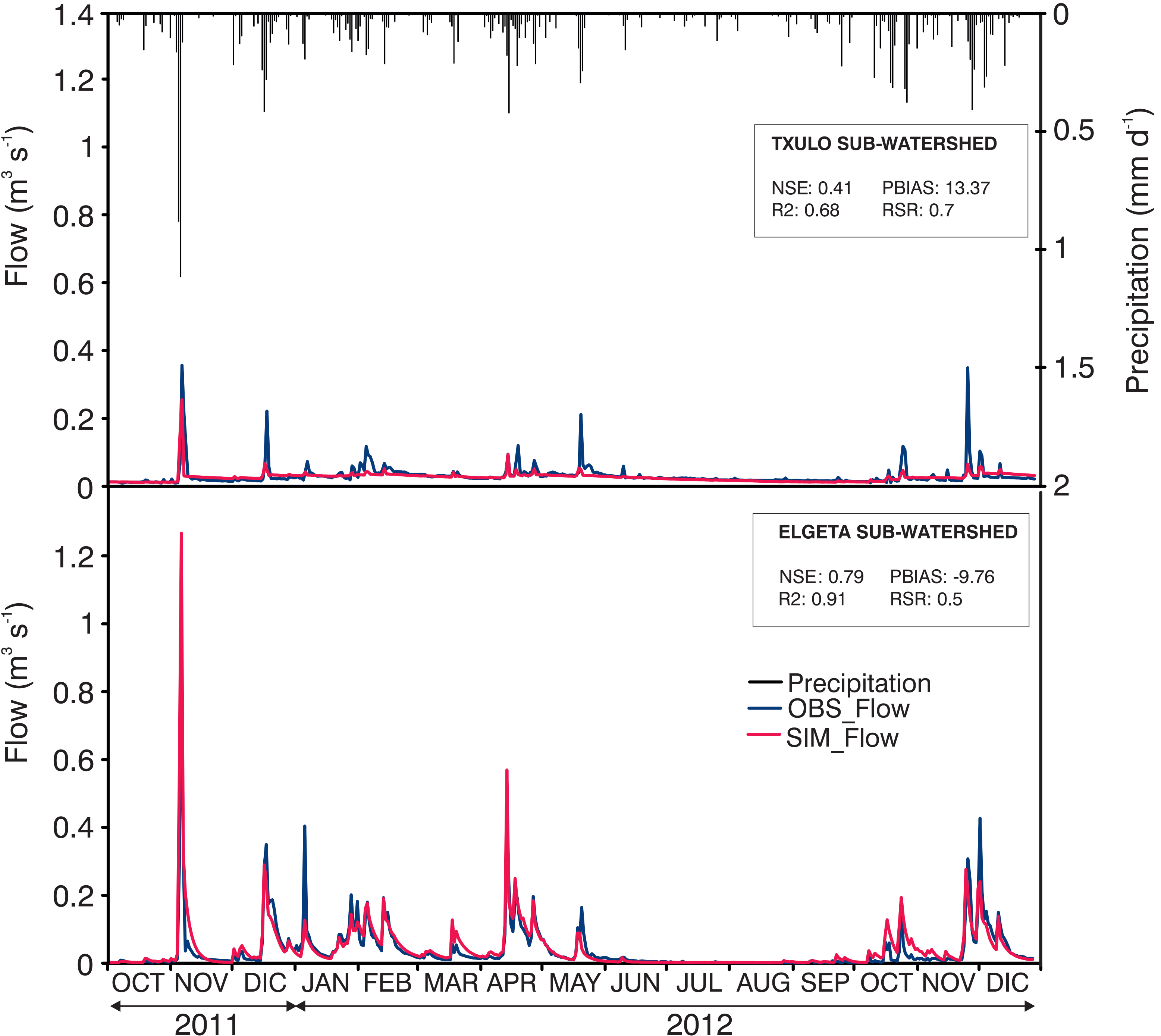
Figure 3. Simulated and observed daily discharge for calibration and validation period and the model evaluation statistics for the outlet of the watershed. Precipitation of the period was included.

Figure 4. Observed (OBS) and simulated (SIM, Step 1 and 2) surface runoff (SURQ) and base flow (BF) calculated using the CMB method (CMB) and base flow filter program (BFP). Data are expressed as a percentage, taking the observed streamflow in the case of the decomposition of the observed hydrograph, and taking the simulated streamflow for the simulated surface runoff and base flow. The period under consideration was 13/4/2011-31/12/2012.

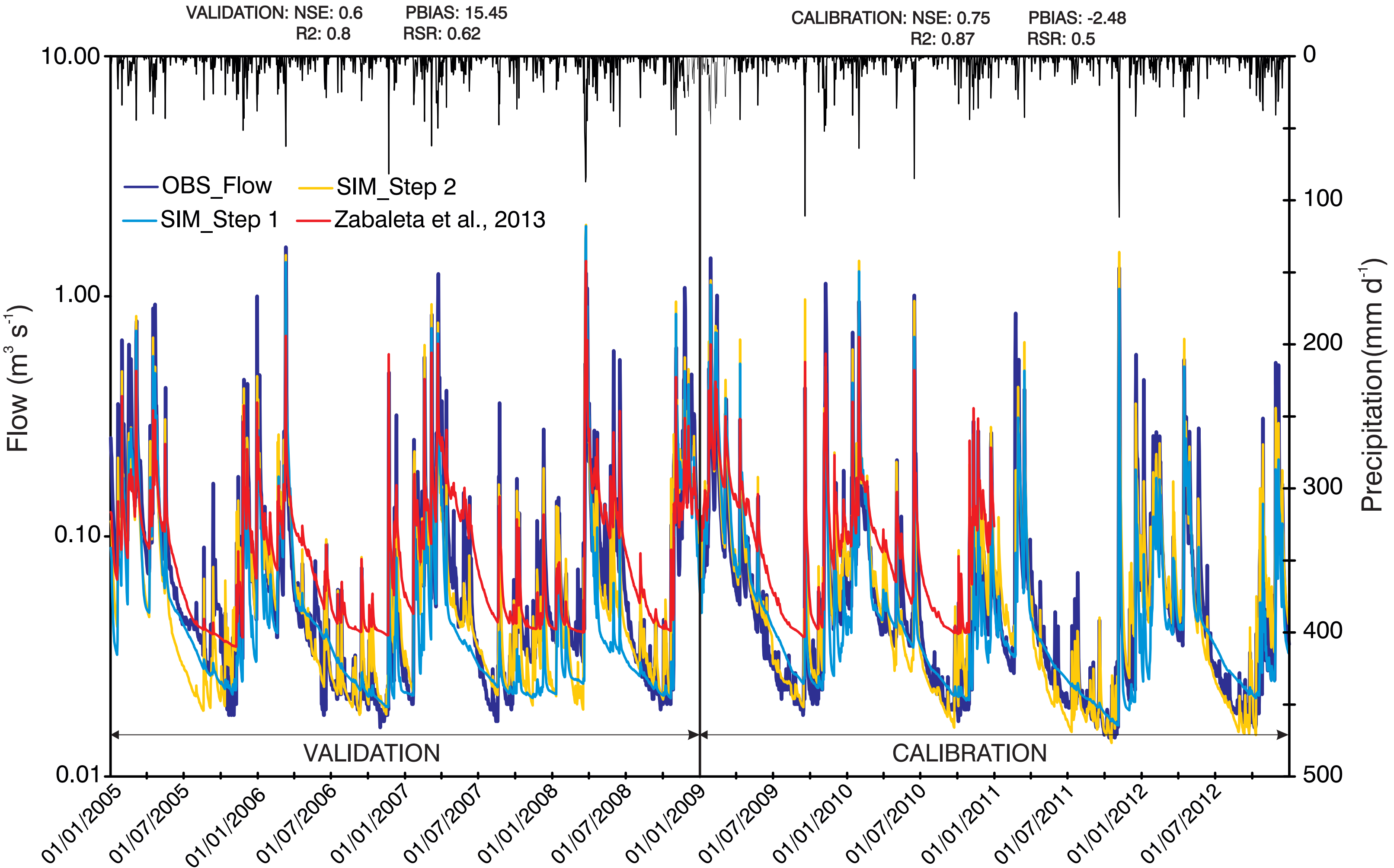
Figure


Donostia/S.Sebastián
Bilbao
Aixola
a)
SUB-WATERSHED DISTRIBUTION MAP
Aixola reservoir
Txulo sub-watershed
Aixola gauging and meteorological station (outlet)
1 Subwatershed number
Diver (d4)
Reach
Sub-basins border
Main sub-watersheds border
Elgeta sub-watershed
d3
d4
d6
d14
d15
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
N
W
E
S
500 m
750 m
b)
SOIL MAP
Rock
Regosol
Cambisol1
Cambisol2
★ Piezometers
c)
LANDUSE MAP
Forest Deciduous
Forest Evergreen
Forest Mixed
Pasture
Range Brush
Urban

Figure


1.4
1.2
1
0.8
0.6
0.4
0.2
0
Flow (m^3 s^{-1})
0
0.5
1
1.5
2
Precipitation (mm d^{-1})
TXULO SUB-WATERSHED
NSE: 0.41
PBIAS: 13.37
R2: 0.68
RSR: 0.7
ELGETA SUB-WATERSHED
NSE: 0.79
PBIAS: -9.76
R2: 0.91
RSR: 0.5
Precipitation
OBS_Flow
SIM_Flow
OCT
NOV
DIC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DIC
2011
2012

Figure


VALIDATION: NSE: 0.6
PBIAS: 15.45
R2: 0.8
RSR: 0.62
CALIBRATION: NSE: 0.75
PBIAS: -2.48
R2: 0.87
RSR: 0.5
OBS_Flow
SIM_Step 2
SIM_Step 1
Zabaleta et al., 2013
Flow (m^3 s^{-1})
10.00
1.00
0.10
0.01
Precipitation(mm d^{-1})
0
100
200
300
400
500
VALIDATION
CALIBRATION
01/01/2005
01/07/2005
01/01/2006
01/07/2006
01/01/2007
01/07/2007
01/01/2008
01/07/2008
01/01/2009
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01/01/2011
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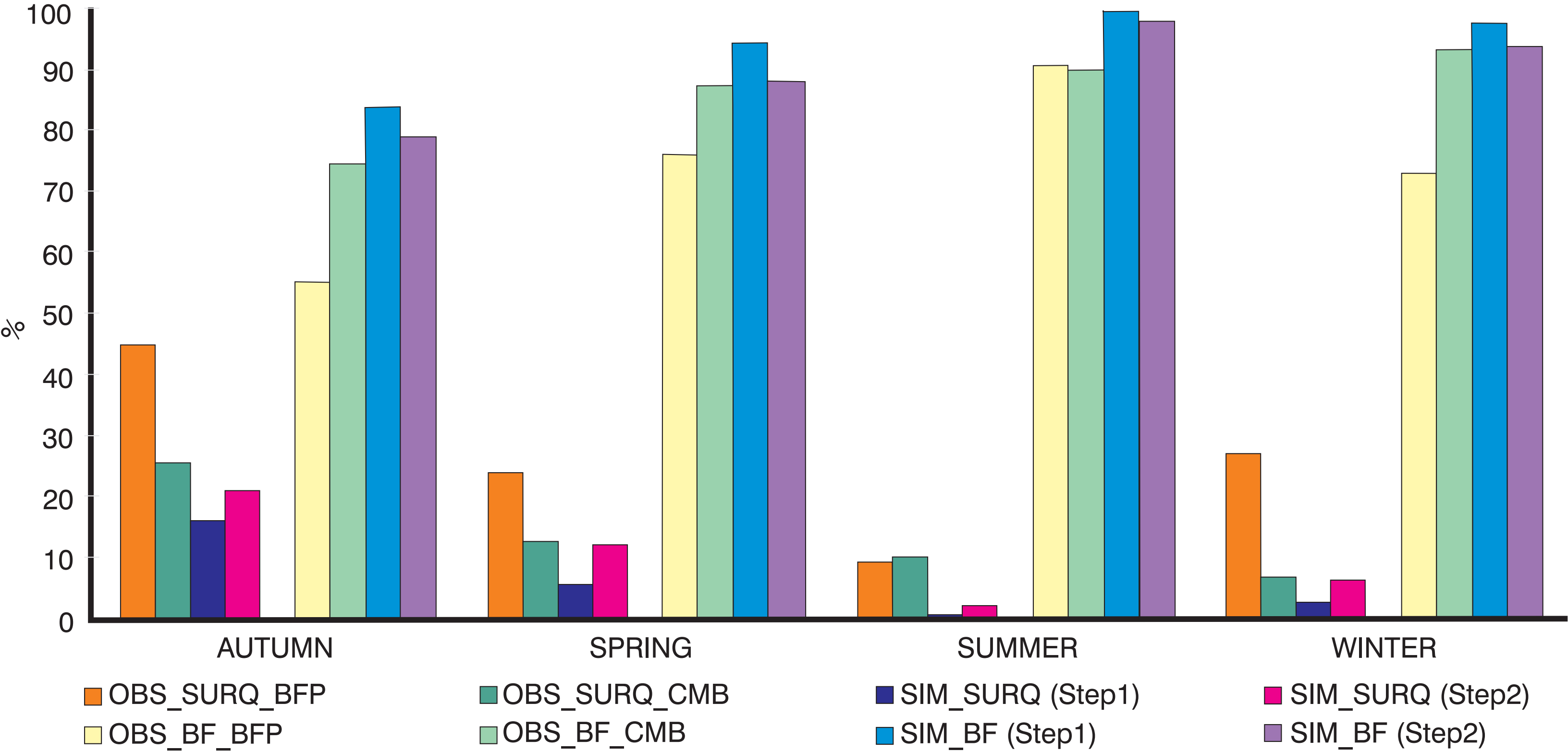
01/01/2012
01/07/2012

Figure



100
90
80
70
60
50
40
30
20
10
0
%
AUTUMN
SPRING
SUMMER
WINTER
OBS_SURQ_BFP
OBS_SURQ_CMB
SIM_SURQ (Step1)
SIM_SURQ (Step2)
OBS_BF_BFP
OBS_BF_CMB
SIM_BF (Step1)
SIM_BF (Step2)