Impacts of climate and land use changes on the hydrological and erosion processes of two contrasting Mediterranean catchments

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Abstract

The impacts of climate and land use changes on streamflow and sediment export were evaluated for a humid (São Lourenço) and a dry (Guadalupe) Mediterranean catchment, using the SWAT model. SWAT was able to produce viable streamflow and sediment export simulations for both catchments, which provided a baseline for investigating climate and land use changes under the A1B and B1 emission scenarios for 2071-2100. Compared to the baseline scenario (1971-2000), climate change scenarios showed a decrease in annual rainfall for both catchments (humid: -12%; dry: -8%), together with strong increases in rainfall during winter. Land use changes were derived from a socio-economic storyline in which traditional agriculture is replaced by more profitable land uses (i.e. corn and commercial forestry at the humid site; sunflower at the dry site). Climate change projections showed a decrease in streamflow for both catchments, whereas sediments export decreased only for the São Lourenço catchment. Land use changes resulted in an increase in streamflow, but the erosive response differed between catchments. The combination of climate and land use change scenarios led to a reduction in streamflow for both catchments, suggesting a domain of the climatic response. As for sediments, contrasting results were observed for the humid (A1B: -29%; B1: -22%) and dry catchment (A1B: +222%; B1: +5%), which is mainly due to differences in the present-day and forecasted vegetation types. The results highlight the importance of climate-induced land-use change impacts, which could be similar to or more severe than the direct impacts of climate change alone.

1 Introduction

The impact of changes in climate and land cover on watershed dynamics has been well established worldwide. Among the most important impacts from a watershed management perspective are potential alterations to the hydrological (Bangash et al., 2013; Kalantari et al. 2014; Khoi and

Suetsugi, 2014; Luo et al., 2013; Mango et al., 2011; Milly et al., 2005; Montenegro and Ragab, 2012; Mourato et al., 2015; Wilson and Weng, 2011) and erosive response (Bangash et al., 2013; García-Ruiz et al. 2013; Khoi and Suetsugi, 2014; Lu et al., 2013; Vanmaercke et al., 2011; Wilson and Weng, 2011). These changes will in turn affect the ecosystem service functioning of watersheds, such as water provisioning and erosion control (Bangash et al., 2013).

The Mediterranean Basin has been identified as one of the most vulnerable regions of the world to climate change, and the Intergovernmental Panel on Climate Change's Fifth Assessment Report points to projected changes to both the hydrological and erosive response of watersheds due to future shifts in precipitation and temperature regimes (IPCC, 2013). Under the projected climate changes, runoff is expected to decrease (IPCC, 2007, 2013; Nunes et al., 2008) as a result of lower rainfall, higher soil water deficits, and higher potential evapotranspiration (PET) (Molina-Navarro et al., 2014; Nunes et al., 2008, 2013), thereby leading to a decrease in streamflow (Lopéz-Moreno et al., 2011, 2014; Molina-Navarro et al., 2014). As for soil erosion, there is greater heterogeneity in the trends across the Mediterranean Basin, as the processes linking climate and erosion are dependent on a number of variables; including rainfall amount and intensity, soil water content, evapotranspiration, and plant cover(García-Ruiz et al. 2013; Nearing et al., 2005; Nunes and Nearing, 2011).

The magnitude of climate change impacts on hydrological and erosion processes is expected to be strongly influenced by land use/cover, as this driver *per se* is known to strongly influence these processes (Cerdan et al. 2010; García-Ruiz and Lana-Renault, 2011; García-Ruiz et al. 2013; Nunes and Nearing, 2011). Several studies conducted in the Mediterranean Basin have indicated that the hydrological behaviour of different land-cover types is linked to the existing vegetation and to its spatial and seasonal variation patterns (García-Ruiz and Lana-Renault, 2011; López-Vicente et al., 2013; Nunes et al., 2010, 2011). For example, a rise in shrub and forest cover has been reported to produce a decline in surface runoff and streamflow discharge (Begueria et al., 2003; Gallart and Llorens, 2004; García-Ruiz and Lana-Renault, 2011). Land cover also affects soil erosion, as land with permanent vegetation cover (shrub, grassland, or forest) typically has lower soil losses and sediment yields than an arable land (Cerdan et al. 2010; García-Ruiz, 2010).

While it is important to consider the individual effects of climate and land use change on hydrological and erosion processes, assessing how their combined effects will interact is crucial for assessments of the future state of water resources (Hoque et al., 2014; Khoi and Suetsugi, 2014; Li et al., 2004; Li et al., 2009; Li et al. 2012). For the Mediterranean region, only a few modelling studies have addressed the combined effects of these drivers (e.g. López-Moreno et al., 2014; Molina-Navarro et al., 2014). Most studies have focused on the effects of climate change without considering land use/cover change as well (Nunes et al., 2008, 2013; Bangash et al., 2013; Kalogeropoulos and Chalkias, 2013; Zabaleta et al., 2014). Others have only evaluated the impacts of land use changes without considering future climate conditions (De Girolamo and Lo Porto, 2012; López-Vicente et al., 2013; Nunes et al., 2011).

All climate and land use change assessment studies have associated uncertainties in the model results and the selected scenarios (see e.g. Ludwig et al., 2010, for a discussion on this issue). Uncertainties in observed data can mislead model calibration (McMillan et al., 2010; Sellami et al., 2013), and the existence of multiple acceptable model formulations and/or parameterizations can lead to different results for different climate conditions (Beven, 2012; Lespinas et al., 2014). Calibrated model parameters often compensate for shortcomings in the model structure and errors in data (Lespinas et al., 2014). Therefore, uncertainty issues can be partly overcome by restricting possible parameter values through direct measurement, by using multiple observed variables in the calibration process (Beven, 2012; Efstratiadis and Koutsoyiannis, 2010), and by evaluating the model for a large range of climatic conditions (Beven, 2012; Xu and Singh, 2004).

Scenario uncertainties include different projections of socio-economic conditions and greenhouse gas emission (IPCC, 2007, 2013); different response of climate to greenhouse gas concentrations given by different Global Circulation Models (GCMs); different climate downscaling results according to the selection of Regional Climate Models (RCMs) or statistical approaches

(Deidda et al., 2013; Maraun et al., 2010); or different land-use scenarios according to different interpretations of future socio-economic conditions (e.g. Stigter et al., 2015). The variability between these scenarios for the Mediterranean can lead to quite different projections of hydrological change (Majone et al., 2015; Piras et al., 2014; Stigter et al., 2014). To mitigate this issue, a smaller number of future scenarios (or even hypothetical scenarios) can be analyzed to detail particular impacts, becoming in effect a study of sensitivity to climate and land use change (Nunes et al., 2008, 2013; Xu and Singh, 2004).

In this work, the impacts of climate and land use changes on streamflow discharge and sediment export were evaluated both individually, to assess the relative strength of their impacts; and in an integrated manner, to provide a more realistic assessment of future (combined) impacts. This study was performed in two small experimental Portuguese basins (i.e. a paired-catchment approach), one located in a humid region (São Lourenço) and the other in a dry region (Guadalupe). These catchments were selected because: (i) each catchment is representative of the landscapes in their region (i.e. north-western and interior-southern Portugal); (ii) the responses to climate and land use changes are expected to differ in each of these regions due to their contrasting climate, soil, and land cover characteristics; and (iii) the availability of several measured parameters and hydrological variables reduces model uncertainty. A limited number of climate and land use scenarios were selected to evaluate the sensitivity of the study sites to these changes.

The specific objectives of the present study were:

i) to calibrate and validate the Soil Water Assessment Tool model (SWAT) for the São Lourenço and Guadalupe basins;

ii) to simulate the separate responses of stream discharge and sediment export for two scenarios of climate and land use change;

iii) to evaluate the effects of two scenarios combining changes in climate and land use.

2 Methodology

2.1 Study sites

The present work was carried out in two small agro-forested catchments in Portugal. The humid catchment – São Lourenço (6.20 km^2; Coordinates: 40° 25' 58''N; 8° 30' 6''W) is located in North Central Portugal (Fig. 1), whereas the dry catchment – Guadalupe (4.49 km^2; Coordinates: 38° 34' 39''N; 8° 2' 26''W) – is located in South Eastern Portugal (Fig. 1).

Due to its proximity to the sea, São Lourenço is significantly influenced by the Atlantic Ocean, resulting in mild and wet winters with strong precipitation events and warm and dry summers. The average annual rainfall and temperature in the region (1973 - 2012) was 925 mm and 15.7 °C (SNIRH, 2014a). Elevations range from 40 m a.s.l. to 100 m a.s.l and gentle slopes (<5%) dominate the area (Fig. 2). The soils are dominated by Humic Cambisols (50%) with high depth and high organic matter content; with a significant proportion of Chromic Luvisols (23%) and Calcaric Cambisols (18%) in the watershed (Fig. 2; DGADR, 2013). As part of an important Portuguese winegrowing region – the Bairrada – almost half of the São Lourenço basin is occupied by vineyards whereas the remaining area is mostly maritime pine plantations and annual rain-fed crops, such as corn, potato, and pasture (Fig 2).

In contrast, Guadalupe has typical inland Mediterranean climate, characterized by highly variable rainfall, few flood events, and an ephemeral watercourse. The average annual rainfall and temperature (1973 - 2012) in Guadalupe was considerably drier (533 mm) than São Lourenço, but differed little in temperature (15.5 °C) (SNIRH, 2014a). The watershed is dominated by moderate slopes (10%) (Fig. 3), and is located between 260 to 380 m a.s.l.. The predominant soils are relatively shallow Cambisols (54%), Luvisols (22%), and Leptosols (21%), which are associated with the intense agricultural production of the watershed in the last decades. This land use has led to severe problems of land degradation, and the area has been identified as having a high risk of desertification (Nunes et al., 2008). As in other dry regions of southern Portugal and Spain, Guadalupe is dominated by the “montado” agro-forestry system, where open cork oak stands are interspersed with annual crops and pastures (Fig. 3).

2.2 Hydrological modelling

The SWAT model (Neitsch et al., 2011) has been widely applied to different size watersheds and applications all over the world, including assessments of the effects of climate and land-cover change on water quantity and soil erosion (SWAT Database, 2014).

SWAT is a conceptual, time-continuous and semi-distributed hydrologic model initially developed to predict changes in landscape management practices on water, sediment, and chemical yields (Arnold et al., 1998; Neitsch et al., 2011). However, its structure also allows SWAT to explicitly account for climate and land use changes. For instance, the model is able to simulate the impacts of temperature changes and soil water deficit on vegetation growth, as well as the effects of climate change on the water balance, and therefore on the processes controlling surface and base flow generation (Neitsch et al., 2011). By simulating changes in vegetation and runoff, SWAT is also able to predict the erosive response. Regarding the effects of land use changes, the model allow for simulation of alternative land use distributions, which in turn affects all the other processes, i.e. water balance, runoff generation, and soil erosion (Neitsch et al., 2011).

SWAT typically operates on a daily time step and accounts for spatial heterogeneities by dividing the watershed into sub-basins, which are further divided into one or more Hydrologic Response Units (HRUs). Each HRU consists of a unique combination of soil, slope, and land use.

The hydrological component of SWAT calculates the daily water balance for each HRU. The model takes into account precipitation, evapotranspiration, soil water balance, surface runoff, subsurface runoff, and aquifer recharge. From the available methods for calculating evapotranspiration in SWAT, the Hargreaves method (Hargreaves et al., 1985) was selected for the present study. Regarding runoff, the model uses the Soil Conservation Service Curve Number method (SCS, 1985) to estimate surface runoff and a kinematic percolation model to predict subsurface runoff (Neitsch et al., 2002). Predictions of peak runoff rates for each HRU are made using the rational method (Neitsch et al., 2002). Once the model determines the water loadings from each HRU, the water flow is routed through the main channel using the variable storage coefficient method (Neitsch et al., 2011).

In SWAT, soil erosion is calculated according to the Modified Universal Soil Loss Equation – MUSLE (Neitsch et al., 2011). Sediment loadings from each HRU are then summed at the sub-basin level, and the resulting loads are routed by streamflow and distributed to the watershed outlet. Sediment transport in the channel network is controlled simultaneously by deposition and degradation processes, which depend on the sediment loads coming from upland areas and on the channel transport capacity.

A complete description of the SWAT model and theory can be found in Neitsch et al. (2011) and Arnold et al. (2011).

2.2.1 Model set-up and input data

SWAT requires as input hydro-meteorological data, a land-cover map, a soil map, and a Digital Elevation Model (DEM); the source of which for the present study is summarized in Table 1. After data compilation, ArcSWAT version 9.3 (Neitsch et al., 2011) was used for watershed delineation and sub-basin discretization using the DEM. In both watersheds, 10 sub-basins were delimited and then divided into multiple HRUs (123 in São Lourenço and 107 in Guadalupe) according to the land cover, soil types, and slope classes presented in Figs. 2 and 3.

Prior to running the model, SWAT databases (Soils, Land Cover/Plant Growth, Fertilizers, Urban) were modified to account for the specific characteristics of each watershed. Soil parameterization was performed according to the existing literature on Portuguese soils (Cardoso, 1965, 1973) and the data collected on soil properties (i.e. soil depth, soil texture, organic matter content, bulk density, hydraulic conductivity) in several soil surveys carried out at the two catchments. As for land cover, parameterization was done according to the literature for

Mediterranean vegetation and crops (Nunes et al., 2008). Information on agricultural and fertilization practices as well as other management operations was obtained from the data published by the Portuguese Ministry of Agriculture (INIA-LQARS, 2000).

2.2.2 Model calibration, validation and performance evaluation

SWAT was calibrated and validated against streamflow and sediment data collected at the São Lourenço and Guadalupe hydrometric stations, which were installed on April 2012 and April 2011, respectively. Daily streamflow was calculated based on water levels recorded at a 2 minute frequency, and the stage-discharge curve of each basin, which in São Lourenço was measured in an artificial regular channel. Daily sediment data for São Lourenço was obtained by interpolating the measured values of total suspended solids (TSS) in water samples collected by an ISCO3700 automatic sampler triggered by a water level sensor through a CR200 data-logger (Campbell Scientific®). The sediment data for Guadalupe was estimated using an OBS-3 optical turbidity sensor (continuous measurements) linked to a CR800 data-logger (Campbell Scientific®), which was calibrated using TSS data from stream water samples collected at various intervals. For São Lourenço, 1-year of data was used for model calibration (May 2012 – May 2013) and another for model validation (May 2013 – May 2014). For Guadalupe, the two periods differed in duration; ca. 1.5 years for calibration (September 2011 – May 2013) and 1 year for validation (May 2013 – May 2014). Prior to calibration, both models were warmed-up (São Lourenço – 15 years; Guadalupe – 9 years) to eliminate initial bias, taking advantage of existing meteorological data.

In addition to the streamflow and sediment records, measurements of runoff, erosion and soil moisture were also calibrated. These were conducted at 6 experimental plots implemented in the vineyard and montado area of the São Lourenço and Guadalupe catchments, respectively. For Guadalupe, actual evapotranspiration, leaf area index, and biomass of pasture and montado were also calibrated using data from 2 eddy covariance towers (Gilmanov et al., 2007; Paço et al., 2009; Reichstein et al., 2003). Model calibration was performed manually and on a daily time step;

streamflow was first calibrated independently, and then was slightly adjusted during a subsequent calibration of sediment yield. The calibrated model parameters are presented in Table 2.

Model performance, defined as the goodness of fit between observed and predicted streamflow and sediment export, was evaluated using the Nash-Sutcliffe coefficient (NSE), and the ratio between the Root Mean Square Error and the sample standard deviation (RSR) (Moriasi et al., 2007). The magnitude of model errors compared to observations was evaluated by the percent of bias, PBIAS (Moriasi et al., 2007). Positive PBIAS values indicate model underestimation, whereas negative values indicate overestimation. According to Moriasi et al. (2007), NSE values greater than 0.5 and RSR values below 0.7 indicate reasonable model performance for monthly simulations of streamflow and sediment export. PBIAS values below 25% for streamflow and below 55% for sediments are also considered reasonable (Moriasi et al., 2007).

2.3 Climate change scenarios

Climate change scenarios were developed for the period between 2071 and 2100, using the ECHAM5 GCM (Roeckner et al., 2003) driven by the A1B (more severe) and B1 (more moderate) emission scenarios, defined by Nakićenović and Swart (2000). GCM simulations were then statistically downscaled to obtain local daily predictions of rainfall and temperature (Fig. 4), using the predictor transformation approach (Maraun et al., 2010). This methodology is described in detail by Veiga (2013), and uses Mean Sea Level Pressure (MSLP) in the Atlantic Ocean as a predictor since it is related with climate in Portugal (e.g. Corte-Real et al., 1998). The methodology consists of three consecutive steps:

1) A relationship was established between the historical MLSP in the Atlantic Ocean (Compo et al., 2011) and rainfall and temperature at two meteorological stations: Coimbra (close to S. Lourenço) and Évora (close to Guadalupe). The relationship with rainfall was determined for 1950-2000 at the seasonal scale using canonical correlation analysis, while the relationship with

temperature was determined for 1970-2000 at the monthly scale using stepwise multiple linear regressions.

2) Future MSLP was estimated from anomalies between ECHAM5 predictions for 2071-2100 and 1971-2000 (reference period) for both the A1B and B1 scenarios. The resulting MSLP predictions were used to calculate a first estimate of future seasonal rainfall and monthly temperature using the above-mentioned relationship. The final estimate of seasonal rainfall and monthly temperature was calculated from anomalies between MSLP-based estimates for 2071-2100 and 1971-2000 for A1B and B1.

3) Daily rainfall and temperature were calculated using the fragments method (Svanidze, 1977). Each future prediction of seasonal rainfall and monthly temperature was compared with the closest period in the historical observations, and the daily values of the historical periods were used to represent the daily values of the future periods.

Since this method did not predict noticeable changes to temperature, the resulting daily time-series was further adjusted by adding a fixed anomaly to each day (following Kilsby et al., 2007), which were selected conservatively as the lower bound of forecasts for each study site by the Regional Climate Models used in projects PRUDENCE (Déqué et al., 2005) and ENSEMBLES (Van Der Linden and Mitchell, 2009). The added anomaly was 2.2°C for the A1B scenario and 1.1°C for the B1 scenario.

2.4 Land use change scenarios

Land use scenarios for both catchments were defined according to the methodology applied by Jacinto et al. (2013), which is shown in Fig. 4. The first step consisted in a linear downscaling of European trends for generic land use types in Portugal (IPCC, 2007; Rounsevell et al., 2006; Verburg et al., 2006). These scenarios forecast a decrease of agricultural area in Portugal for 2100, of 73% and 54% for emissions scenario A1B and B1 respectively, and suggest a number of possible land-cover type replacements including forestry and crops for bio-fuel production.

Local trends were then defined based on an analysis of historical land use patterns in order to capture the socio-ecological characteristics of both study sites (Graffin et. al, 2004). This included an analysis of literature of agriculture and forest change (e.g. Jones et al., 2011; Moreira et al., 2001; Tavares et al., 2012), and a comparison of land use between 1990, 2000, and 2006 using Corine land cover maps. These trends were used to identify patterns of land use change in the second half of the 20th century (a period of large-scale agricultural abandonment and afforestation in Portugal) to provide further insights on which types of agricultural areas would preferentially be abandoned at each study site, and what the likely replacing land uses would be.

Finally, the socio-economic trends used to generate scenarios A1B and B1 were analyzed to gain insight into the driving forces behind land use changes, taking into account that the A1B scenario would put greater emphasis on economic value while the B1 scenario would also emphasize nature conservation values (IPCC, 2007). Generic land use change rules for A1B and B1 were created from IPCC (2007), Rounsevell et al. (2006) and Verburg et al. (2006). These generic rules were combined with the local trend analysis to define: (i) the most likely crops subject to abandonment in the A1B and B1 scenarios, assuming a similar degree of abandonment as forecasted at the Portuguese scale; and (ii) likely replacement land-cover or crops in the A1B and B1 scenarios. This approach ensured consistency between climate and land use changes since land use scenarios followed the same storylines as climate change scenarios.

3 Results

3.1 Model calibration and validation

The model results based on the performance indicators considered in the present study are shown in Table 3. A good agreement was found between observed and predicted monthly streamflow for both catchments and for both the calibration and validation period. The sediment export predicted for São Lourenço fit reasonably well with the measured values, despite some model underestimation in both the calibration (PBIAS = 28%) and validation period (PBIAS = 32%). For the sediment export in the Guadalupe catchment, model performance might be considered reasonable for the validation period but not for the calibration period (Table 3).

Model performance for daily streamflow and sediment export (Figs. 5 and 6) was worse than for monthly values, particularly in Guadalupe (Table 3).

3.2 Future scenarios

3.2.1 Climate change scenarios

Compared to the baseline period of 1971 to 2000, the forecasts for 2071 to 2100 indicated a small decrease in annual rainfall for both São Lourenço (ca. 12%) and Guadalupe (ca. 8%) together with higher rainfall in winter, on average 19% and 40% respectively, for the humid and dry catchment (Fig. 7). For both catchments, the A1B and B1 scenarios differed mainly in seasonal rainfall distribution, but not in the annual rainfall volumes (Fig. 7). Due to the downscaling method used (see Section 2.3), the same changes in average annual temperature were predicted for the two catchments (Fig. 7): an increase of 2.2°C was forecasted for scenario A1B as opposed to an increase of 1.1°C for scenario B1.

3.2.2 Land use change scenarios

Future land use changes for the São Lourenço and Guadalupe catchments are presented in Tables 4 and 5, respectively. In accordance with the forecasts for Portugal as described earlier, a large decrease in agricultural lands for food production was assumed under scenarios A1B and B1, but with a larger change in the A1B scenario.

The differences between the study sites are related to the different historical land use change trends in the latter half of the 20th century, as described above. In the northern region, traditional agricultural crops such as potato and pastures were predicted to be replaced primarily by corn (for biofuel production) and by commercial forests (Table 4), all of which are already present locally. In the southern region, traditional crops (wheat and other cereals) and pasture are predicted to be replaced by sunflower for biofuel production and abandoned to become shrublands (Table 5). While sunflower is not present locally, it is cultivated in other places in southern Portugal and has a high potential to tolerate the warmer and drier conditions forecasted under climate change (Camacho-B et al., 1974).

The differences between the A1B and B1 scenarios are related to their storylines, also as described above. Hence the A1B scenario is more focused on economic development, whereas the B1 scenario is more directed towards environmentally-friendly options (IPCC, 2007). Under scenario A1B, the existing permanent pastures and mixed forests in São Lourenço were foreseen to be converted into eucalypt forests, because this is a more valuable species from the economic point of view. Under the B1 scenario these areas were converted into pine forests, as it is a more appropriate species from an environmental point of view (Table 4). Likewise, small vineyard areas in São Lourenço were assumed to be replaced by corn and eucalypt plantations under the A1B scenario and to be maintained under scenario B1.

For Guadalupe, the areas permanently occupied by pastures were assumed to be converted into sunflower plantations to a much larger extent under the A1B scenario than under the B1 scenario (Table 5). As for pastures associated with the “montado” system, in areas where oak cover is currently less than 50%, pastures were assumed to be fully converted into sunflower plantations under the A1B scenario, but maintained under the B1 scenario. In areas with more than 50% oak cover, pastures were assumed to be abandoned and naturally replaced by Mediterranean shrublands for both scenarios.

3.3 Effects of climate changes

Under both climate change scenarios, annual streamflow was forecasted to decrease by 13% in the São Lourenço basin (Fig. 8). This decrease in streamflow was accompanied by large decreases in actual evapotranspiration (ET) by the main land cover types of vine (-10 to -11%) and maritime pine

(-7 to -8%), as shown in Table 6. In Guadalupe, the reduction in streamflow was higher (Fig. 8), from a 14% reduction in the A1B scenario, to an 18% decrease in the B1 scenario. However, the decreases in actual ET from the main land cover types of oak (-4 to -6%) and pasture (-4 to -5%) were smaller than in the humid catchment (Table 7).

Regarding sediment export, the model predicted a decrease of 9% in the A1B scenario and of 11% in the B1 scenario for the São Lourenço basin (Fig. 9). For Guadalupe, an increase in sediment export of 24% and 22% was forecasted for the A1B and the B1 scenarios respectively (Fig. 9).

3.4 Effects of land use changes

In contrast to the predicted climate change impacts, land use changes led to a small increase in average annual streamflow for both catchments (São Lourenço: 0.2 – 1%; Guadalupe: 0.3 – 6%) under both scenario A1B and B1 (Fig. 8).

Sediment export exhibited different behaviors in the two catchments. In São Lourenço, a decrease of 10% (B1 scenario) and 18% (A1B scenario) in annual sediment export was predicted due to land use changes (Fig. 9). In Guadalupe, erosion was forecasted to increase for both scenarios, by 257% in the A1B scenario and by 9% in the B1 scenario.

3.5 Combined effects of climate and land use changes

For both basins, the decrease in streamflow caused by climate change was offset by the increase caused by land use changes (Figs. 8 and 10). In São Lourenço, the streamflow reduction was greater under the A1B scenario, whereas in Guadalupe the reduction was greater under the B1 scenario (Fig. 8).

The decrease in sediment export caused by climate change in São Lourenço was cumulative with the decrease caused by the land use change, leading to an overall reduction of 29% and 22%, for scenario A1B and B1 respectively (Fig. 9). For Guadalupe, by contrast, the increase caused by climate change did not added up to the increase caused by land use change. In this catchment, the overall change in sediment export relative to the baseline scenario amounted to an increase of 222% for scenario A1B and of 5% for scenario B1 (Fig. 9).

4 Discussion

4.1 Model performance

Based on the criteria for model performance established by Moriasi et al. (2007), the model adequately simulated monthly streamflow discharge in both catchments (Table 3). The model also adequately simulated sediment export in São Lourenço, despite some underestimation in both the calibration and validation periods (Table 3). This underestimation may be in part due to the method of estimating sediment export, as there was not a continuous measurement of sediment concentrations in this basin.

Monthly sediment export predictions in Guadalupe were only accurate for the validation period (Table 3). However, this can be consider an artefact, since the single sediment peak during the calibration period was located between two months (March and April 2013).Daily-scale model errors within this relatively short time span propagate into the monthly analysis, as can be seen in Fig. 6. When the evaluation is corrected for this artefact (i.e. comparing 30-day averages), the RSR decreases to 0.3 and NSE increases to 0.86, indicating an accurate simulation of monthly sediments in Guadalupe during the calibration period as well.

As the model performance statistics RSR and NSE are known to be overly sensitive to model fit to peak streamflow events (Beven, 2012), a poorer performance for Guadalupe (especially for sediments) would be expected compared with São Lourenço, especially at the daily scale (Table 3 and Figs. 5 and 6). A similar explanation can be given for the lower model performance at the daily scale compared with the monthly scale, also discussed by Moriasi et al. (2007) for the SWAT model, since performances conducted on monthly measurements tend to smooth out the predicted error by reducing the peaks and troughs in the data.

SWAT was thus successfully applied to both catchments, indicating that it is a valid tool for simulating the effects of climate and land use changes. Arguably, an assessment of data and model uncertainty would have been important for this study since it would impact the predictions for the chosen scenarios; it would also have been interesting to compare model and scenario uncertainty (discussed below). Uncertainty in streamflow and especially sediment data could limit the validity of the SWAT calibration (Sellami et al., 2013), but this was not quantified. The short period for data collection could also limit the variability of conditions used for calibration (Lespinas et al., 2014; Piras et al., 2014). However, the marked intra-annual variability, combined with the selection of a drought year (2011/2012) for calibration in Guadalupe, could have helped to limit the importance of this issue. In fact, Lespinas et al. (2014) found the length of the calibration period to be less important than the selection of model structure (in their case, the evapotranspiration calculation method) for reducing uncertainty. In this case, the use of streamflow, runoff, soil moisture and (in Guadalupe) evapotranspiration data would have helped to decrease uncertainty through a multi-objective calibration approach (Efstratiadis and Koutsoyiannis, 2010; Beven, 2012). Furthermore, measured data was used to severely restrict the range of calibrated parameters (SOL_AWC, USLE_K, ALPHA_BF and DEP_IMP in Table 2) which could have further limited parameter uncertainty (Beven, 2012). Finally, model structure could have contributed for uncertainty, notably due to the erosion simulation method not accounting for rain-splash erosion (Arnold et al., 2011).

4.2 Effects of climate changes

The impacts of climate change scenarios on stream discharge (Fig. 8) seemed to be related to the decrease in precipitation forecasted for both catchments (Fig. 10). These results agree with findings from studies in other basins of the Iberian Peninsula (e.g. Lopéz-Moreno et al., 2014; Molina-Navarro et al., 2014; Nunes et al., 2008, 2013; Zabaleta et al., 2014), as well as elsewhere in the Mediterranean (e.g. Lespinas et al., 2014; Piras et al., 2014; Stigter et al., 2014). In these studies, a decrease in precipitation due to climate changes has been identified as the main cause of reduced surface water availability. In most of these basins, as in the present ones, the decrease in precipitation results in a greater decrease in surface water. For example, Molina-Navarro et al. (2014) estimated in the Ompólveda River (Spain) that an annual precipitation decrease of 6% (scenario AB1) to 9% (scenario B1) in average would lead to a 22% (scenario A1B) to 34% (scenario B1) reduction in annual streamflow.

Although the greater decrease in precipitation at the humid site of São Lourenço (see section 2.3) would suggest a more pronounced impact on streamflow, the reverse was found in the present study. In São Lourenço, a larger decrease (-7 to -8%) in ET (Fig. 10) can be attributed to the large decreases in the main land-cover types of vine (-9 to -11%) and maritime pine (-7 to -8%), as seen in Table 6. In Guadalupe, the lower decrease in ET (-4 to -6%) is linked with lower decreases in the main covers of oak (-4 to -6%) and pasture (-4 to -5%), as seen in Table 7. The differences between the catchments may be that vine and maritime pine are less able to control evapotranspiration than Mediterranean evergreen oaks, while annual crops benefit from warmer winters by increased growth under wet conditions (Nunes and Seixas, 2011). As a result, the impacts of climate changes on water yield were slightly more pronounced at Guadalupe (-14 to -18%) than in São Lourenço (-13%).

With respect to sediment export, the 9 to 11% decrease in annual export predicted for São Lourenço may be due to the decrease in precipitation predicted for this catchment. Reduction in rainfall is generally linked with decreased runoff and soil erosion (Kalogeropoulos and Chalkias, 2013; Nunes et al., 2008; Perazzoli et al., 2013; Zabaleta et al., 2014), particularly in regions where there is year round crop cover (Cerdan et al., 2010; Nunes et al., 2011). The most important land-cover types in São Lourenço (i.e. vineyards and maritime pine) are permanent, and both showed a decrease in erosion (Table 8). Similar results have been reported in other humid regions for climate change scenarios forecasting a reduction in precipitation (Bangash et al., 2013; Khoi and Suetsugi, 2014; Lu et al., 2013; Mullan, 2013). In Guadalupe, on the other hand, sediment export increased under both climate change scenarios, mostly due to large increases in erosion for wheat and pasture (i.e. annual crops; Table 9). The increase in precipitation forecasted in winter months, which is associated with the generally low vegetation cover during the cold season, increased soil erosion in this catchment. This finding agrees with the results of other authors (Khoi and Suetsugi, 2014; Li et al., 2012; Nunes et al., 2008). However, it should be noted that the permanent vegetation cover in this catchment (i.e. oak and olive groves) showed a reduction in erosion rates (Table 9) similar to the findings from the humid catchment (Table 8).

As discussed earlier, the uncertainty in climate scenario was not considered in this study. Two greenhouse gas emission scenarios were assessed, but only one GCM and downscaling method was applied. The resulting climate predictions were within the bounds simulated by the PRUDENCE (Déqué et al., 2005) and ENSEMBLES projects (Van Der Linden and Mitchell, 2009), but close to the lowest degree of change (see Nunes et al., 2008). A more complete assessment should consider uncertainty in GCM and downscaling methods, and in particular assess the impacts of more extreme climate change scenarios.

4.3 Effects of land use changes

In contrast to the climate change impacts, land use change had a minor impact on stream discharge (Fig. 8). For São Lourenço, a very small increase in discharge was predicted under both scenarios, despite an increase in ET (Fig. 10). This mostly was due to the expansion of corn, which is irrigated and adds another source of water to the catchment. The replacement of vineyards and pastures by forests and cereals also led to higher interception and transpiration, as seen in Table 6. This finding agrees with previous studies examining the impact of cereals (García-Ruiz and Lana-Renault, 2011; López-Vicente et al., 2013) and of forests (Jordan et al., 2014; Khoi and Suetsugi, 2014; López-Moreno et al., 2014; Molina-Navarro et al., 2014; Montenegro and Ragab, 2012). However, a decrease in ET in eucalypts should also be noted (Table 6) and is linked to its expansion to soils with lower water holding capacity. In contrast, the higher increase in flow discharge in Guadalupe under the A1B scenario was mainly related to a decrease in ET (Figs. 8 and 10), linked with the conversion of pastures into sunflower plantations, since the latter is a spring crop with lower cover and water demands (Table 7).

With respect to soil erosion, the larger decrease (-18%) in sediment export in São Lourenço under scenario A1B (Fig. 9) was mainly the result of a reduction in vineyard areas (Table 4). This crop type has previously been found to have the highest erosion rates (Table 8) among the cultures typically cultivated in the Mediterranean basin (Cerdan et al., 2010). By contrast, the decrease observed under scenario B1 (-10%) resulted from the conversion of pasture into pine plantations, since forests typically have lower erosion rates (Table 8) than grasslands (e.g. Cerdan et al., 2010; García-Ruiz and Lana-Renault, 2011; Nunes et al., 2011). For Guadalupe, on the other hand, the replacement of pasture by sunflower (A1B scenario) led to a sharp increase in soil erosion (+257%). This may be attributed to the lack of ground cover during the wet season leading to higher soil losses (Table 9) than would occur with permanent vegetation cover (Cerdan et al., 2010; Nearing et al., 2005; Nunes et al., 2011). For scenario B1, a considerably smaller increase in sediment export (+9%) was observed in Guadalupe, largely because there was less of a conversion of pasture into sunflower than in the A1B scenario (Table 5), but also because the erosion rates of sunflower and wheat (which was fully replaced by sunflower in scenario B1) tend to be very similar (respectively, 1.34 and 1.67 tons ha^{-1}; Table 9).

From the results of the present study, the differences between the two catchments with regards to sediment export were largely related to the growing cycle of the different crops (García-Ruiz and Lana-Renault, 2011; Nearing et al., 2004). In the humid area, most crops have year-round soil cover, whereas in the dry areas soils are often bare in the winter. This reduces the protection of soils against rain-splash and particle detachment during the rainy season, thereby exposing the soils to enhanced erosion (Cerdan et al., 2010; García-Ruiz and Lana-Renault, 2011; Nearing et al., 2004, 2005; Nunes et al., 2008).

The land use change scenarios assumed a single societal response for each socio-economic storyline, but these responses can have a high degree of uncertainty (see Stigter et al., 2015). For example, an incentive for planting vineyards instead of eucalypts in São Lourenço, or olive trees instead of sunflower in Guadalupe, could have led to different erosion rates. A more complete work should consider different plausible land-use changes to assess a range of impacts.

4.4 Combined effects of climate and land use changes

Climate and land use changes showed off-setting effects on stream discharge and sediment export at the humid catchment. In this watershed, flow discharge and sediment export were forecasted to decrease, particularly under the A1B scenario (Figs. 8 and 9), as a combined effect of reduced precipitation and cultivation of more soil-protective crops (Nunes et al., 2008). A different response was observed for the dry catchment, as a decrease in streamflow and an increase in sediment export was predicted as a result of combined climate and land use changes (Figs. 8 and 9). For Guadalupe, the cultivation of less water-demanding species was not able to offset the reduction in stream discharge resulting from reduced precipitation. On the other hand, the increase in sediment export associated with the cultivation of highly erosion-prone crops was not aggravated by the higher rainfall amounts forecasted for winter months. In fact, the combined impact of climate and land use changes on soil erosion, particularly under the A1B scenario was less severe than would be expected, mostly due to a decrease in erosion from sunflower under the combined scenarios (from 1.44 to 1.30 tons ha^{-1}; Table 9), but also due to the decrease in olive groves. A decrease in erosion under climate change for spring crops could be associated with warmer winters leading to more vegetation cover in the wet season (Nunes and Seixas, 2011). Nonetheless, the high erosion rates predicted for Guadalupe, which are higher than the tolerable soil erosion rates in Europe (≈ 1 tons ha^{-1}; Verheijen et al., 2012), might pose severe problems for soil productivity due to the shallowness and poor quality of local soils (Nunes et al., 2008).The combined scenario analysis also did not address the uncertainties which underlie climate and land-use scenarios. One method to ensure this in a more complete work would be to adopt an uncertainty assessment framework, such as the one proposed by Ludwig et al. (2010), to address uncertainty at each step of the impact assessment study.

5 Conclusions

In the present work, SWAT was successfully applied to a humid and dry Mediterranean catchment, demonstrating its application as a valid tool for predicting the impacts of climate and land use changes on streamflow and sediment export.

From the integrated analysis of the effect of the two environmental stressors, climate changes were predicted to have a more pronounced impact on water availability than land use changes. The reverse was predicted for sediment export, which reinforces the importance of land use changes for the future state of Mediterranean soils and for minimizing the indirect effects of climate changes. In this case, the potential negative impact of the expansion of sunflower cultivation for soil protection in the dry site is stressed, suggesting alternative land use policies with equivalent economic value, such as the expansion of olive groves.

The results of this study stress the importance of present-day land cover for climate change impacts. The humid catchment, with permanent vegetation cover, is expected to experience less negative impacts on available water resources and even an increase of soil protection. The dry catchment by contrast, which has either drought-adapted permanent vegetation or annual winter crops, is expected to experience larger negative impacts on both water resources and soil protection. While vegetation cover is an indirect function of climate, these results also point to land use policies that could help mitigate the impacts of climate change on soil degradation, e.g. by promoting the maintenance of vegetation with permanent cover, such as pasture, olive groves, or natural shrublands.

This study did not address scenario uncertainty, i.e. from greenhouse gas emission, selection of climate model and downscaling method, and selection of socio-economic scenario, since the relatively limited objectives only required a small number of plausible scenarios. However, a complete assessment of potential climate change impacts should take these uncertainties into account, especially by considering a large range of GCM/RCM combinations and of socio-economic responses.

From the present work, it becomes evident that an integrated approach combining the effects of climate and land cover change is crucial for a realistic evaluation of the future state of natural resources. Despite being a starting point towards a better understanding of the direct and indirect impacts of climate change on Mediterranean watersheds, this study provides important information that can be useful for decision-makers to design adaptive measures to climate changes. Future work should address the range of foreseeable scenarios for the study area, to take into account the uncertainty inherent to climate and land use change predictions.

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Figure captions

Fig. 1. Map of Portugal showing the location of the study sites; and the UNEP aridity Index (Middleton and Thomas, 1997), calculated using spatial datasets for long-term average rainfall and potential evapotranspiration (SNIRH, 2014b).

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Fig. 10. Impacts of climate, land use and combined climate and land use change scenarios on the water balance of the São Lourenço and Guadalupe catchments. ET – actual evapotranspiration.

Tables

Table 1. Input data for SWAT application to São Lourenço and Guadalupe.

Data type	Description	Source
Topography	Digital Elevation Model (10 m)	IGeoE (2013)[1, 2]
Soils	Soil map (1:25000)	DGADR (2013) [1, 2]
Land use	Land use/cover classification map (1:25000)	IGeoE (1990, 2007) [1, 2]
Hydrography	Daily streamflow and baseflow data and stage discharge curves	Field data[1, 2]
Meteorology	Daily precipitation, maximum and minimum temperatures, solar radiation, relative humidity and wind speed	Field data[1, 2], SNIRH (2014a)[1], NCDC (2014)[1]

[1] São Lourenço; [2] Guadalupe

Table 2. Calibrated SWAT parameters.

Parameter	Description	Units
SOL_AWC	Available water capacity of the soil layer	mm H_2O/ mm
USLE_K	USLE equation soil erodibility factor	-
USLE_C	Minimum value of USLE C factor applicable to the land cover	-
RSDCO_PL	Plant residue decomposition factor	fraction
GW_DELAY	Groundwater delay	days
ALPHA_BF	Baseflow alpha factor	$days^{-1}$
GWQ_MIN	Threshold depth of water in the shallow aquifer required for return flow to occur	mm H_2O
GW_REVAP	Groundwater re-evaporation coefficient	fraction
RCHRG_DP	Deep aquifer percolation fraction	fraction
ESCO	Soil evaporation compensation factor	-
EPCO	Plant uptake compensation factor	-
DEP_IMP	Depth to impervious layer for modelling perched water tables	mm

Table 3. Model performance regarding streamflow and sediment export at the São Lourenço and Guadalupe catchment, for the calibration and validation periods. NSE – Nash-Sutcliffe coefficient; RSR – ratio between the Root Mean Square Error and the sample standard deviation; PBIAS – percent of bias.

Variable	Catchment	Data	Period	NSE	RSR	PBIAS
Streamflow	São Lourenço	Daily	Calibration	0.83	0.41	0.44
			Validation	0.84	0.40	-3.34
		Monthly	Calibration	0.92	0.27	0.44
			Validation	0.97	0.15	-3.34
	Guadalupe	Daily	Calibration	0.56	0.66	1.14
			Validation	0.31	0.83	6.96
		Monthly	Calibration	0.86	0.36	0.87
			Validation	0.83	0.40	6.68
Sediment export	São Lourenço	Daily	Calibration	0.60	0.63	46.53
			Validation	0.58	0.66	35.94
		Monthly	Calibration	0.70	0.52	28.36
			Validation	0.65	0.56	31.52
	Guadalupe	Daily	Calibration	-1.73	1.65	-5.75
			Validation	-7.74	2.95	-21.86
		Monthly	Calibration	-0.37	1.13	-5.74
			Validation	0.73	0.51	-22.66

Table 4. Present and predicted future land cover in the São Lourenço catchment.

Land use	SWAT code	Present		Scenario A1B		Scenario B1	
		Area (ha)	%	Area (ha)	%	Area (ha)	%
Vineyards	VINE	272.6	43.9	230.4[a]	37.1	272.6	43.9
Maritime pine	MPIN	164.3	26.5	164.3	26.5	193.4	31.2
Annual crops							
Corn	CORN	74.9	12.1	147.9	23.9	110.2	17.8
Potato	POTA	17.6	2.8	0.0[b]	0.0	0.0[b]	0.0
Pasture	WPAS	17.6	2.8	0.0[b]	0.0	0.0[b]	0.0
Urban area	URHD	28.5	4.6	28.5	4.6	28.5	4.6
Permanent	PAST	18.5	3.0	0.0[c]	0.0	0.0[d]	0.0
Eucalypt	EUCP	16.7	2.7	48.9	7.9	16.7	2.7
Mixed forests	MIXF	9.6	1.5	0.0[e]	0.0	0.0[f]	0.0

[a] Vineyards partially converted into corn and eucalypt plantations; [b] potato and pastures converted into corn; [c] permanent pastures converted into eucalypt; [d] permanent pastures converted into maritime pine; [d] mixed forests converted into eucalypt plantations; [d] mixed forests converted into maritime pine plantations.

Table 5. Present and predicted future land cover in the Guadalupe catchment.

Land use	SWAT code	Present		Scenario A1B		Scenario B1	
		Area (ha)	%	Area (ha)	%	Area (ha)	%
Cork/holm oak	FRSS	197.9	44.0	197.9	44.0	197.9	44.0
Annual crops (Wheat)	WCRL	48.1	10.7	0.0[a]	0.0	0.0[a]	0.0
Pasture	WPAS	190.4	42.4	25.6[b, c]	5.7	107.7[c]	24.0
Olive groves	OLVG	11.7	2.6	11.7	2.6	11.7	2.6
Urban	URMD	1.3	0.3	1.3	0.3	1.3	0.3
Sunflower	SUNF	-	-	130.2[a, b]	29.0	48.1[a]	10.7
Shrublands	SHRM	-	-	82.7[c]	18.4	82.7[c]	18.4

[a] Annual crops converted into sunflower; [b] pastures under lower-density oaks (30-50%; Fig. 3) converted into sunflower; [c] pastures under higher-density oaks (>50%; Fig. 3) converted into shrublands.

Table 6. Average actual evapotranspiration (ET; mm y^{-1}) for the São Lourenço crops, under different climate and land use scenarios. VINE – Vineyards; MPIN – Maritime pine; POTA – Potato; WPAS – Pasture; PAST – Permanent pasture; EUCP – Eucalypt; MIXF – Mixed forests.

Scenarios	Precipitation (mm)	ET (mm y^{-1})							
		VINE	MPIN	CORN	POTA	WPAS	PAST	EUCP	MIXF
Baseline	1064.3	478.0	462.5	749.9	676.5	516.7	531.7	690.1	600.6
A1B_Climate	940.0	432.8	428.7	729.8	668.1	473.8	489.4	634.7	543.6
B1_Climate	939.5	427.4	427.7	736.9	670.5	468.8	483.1	624.9	535.8
A1B_Land use	1064.3	470.1	462.5	750.2	-	-	-	617.0	-
B1_Land use	1064.3	478.0	461.2	748.8	-	-	-	690.1	-
A1B_Climate+Land use	940.0	425.1	428.7	730.5	-	-	-	560.9	-
B1_Climate+Land use	939.5	427.4	426.8	736.2	-	-	-	624.9	-

Table 7. Average actual evapotranspiration (ET; mm y^{-1}) for the Guadalupe crops, under different climate and land use scenarios. FRSS – Cork/holm oak; SHRM – Mediterranean shrublands; WCRL – Wheat; WPAS – Pasture; OLVG – Olive groves; SUNF – Sunflower.

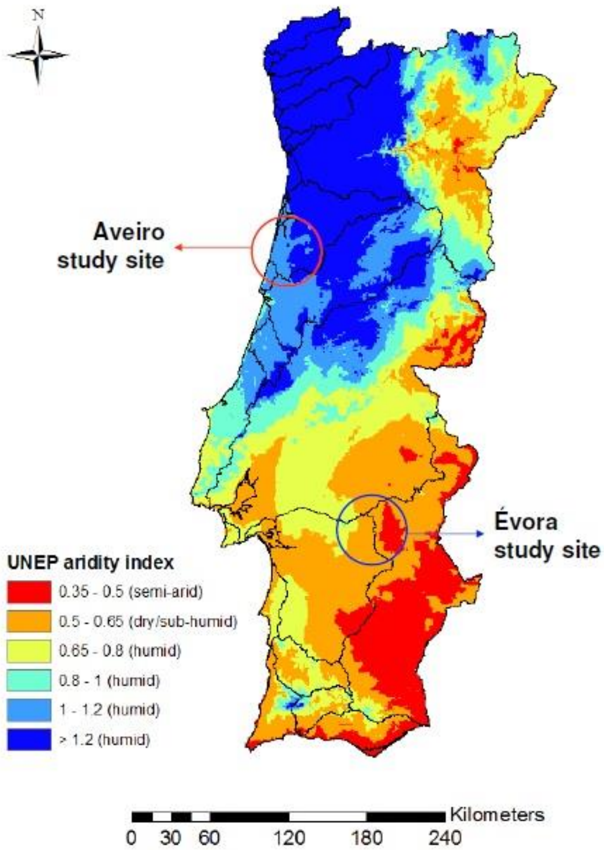
Scenarios	Precipitation	ET (mm y^{-1})					
	(mm)	FRSS	SHRM	WCRL	WPAS	OLVG	SUNF
Baseline	333.0	357.4	-	366.6	362.7	386.3	-
A1B_Climate	306.3	337.2	-	347.4	343.6	363.3	-
B1_Climate	306.1	344.1	-	352.5	348.7	371.9	-
A1B_Land use	333.0	356.3	380.7	-	-	386.3	346.2
B1_Land use	333.0	357.5	380.7	-	362.7	386.3	351.1
A1B_Climate+Land use	306.3	335.5	360.2	-	-	363.3	324.9
B1_Climate+Land use	306.1	344.2	367.9	-	348.7	371.9	337.4

Table 8. Average sediment yield (tons ha^{-1} y^{-1}) for the São Lourenço crops, under different climate and land use scenarios. VINE – Vineyards; MPIN – Maritime pine; POTA – Potato; WPAS – Pasture; PAST – Permanent pasture; EUCP – Eucalypt; MIXF – Mixed forests.

Scenarios	Sediment yield (tons ha^{-1} y^{-1})							
	VINE	MPIN	CORN	POTA	WPAS	PAST	EUCP	MIXF
Baseline	1.108	0.005	0.056	1.420	0.935	0.461	0.001	0.002
A1B_Climate	0.955	0.003	0.045	1.957	0.756	0.368	0.001	0.004
B1_Climate	0.962	0.003	0.044	1.778	1.074	0.500	0.001	0.004
A1B_Land use	1.108	0.005	0.051	-	-	-	0.002	-
B1_Land use	1.108	0.005	0.053	-	-	-	0.001	-
A1B_Climate+Land	0.952	0.004	0.041	-	-	-	0.002	-
B1_Climate+Land use	0.962	0.004	0.041	-	-	-	0.001	-

Table 9. Average sediment yield (tons ha^{-1} y^{-1}) for the Guadalupe crops, under different climate and land use scenarios. FRSS – Cork/holm oak; SHRM – Mediterranean shrublands; WCRL – Wheat; WPAS – Pasture; OLVG – Olive groves; SUNF – Sunflower.

Scenarios	Sediment yield (tons ha^{-1} y^{-1})					
	FRSS	SHRM	WCRL	WPAS	OLVG	SUNF
Baseline	0.091	-	1.359	0.089	2.928	-
A1B_Climate	0.082	-	2.167	0.111	2.675	-
B1_Climate	0.077	-	2.058	0.132	2.497	-
A1B_Land use	0.091	0.037	-	-	2.928	1.442
B1_Land use	0.091	0.037	-	0.087	2.928	1.672
A1B_Climate+Land use	0.082	0.032	-	-	2.675	1.297
B1_Climate+Land use	0.077	0.028	-	0.132	2.497	1.473



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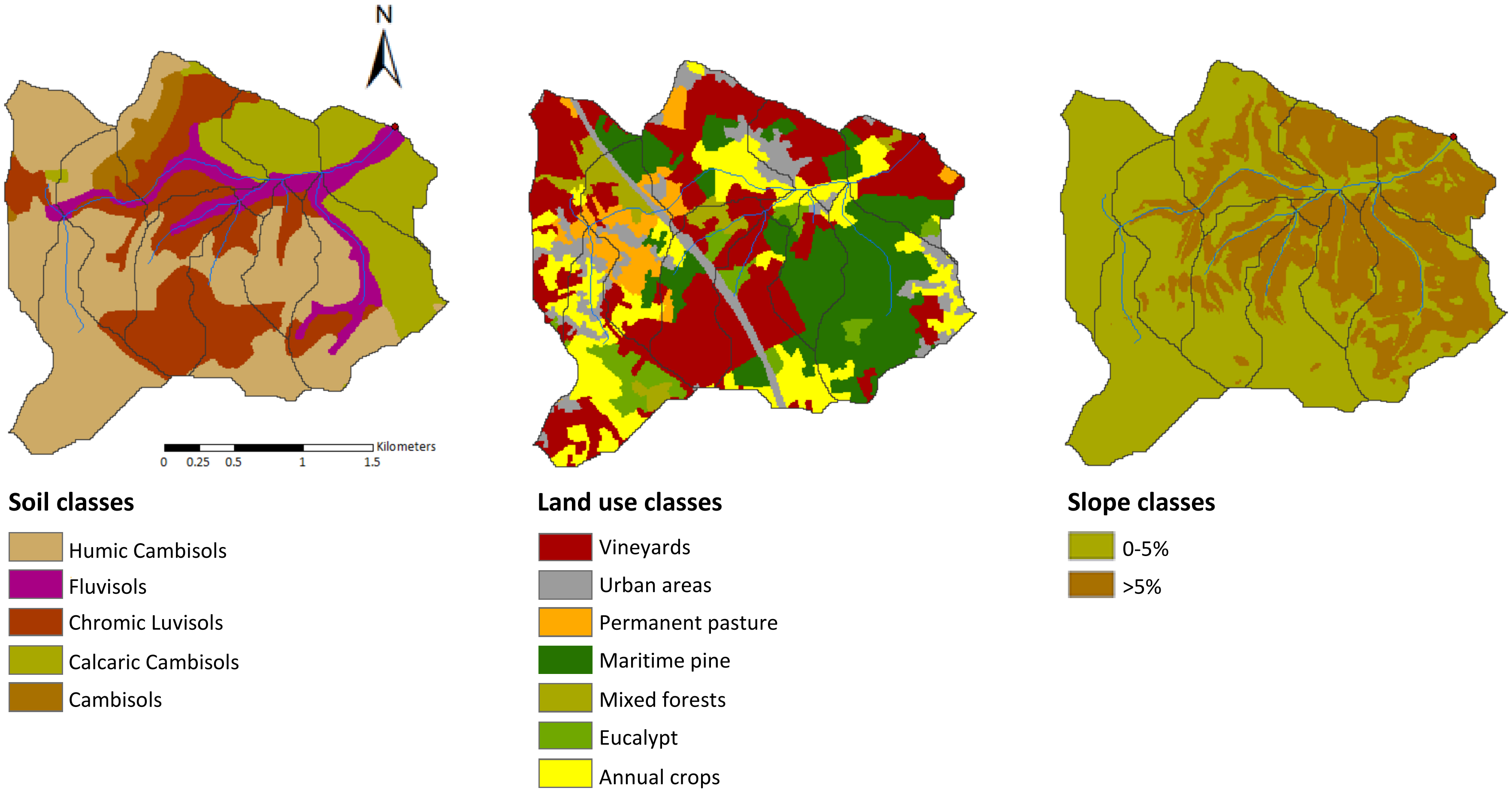


Fig. 2. Soil, land use and slope classes defined for São Lourenço.

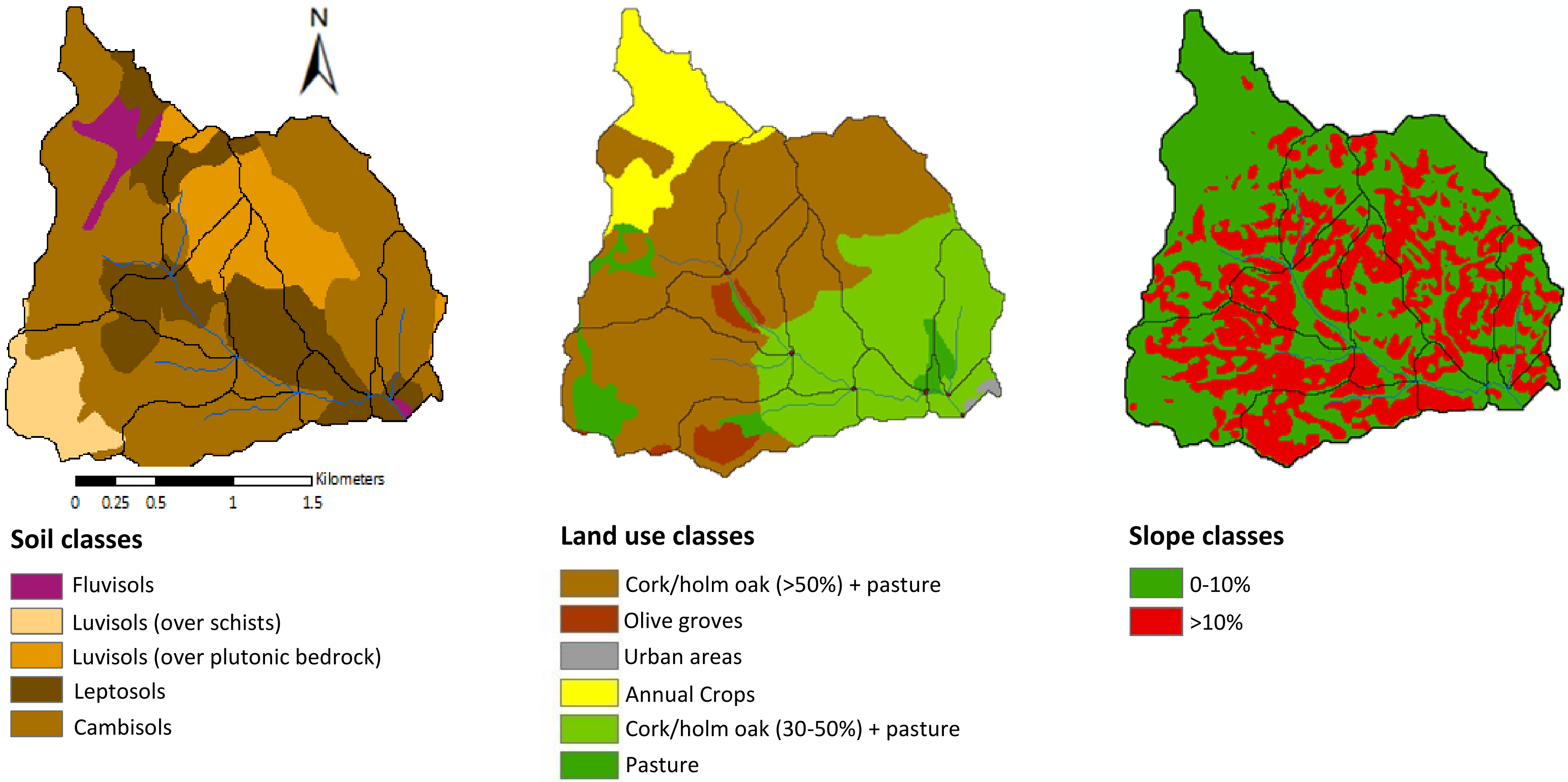
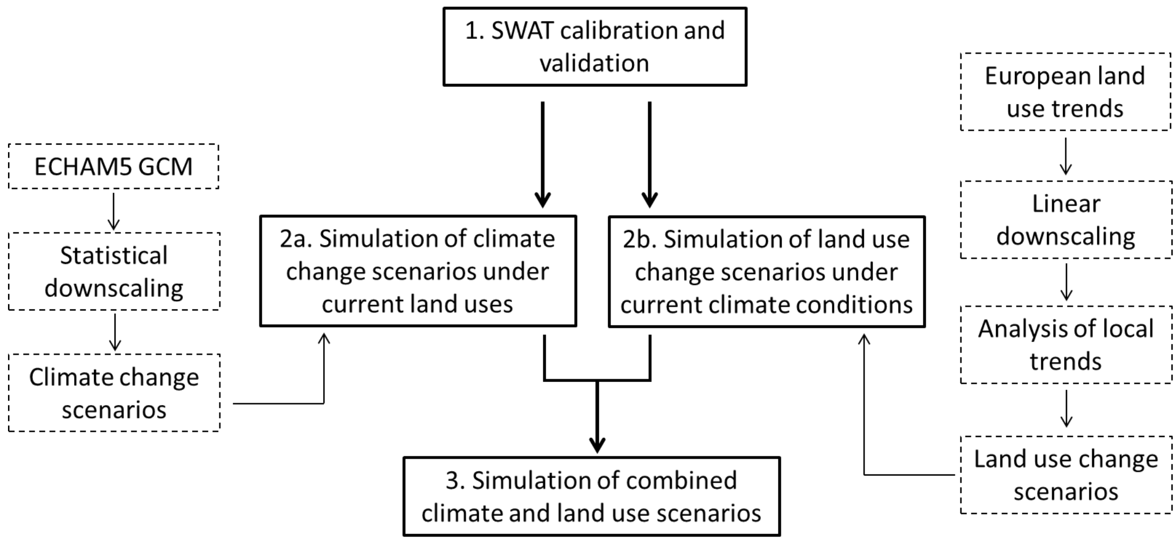


Fig. 3. Soil, land use and slope classes defined for Guadalupe.



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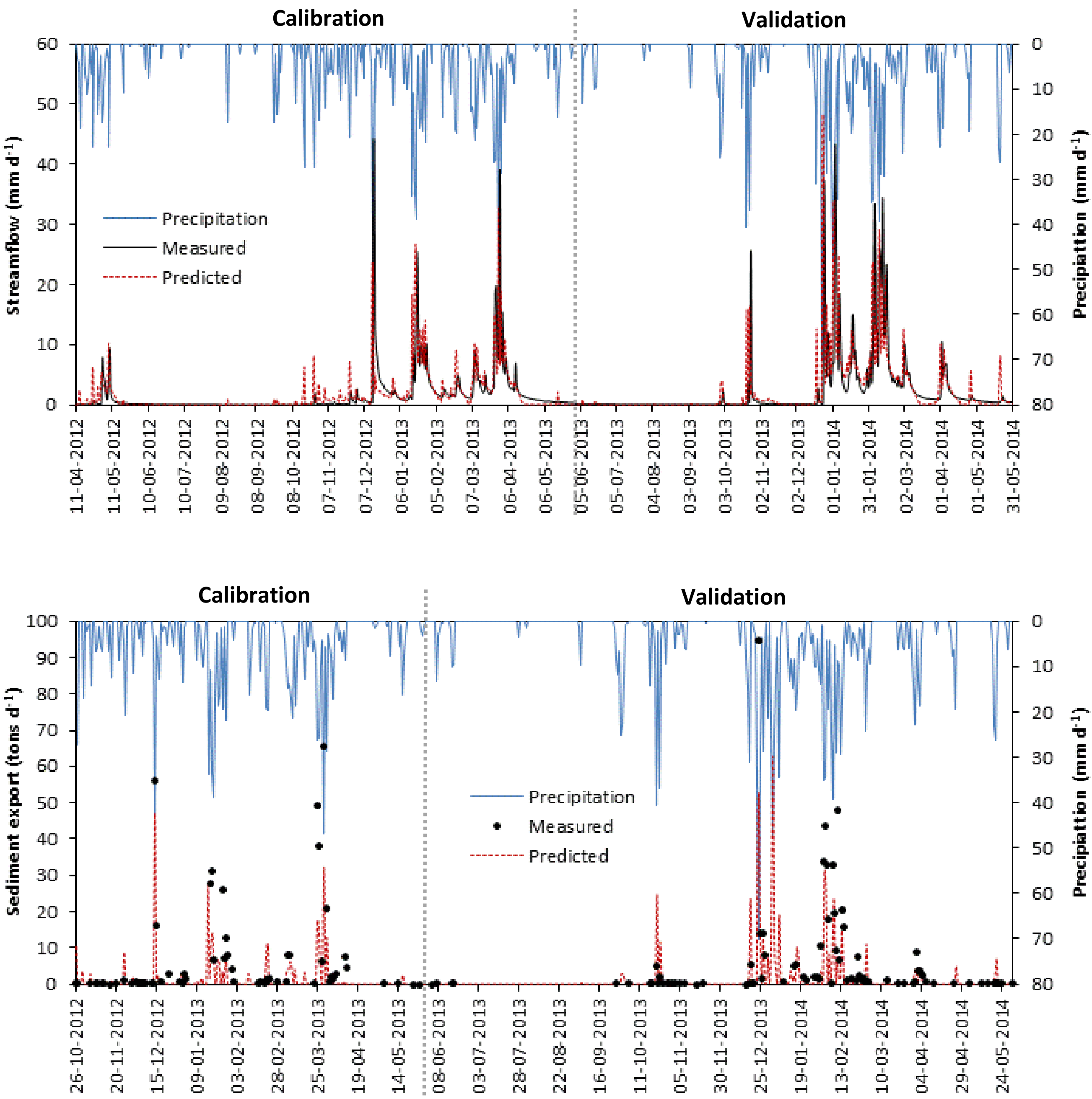

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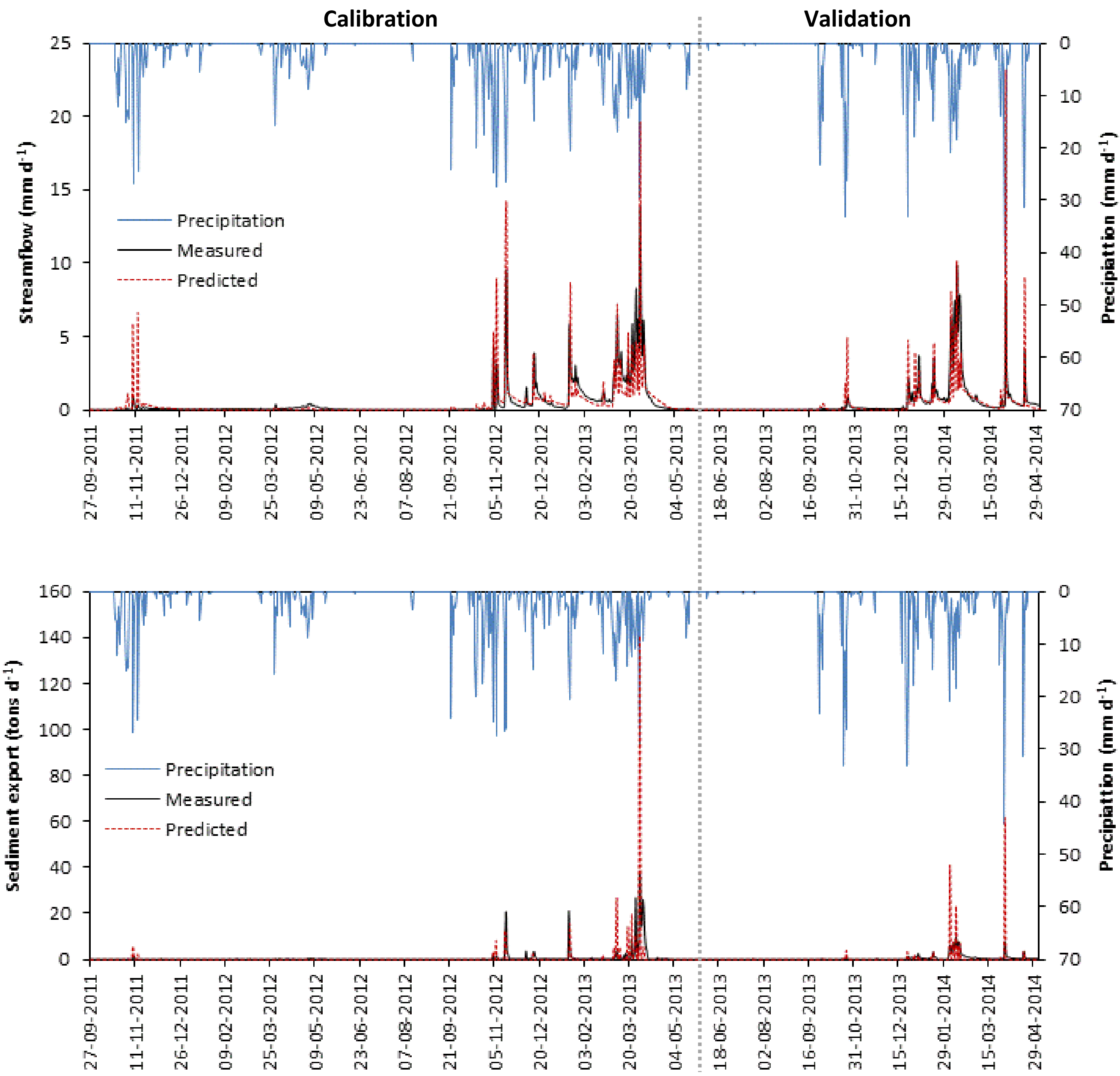
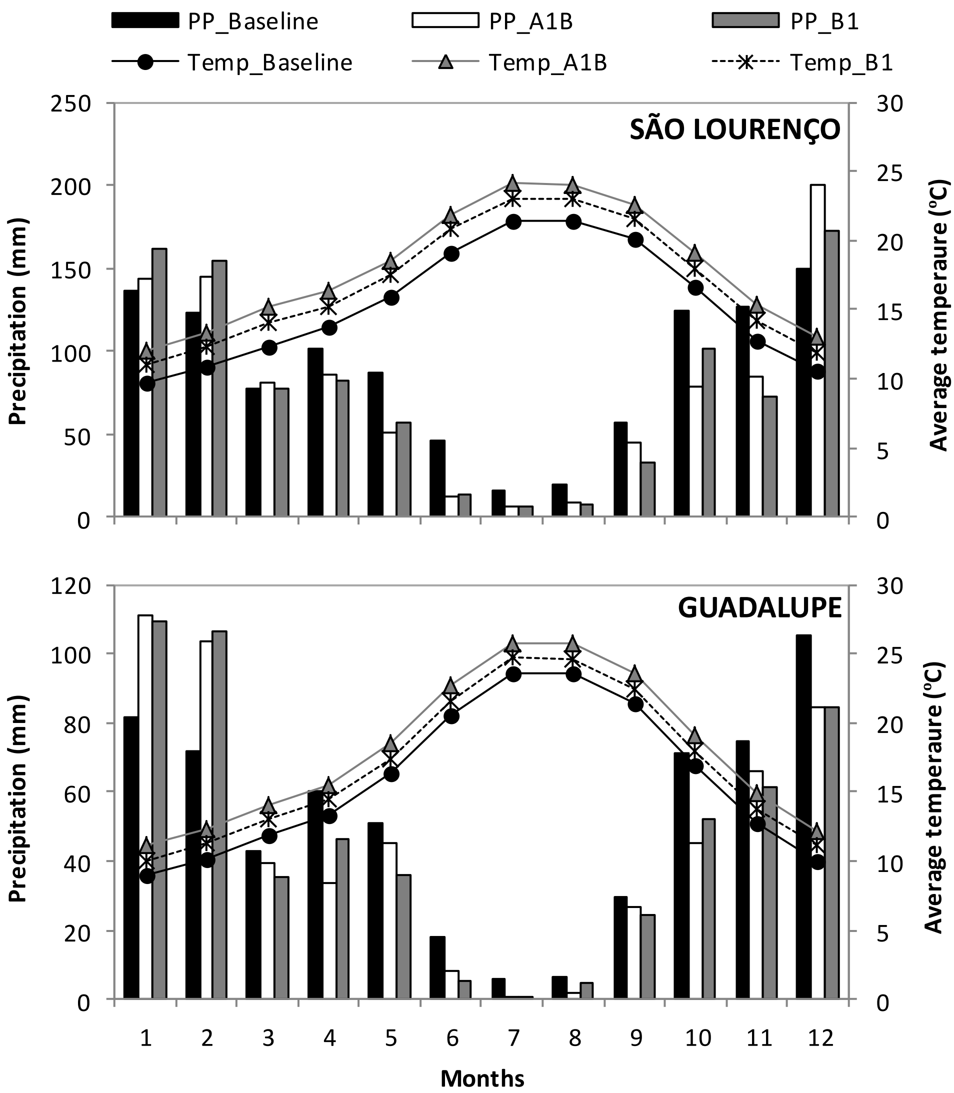


Fig. 6. Predicted and measured monthly streamflow (*top*) and sediment export (*bottom*) at the Guadalupe catchment, for the calibration and validation periods.



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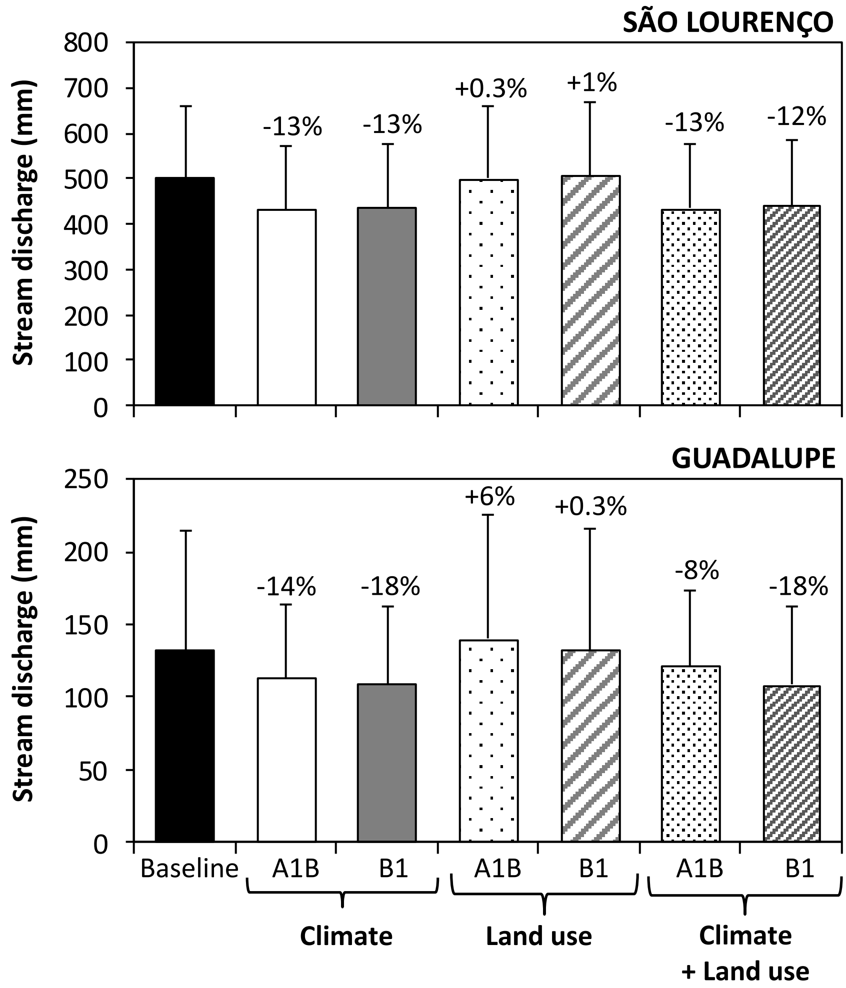


Fig. 8. Average annual (± standard deviation) stream discharge under different scenarios of climate, land use and combined climate and land use changes, in the São Lourenço and Guadalupe catchment.

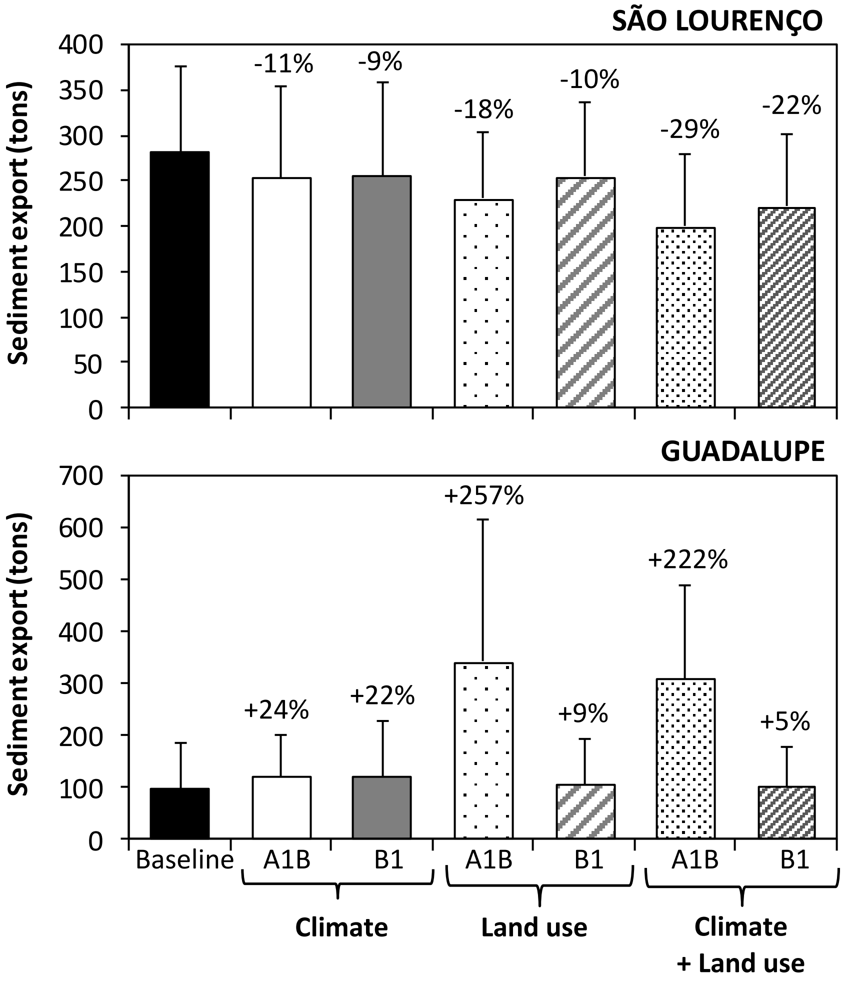
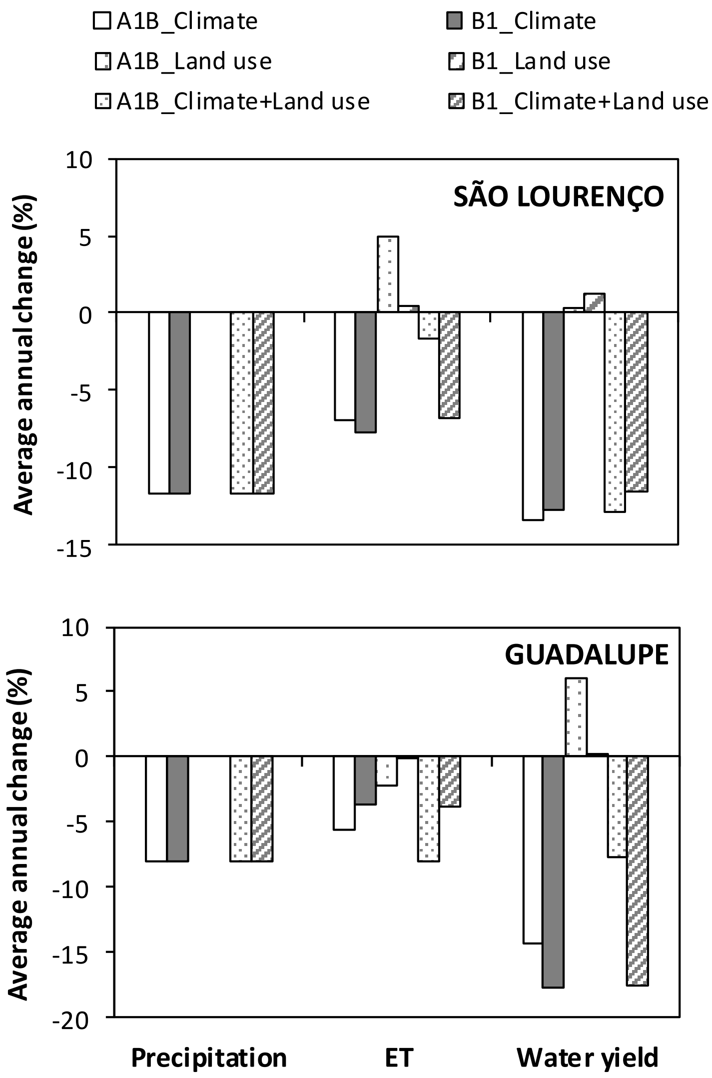


Fig. 9. Average annual (± standard deviation) sediment export under different scenarios of climate, land use and combined climate and land use changes, in the São Lourenço and Guadalupe catchment.



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