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Assessment of hydrology, sediment and particulate organic carbon yield in a large agricultural catchment using the SWAT model

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SUMMARY

The Soil and Water Assessment Tool (SWAT, 2005) was used to simulate discharge and sediment transport at daily time steps within the intensively farmed Save catchment in south-west France (1110 km²). The SWAT model was applied to evaluate catchment hydrology and sediment and associated particulate organic carbon yield using historical flow and meteorological data for a 10-years (January 1999–March 2009). Daily data on sediment (27 months, January 2007–March 2009) and particulate organic carbon (15 months, January 2008–March 2009) were used to calibrate the model. Data on management practices (crop rotation, planting date, fertiliser quantity and irrigation) were included in the model during the simulation period of 10 years.

Simulated daily discharge, sediment and particulate carbon values matched the observed values satisfactorily. The model predicted that mean annual catchment precipitation for the total study period (726 mm) was partitioned into evapotranspiration (78.3%), percolation/groundwater recharge (14.1%) and abstraction losses (0.5%), yielding 7.1% surface runoff. Simulated mean total water yield for the whole simulation period amounted to 138 mm, comparable to the observed value of 136 mm. Simulated annual sediment yield ranged from 4.3 t km⁻² y⁻¹ to 110 t km⁻² y⁻¹ (annual mean of 48 t km⁻² y⁻¹). Annual yield of particulate organic carbon ranged from 0.1 t km⁻² y⁻¹ to 2.8 t km⁻² y⁻¹ (annual mean of 1.2 t km⁻² y⁻¹). Thus, the highest annual sediment and particulate carbon yield represented 25 times the minimum annual yield. However, the highest annual water yield represented five times the minimum (222 mm and 51 mm, respectively). An empirical correlation between annual water yield and annual sediment and organic carbon yield was developed for this agricultural catchment. Potential source areas of erosion were also identified with the model. The range of the annual contributing erosive zones varied spatially from 0.1 to 6 t ha⁻¹ according to the slope and agricultural practices at the catchment scale.

1. Introduction

Intensive agriculture has led to environmental degradation through soil erosion and associated carbon losses from agricultural land to stream networks (Sharma and Rai, 2004). The global river network is increasingly being recognised as a major component of the carbon cycle due to the important role of rivers in the terrestrial water cycle, regulating the mobilisation and transfer of components from land to sea. Studies seeking a better understanding of the global carbon cycle have expressed increasing concern over the quantification of sediment and carbon transport by rivers to the sea (Milliman and Syvitski, 1992; Ludwig and Probst, 1998).

The erosion of carbon from land and its subsequent transport to sea via rivers represents a major pathway in the global carbon cycle (Kempe, 1979; Degens et al., 1984). Organic carbon is estimated to constitute ~40% of the total flux of carbon carried by the world's rivers (1 Gt y⁻¹) (Meybeck, 1993).

Effective control of water and soil losses in agricultural catchments requires the use of best management practice (BMP). Quantifying and understanding sediment transfer from agricultural land to watercourses is also essential in controlling soil erosion and in implementing appropriate mitigation practices to reduce stream sediment transport and associated pollutant loads, and hence improve surface water quality downstream (Heathwaite et al., 2005). However, field measurements and collection of data on suspended sediment and particulate organic carbon are generally difficult tasks, rarely achieved over long timescales in large catchments (Oeurng et al., 2011).

Appropriate tools are needed for better assessment of long-term hydrology and soil erosion processes and as decision support for

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planning and implementing appropriate measures. The tools include various hydrological and soil erosion models, as well as geographical information system (GIS). Due to technological developments in recent years, distributed catchment models are increasingly being used to implement alternative management strategies in the area of water resource allocation and flood control (Setegn et al., 2009). Many hydrological and soil erosion models are designed to describe hydrology, erosion and sedimentation processes. Hydrological models describe the physical processes controlling the transformation of precipitation to runoff, while soil erosion modelling is based on understanding the physical laws of processes that occur in the natural landscape (Setegn et al., 2009). Distributed hydrological models, mainly simulating processes such as runoff and the transport of sediment and pollutants in a catchment, are crucial for providing systematic and consistent information on water availability, water quality and anthropogenic activities in the hydrological regime (Yang et al., 2007). A physically-based distributed model is preferable, since it can realistically represent the spatial variability of catchment characteristics (Mishra et al., 2007). A number of water quality models at catchment scale have been developed (Borah and Bera, 2003). Among these models, Soil and Water Assessment Tool (SWAT) is frequently used to assess hydrology and water quality in agricultural catchments. To date, a number of SWAT applications to study hydrology and sediment transport in small and large catchments have been undertaken in different regions of the world (see SWAT Literature database: https://www.card.iastate.edu/swat_articles/).

The objective of the present study was to apply the SWAT model to an agricultural watershed (the Save catchment in the Gascogne area of south-west France) in order to:

- assess long-term catchment hydrology and sediment-associated particulate organic carbon transport,
- quantify annual sediment and carbon yields from this agricultural catchment,
- identify controls parameters of sediment and carbon yields during a long period of 10 years,
- identify contributing erosive zones in the catchment.

2. Materials and methods

2.1. Study area

The Save catchment in the area of Coteaux Gascogne is a 1110 km² agricultural catchment. The Save river has its source in the piedmont zone of the Pyrenees Mountains (south-west France), joining the Garonne River after a 140 km course with a linear shape and an average slope of 3.6‰ (Fig. 1A). The altitude ranges from 92 m to 663 m (Fig. 1B). This catchment lies on detrital sediments from the Pyrenees Mountains. It is bound on the east by the Garonne River, on the south by the Pyrenees and on the west by the Atlantic Ocean. Throughout the Oligocene and Miocene, this catchment served as an emergent zone of subsidence, receiving sandy, clay and calcareous sediments derived from the erosion of the Pyrenees Mountains, which were in an orogenic phase at that time. The substratum of the catchment consists of impervious Miocene molassic deposits.

The calcic soils are dominated by a clay content ranging from 40% to 50%, while the non-calcic soils are silty (50–60%). Non-calcic silty soils, locally named *boulbènes*, represent less than 10% of the soils in this area. The major soils of the Save catchment are presented in Fig. 1C. The upstream part of the catchment is a hilly

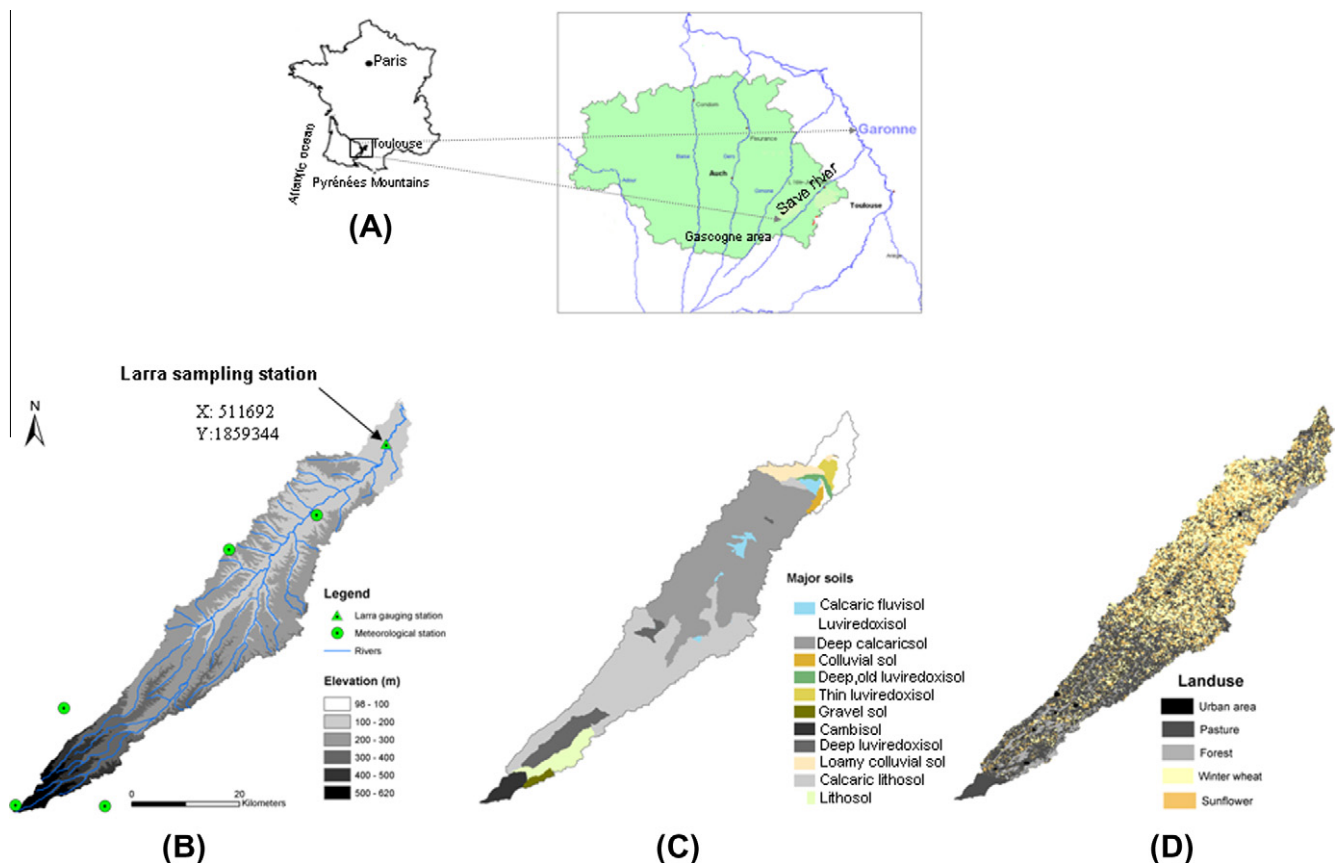


Fig. 1. (A) Location of study area; (B) topographical map; (C) major agricultural landuses (D) major soil types in the Save catchment.

agricultural area mainly covered with patchy forest and dominant pastures, while the lower part is flat and devoted to intensive agriculture, with sunflower and winter wheat dominating the crop rotation (Fig. 1D).

The climatic conditions are oceanic, with annual precipitation of 700–900 mm and annual Penman real evapotranspiration of 500–600 mm. The dry period runs from June to August (the month with maximum deficit) and the wet period from October to May. The hydrological regime of the catchment is mainly pluvial, i.e. regulated by rainfall, with maximum discharge in May and low flows during summer (July–September). The catchment substratum is an impermeable molassic material. River discharge is mainly supplied by surface and subsurface runoff. Groundwater contribution to river discharge is very low and limited to alluvial phreatic aquifers. The maximum instantaneous discharge at the Larra gauging station (outlet of the watershed) for the long-term period (1965–2006) is $620 \text{ m}^3 \text{ s}^{-1}$ (1 July 1997), while low water discharge is about $0.91 \text{ m}^3 \text{ s}^{-1}$ and is sustained by a nested canal at the catchment head ($0.004 \text{ m}^3 \text{ s}^{-1}$) at a point 100 km upstream from the outlet of the basin at Larra station, since water is used for irrigation along its course. The mean annual discharge at the Larra gauging station (1965–2006) is $6.29 \text{ m}^3 \text{ s}^{-1}$ (data from Compagnie d'Aménagement des Coteaux de Gascogne, CACG).

2.2. Observed data

2.2.1. Catchment water quality monitoring

A Sonde YSI 6920 (YSI Incorporated, Ohio, USA) measuring probe and Automatic Water Sampler (ecoTech Umwelt-Meßsysteme GmbH, Bonn, Germany) with 24 1-l bottles has been installed at the Save catchment outlet (Larra bridge) since January 2007 for water quality monitoring. The Sonde is positioned near the bank of the river under the bridge, where the homogeneity of water movement is considered representative of all hydrological conditions. The pump inlet is placed next to the Sonde pipe. The Sonde is programmed to activate the automatic water sampler to pump water at water level variations Δx (cm) ranging from 10 cm to 30 cm, depending on seasonal hydrological conditions for both the rising and falling stage. This sampling method provides a high sampling frequency during storm events (three samples per week to four samples per day during flood events). Manual sampling is also carried out using a 2-l bottle lowered from the Larra bridge, near the Sonde position, at weekly intervals when water levels are not remarkably varied. The total instantaneous water samples from both automatic and manual sampling from January 2007 to March 2009 amounted to 246 samples.

2.2.2. Determination of suspended sediment and POC concentrations

Water samples were analysed in the laboratory to determine suspended sediment concentration (SSC) using a nitrocellulose filter (GF 0.45 μm) and drying at 40 °C for 48 h. Volumes of water ranging from 150 to 1000 ml were filtered according to the suspended sediment load. Suspended sediment concentration data were determined for samples collected using the automatic and manual sampling methods described above over a range of hydrological conditions (Oeurng et al., 2010a,b). Daily SSC values were calculated from the mean of instantaneous SSC for a given day.

Particulate organic carbon (POC) was analysed on samples collected from January 2008 to March 2009. Water samples were filtered by glass microfibre filter paper (GF/F 0.7 μm) for determination of particulate organic carbon (POC). The filter paper containing suspended sediment was then acidified with HCl 2 N in order to remove carbonates and dried at 60 °C for 24 h. Particulate organic carbon analyses were carried out using a LECO CS200 analyser (Etcheber et al., 2007; Oeurng et al., 2011). The SSC values obtained using the nitrocellulose and glass microfibre filters were identical.

2.3. Modelling approach

2.3.1. The SWAT model

SWAT, the Soil and Water Assessment Tool (SWAT 2005), is a physically-based, distributed, agro-hydrological model that operates on a daily time step (as a minimum) at watershed scale. SWAT is designed to predict the impact of management on water, sediment and agricultural chemical yields in ungauged catchments (Arnold et al., 1998). The model is capable of continuous simulation for dissolved and particulate elements in large complex catchments with varying weather, soils and management conditions over long time periods. SWAT can analyse small or large catchments by discretising into sub-basins, which are then further subdivided into hydrological response units (HRUs) with homogeneous land use, soil type and slope. The SWAT system embedded within geographical information system (GIS) can integrate various spatial environmental data, including soil, land cover, climate and topographical features. Theory and details of hydrological and sediment transport processes integrated in SWAT model are available online in SWAT documentation (<http://swatmodel.tamu.edu/>).

2.3.2. Hydrological modelling component in SWAT

SWAT uses a modification of the SCS curve number method (USDA Soil Conservation Service, 1972) to compute surface runoff volume for each HRU. Peak runoff rate is estimated using a modification of the Rational Method (Chow et al., 1998). Daily rainfall data are used for calculations. Flow is routed through the channel using a variable storage coefficient method (Williams, 1969) or the Muskingum routing method (Cunge, 1969). In this work, SCS curve number and Muskingum routing methods, along with daily climate data, were used for surface runoff and streamflow computations. In this study, the Penman method was used to estimate potential evapotranspiration (Monteith, 1965).

2.3.3. Suspended sediment modelling component in SWAT

The sediment from sheet erosion for each HRU is calculated using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). Details of the USLE equation factors can be found in Neitsch et al. (2005).

The sediment concentration is obtained from the sediment yield, which corresponds to flow volume within the channel on a given day. The transport of sediment in the channel is controlled by simultaneous operation of two processes: deposition and degradation. Whether channel deposition or channel degradation occurs depends on the sediment loads from the upland areas and the transport capacity of the channel network. If the sediment load in a channel segment is larger than its sediment transport capacity, channel deposition will be the dominant process. Otherwise, channel degradation occurs over the channel segment.

2.4. SWAT data input

The Arc SWAT interface for SWAT version 2005 (Winchell et al., 2007) was used to compile the SWAT input files. The SWAT model requires input on topography, soils, landuse and meteorological data.

- Digital elevation map (DEM) with a resolution of 25 m \times 25 m from BD TOPO R IGN France.
- Soil data at the scale of 1:80,000 from Macary et al. (2006) and soil properties from Lescot and Bordenave (2009).
- Landuse data from Landsat 2005 for calibrating the agricultural practices and rotations (Macary et al., 2006). The landuse data from three other Landsat images (2001, 2003 and 2008) do not show significant differences in land use (less than 5%).

The management practices were taken into account in the model for simulation. The dominant land uses in the catchment were pasture, sunflower/winter wheat in rotation. The starting dates of plant beginning, amounts, date of fertiliser and irrigation applications were included. For pasture area, there is one rotation of maize during a period of 4 years. Tillage is carried out during April within this area. For sunflower–winter wheat rotation, the planting date of sunflower is April 10 and harvest is on July 10. After that, winter wheat begins on October 9 and is harvested on July 10 in the following year. The rotation of winter wheat–sunflower follows the same pattern, with winter wheat being planted on October 9 and harvested on July 10. In the following year, sunflower is planted on April 10, then is harvested on July 10. The soil is uncovered from July through April for this rotation once every two years.

- Meteorological data included five rainfall stations with daily precipitation from Meteo France (Fig. 1A). Some past and missing data were generated for some stations by linear regression equation from the data of the nearest stations with complete measurements. Two stations at the upstream part having a complete set of measurements of daily minimum and maximum air temperature, wind speed, solar radiation and relative humidity were used to simulate the potential evapotranspiration (PET) in the model by the Penman method.
- The catchment was discretised into 91 sub-basins with dominant landuse and soil classification. The main dominant landuses in the Save catchment are pasture, sunflower and winter wheat. Fig. 3 shows the 91 sub-basins in the Save catchment.

2.5. Model evaluation

The performance of the model in simulating discharge and sediment was evaluated graphically and by Nash–Sutcliffe efficiency (E_{NS}) and coefficient of determination (R^2):

$$E_{NS} = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2}$$

$$R^2 = \left\{ \frac{\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S})}{[\sum_{i=1}^n (O_i - \bar{O})^2]^{0.5} [\sum_{i=1}^n (S_i - \bar{S})^2]^{0.5}} \right\}^2$$

where O_i and S_i are the observed and simulated values, n is the total number of paired values, \bar{O} is the mean observed value and \bar{S} is the mean simulated value.

E_{NS} ranges from negative infinity to 1, with 1 denoting perfect agreement between simulated and observed values. Generally E_{NS} is very good when E_{NS} is greater than 0.75, satisfactory when E_{NS} is between 0.36 and 0.75, and unsatisfactory when E_{NS} is lower

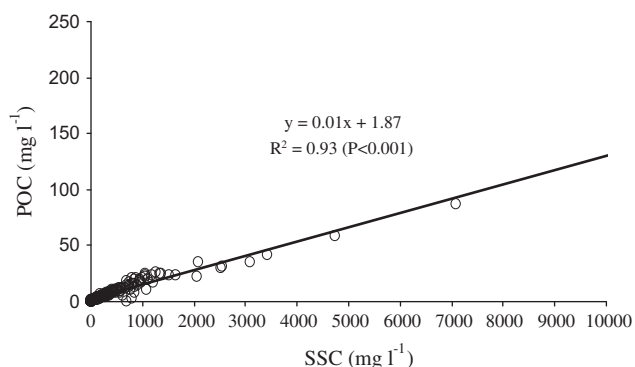


Fig. 2. Relationship between instantaneous suspended sediment concentration (SSC) and particulate organic carbon (POC) at Larra sampling station.

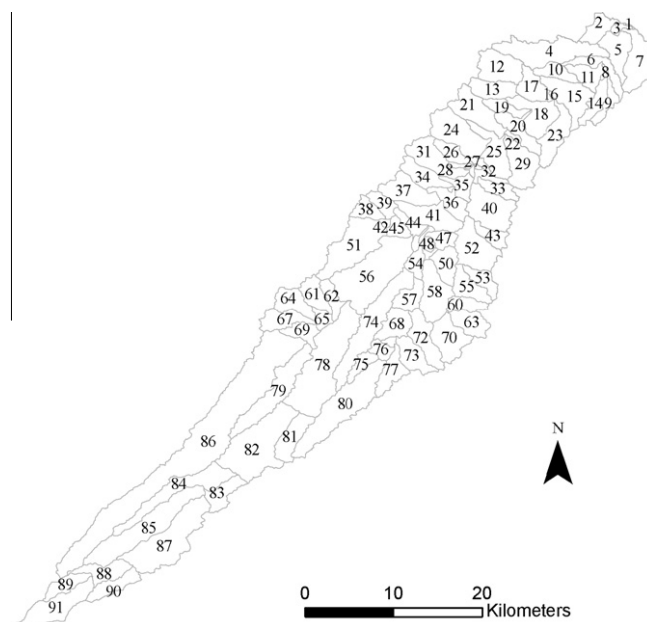


Fig. 3. Map showing 91 sub-basins in the Save catchment.

than 0.36 (Nash and Sutcliffe, 1970; Krause et al., 2005). However, a shortcoming of the Nash–Sutcliffe statistic is that it does not perform well in periods of low flow, as the denominator of the equation tends to zero and E_{NS} approaches negative infinity with only minor simulation errors in the model. This statistic works well when the coefficient of variation for the data set is large (Pandey et al., 2008). The coefficient of determination (R^2) is the proportion of variation explained by fitting a regression line and is viewed as a measure of the strength of a linear relationship between observed and simulated data. R^2 ranges between 0 and 1. If the value is equal to one, the model prediction is considered to be ‘perfect’.

2.6. Calibration process

The period July–December 1998 served to initialise variables for the model. The calibration was carried out at daily time steps using flow data for the hydrological years from January 1999 to March 2009 and suspended sediment data for January 2007–March 2009. The capability of a hydrological model to adequately simulate streamflow and sedimentation processes typically depends on the accurate calibration of parameters (Xu et al., 2009). Parameters can either be estimated manually or automatically. In this study, the calibration was done manually based on physical catchment understanding and sensitive parameters from published literature (e.g. Bärlund et al., 2007; Xu et al., 2009) and calibration techniques from the SWAT user manual. After calibration of flow, calibration of sediment was carried out. The SCS curve number (CN2) is a function of soil permeability, landuse and antecedent soil water conditions. This parameter is important for surface runoff. The baseflow recession coefficient (ALPHA_BF) is a direct index of groundwater flow response to changes in recharge. This parameter is necessary for baseflow calibration. The sensitive parameters for predictions of sediment are a linear parameter for calculating the maximum amount of sediment that can be entrained during channel sediment routing (SPCON), an exponential parameter for calculating the channel sediment routing (SPEXP), and a peak rate adjustment factor (PRF), which is sensitive to peak sediment. There is no channel protection; however, the channel banks are covered by riparian vegetation along the Save river.

3. Results and discussion

The relationship between SSC and POC concentration was found to have an R^2 value of 0.93 (Fig. 2). Based on this relationship, long-term POC could be computed from simulated SSC obtained from SWAT.

3.1. Discharge simulation and hydrological assessment

Simulations were carried out for the period January 1999–March 2009. Flow and sediment calibration was based on daily simulations. Table 1 presents the calibrated parameters for discharge, suspended sediment and the range of SWAT parameter values, while Fig. 4 graphically illustrates observed and simulated daily discharge at the Larra gauging station. Simulated discharge followed a similar trend to observed discharge. However, simu-

lated peak discharge was underestimated during some flood periods such as an event in June 2000, which was the largest flood observed in the study area since 1985 (data from CACG). In any case, SWAT could not accurately simulate the flood discharge when the river overflowed, as in the June 2000 flood. Daily simulated discharge was also overestimated for some periods, e.g. in May 2007. Larger errors occurred when simulated peak and average flows differed significantly from the measured values. It should be noted that the hydrological regime of the Save fluctuates significantly, possibly resulting in difficulty in discharge calibration. The statistical performance was satisfactory, with a daily E_{NS} value of 0.53 and an R^2 value of 0.56. The daily discharge data higher than $40 \text{ m}^3 \text{ s}^{-1}$ were extrapolated from the rating curve at Larra station, so the inaccuracy in the measurement of daily discharge higher than $40 \text{ m}^3 \text{ s}^{-1}$ explains the difficulties in simulating discharge during high flood events. Water extraction in summer and during the win-

Table 1
Parameters used to calibrate flow and sediment at Larra gauging station.

Parameter	Parameters used to calibrate flow				
	Definition	Min. value	Max. value	Calibrated value	
basins.bsn	ESCO	Soil evaporation compensation factor	0	1	0.5
	EPCO	Plant water uptake compensation factor	0	1	1
	ICRK	Crack flow (1 = model crack flow in soil)			Active
	SURLAG	Surface runoff lag time	0	10	1
*.GW	GW_DELAY	Groundwater delay	0	500	30
	GW_REVAP	Groundwater revap	0.02	0.2	0.05
	RCHRG_DP	Deep aquifer percolation factor	0	1	0.15
	ALPHA_BF	Baseflow alpha factor	0	1	0.5
*.soil	SOL_AWC	Available water capacity of the soil layer	0	1	0.2
*.sub	CH_N1	Manning's "n" value for tributary channels	0.01	0.5	0.025
*.rte	CH_N2	Manning's "n" value for main channel	0.01	0.5	0.04
*.hru	OV_N	Manning's "N" for overland flow	0.01	0.5	0.19
*.mgt	CN2	SCS curve number	35	98	80 (cultivated) 65 (urban) 70 (forest)
<i>Parameters used to calibrate sediment</i>					
File					
*.bsn	PRF	Peak rate adjustment factor for sediment routing	0	2	0.58
*.rte	CH_COV	Channel cover factor	-0.001	1	1
*.rte	CH_EROD	Channel erodibility factor	-0.05	0.6	0.0001
*.bsn	SPCON	Linear parameters for calculating the channel sediment routing	0.0001	0.01	0.01
*.bsn	SPEXP	Exponent parameter for calculating the channel sediment routing	1	2	2

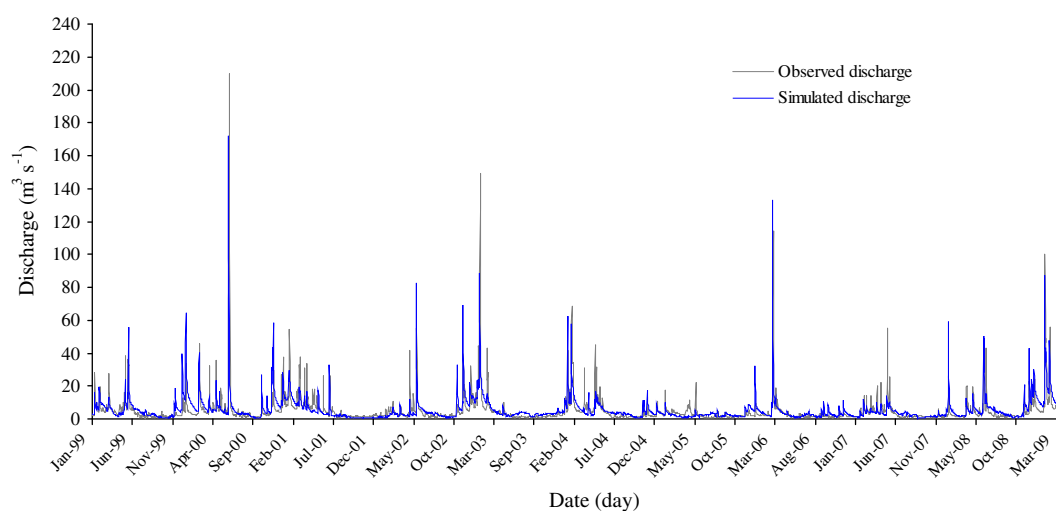


Fig. 4. Observed and simulated daily discharge at Larra station (January 1999–March 2009).

ter period to sustain flow discharge in the Save river also contributes to the uncertainty in baseflow calibration.

For the calibrated parameter set, the model predicted that mean annual rainfall for the total simulation period over the area of the catchment (726 mm) is mainly removed through evapotranspiration ET (78.3%), percolation/groundwater recharge (14.1%) and transmission loss/abstraction (0.5%), yielding surface runoff of 7.1%. The computed water balance components indicated rather high mean annual ET rates (78.3% of mean annual rainfall). This value is similar to the ET (72%) of an agricultural catchment in an arid area in Tunisia studied by Ouessar et al. (2009). However, the groundwater recharge rate (14.1% of mean annual rainfall) of the Save catchment was lower than that of the Tunisian catchment (22%). This can be attributed to limitation of groundwater recharge by the Save catchment substratum, which is relatively impermeable due to its high clay content. Simulated mean total water yield for the whole simulation period amounted to 138 mm, which is comparable to the observed value of 136 mm (1985–2008). In this large intensive agricultural catchment, most rainfall was evapotranspired throughout the year.

3.2. Suspended sediment simulation and yield

The observed values of suspended sediment were compared with simulated sediment values for the period January 2007–March 2009. Fig. 5 shows observed and simulated discharge and observed and simulated suspended sediment concentration during the suspended sediment sampling period at Larra gauging station. Similar trends were found for observed and simulated sediment concentrations. During floods in June 2007 and January 2008, there were no observed sediment data due to damage to the sampling instrument. However, the simulated sediment was underestimated and overestimated during some flood events. The underestimation

occurred for a flood event in June 2008 when rainfall intensity was extreme, resulting in severe sediment load transport (Oeurng et al., 2010a). In practice, high-intensity and even short duration rainfall can generate more sediment than simulated by the model on the basis of daily rainfall (Xu et al., 2009). The statistical analysis showed reasonable agreement between observed and simulated daily values, with an R^2 value of 0.51, and a NS of 0.31. The sediment fluxes and concentrations are most important during flood events, which is why the NS and R^2 values are not very high. However, at the annual scale, the model predicted annual sediment yield which significantly matched the 2 years of observed sediment yield at the outlet studied by Oeurng et al. (2010a) (Fig. 6B).

Oeurng et al. (2010a) showed that one extreme flood event in June 2008 in the Save catchment yielded a sediment load of 63% of the annual sediment yield in 2008. Benaman and Shoemaker (2005) analysed high flow sediment event data to evaluate the performance of the SWAT model in the 1178 km² Cannonville catchment and concluded that SWAT tended to underestimate the loads for high loading events (greater than 2000 metric tons). The main disadvantage of SWAT is the very simplified suspended sediment routing algorithm as described in Section 2.3.3. Furthermore, SWAT allows all soil eroded by runoff to reach the river directly, without considering sediment deposition remaining on surface catchment areas.

The simulated sediment yield of other years is also presented in Fig. 6B. The annual sediment yield from the Save catchment showed great variability, ranging from 4766 t to 123,000 t, representing a mean specific sediment yield of 48 t km⁻² y⁻¹. The sediment yield in 2000 was the highest of all simulated annual sediment yields and could be attributed to a major flooding period when daily maximum discharge reached 210 m³ s⁻¹. The lowest sediment yield occurred in the driest year (2005), when no major flood events were observed during the whole year. The great vari-

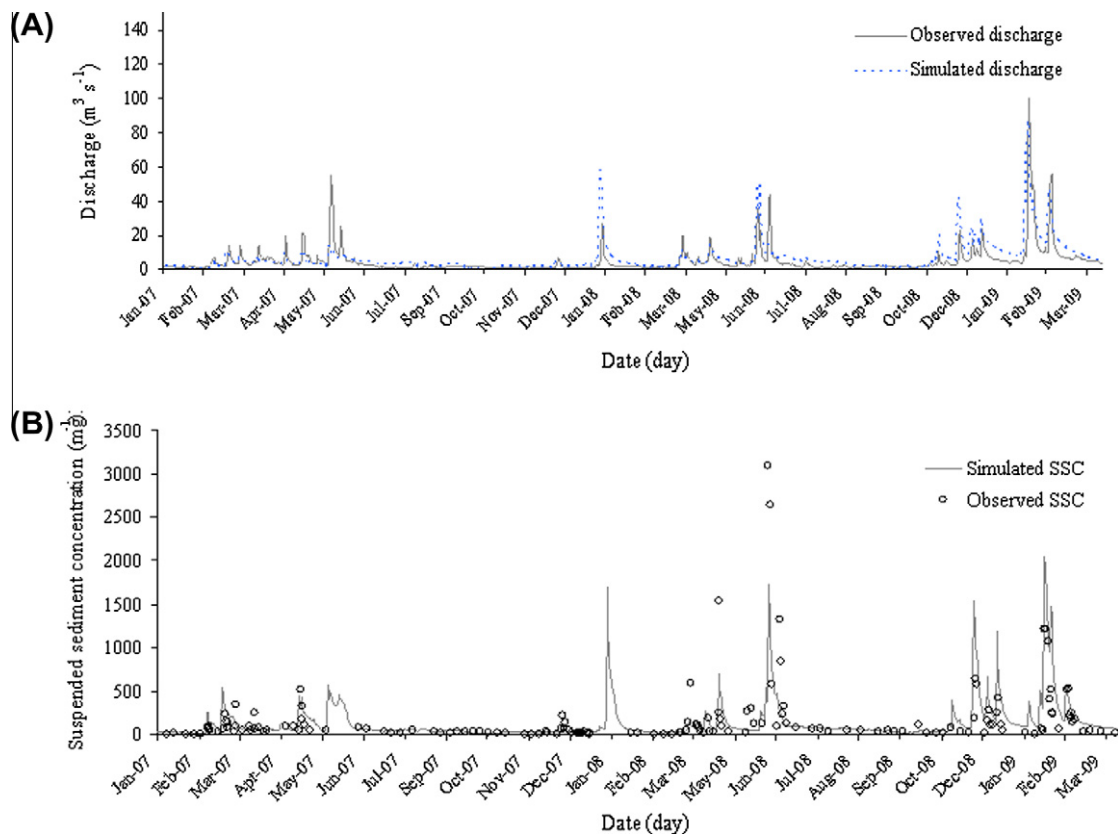


Fig. 5. Observed and simulated daily discharge (A) and observed and simulated suspended sediment concentration (B) at Larra sampling station (January 2007–March 2009).

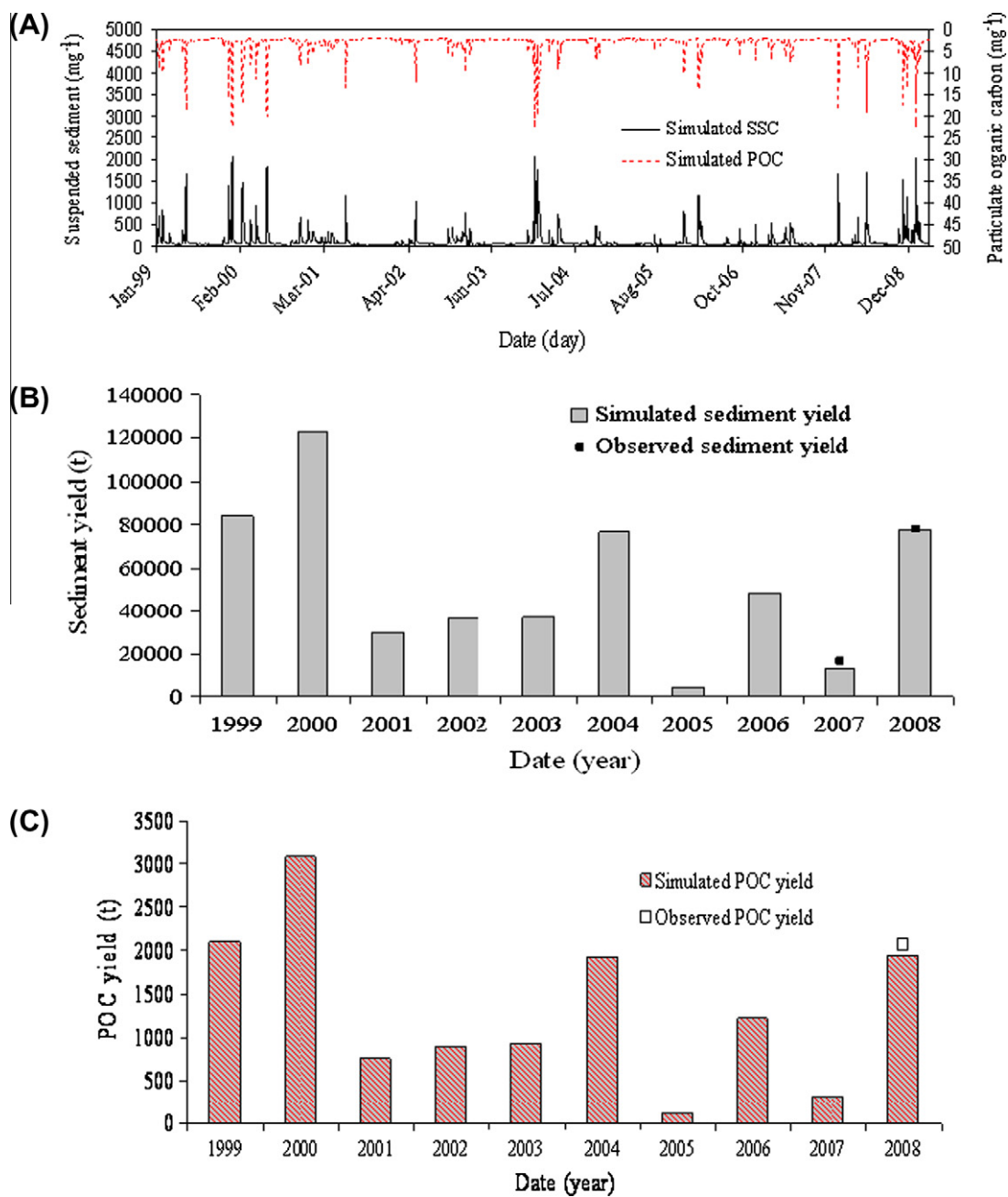


Fig. 6. (A) Simulated daily suspended sediment concentration (SSC) and particulate organic carbon (POC) (January 1999–March 2009), (B) simulated annual sediment yield (1999–2008) and observed annual sediment yield (2007–2008) and (C) simulated annual particulate organic carbon yield (POC) (1999–2008) and observed annual POC yield (2008).

ability of sediment yield in the Save catchment mainly resulted from hydrological fluctuations from season to season and year to year. Oeurng et al. (2010a) showed that hydro-climatological variables (total precipitation during flood event, flood discharge, flood duration, flood intensity and water yield) are the main factors controlling sediment load transport in the Save catchment. The annual sediment yield from the model was significantly correlated with annual water yield, with an R^2 value of 0.82 (Fig. 7). Based on this strong empirical correlation, annual water yield could be used to estimate annual sediment yield for long-term periods within this catchment.

The sediment yield ranged from $4.3 \text{ t km}^{-2} \text{ y}^{-1}$ to $110 \text{ t km}^{-2} \text{ y}^{-1}$ (annual mean of $48 \text{ t km}^{-2} \text{ y}^{-1}$) in the Save catchment, which covers the range reported for the Garonne River ($11\text{--}74 \text{ t km}^{-2} \text{ y}^{-1}$) by Coynel (2005). The 1330 km^2 Baïss catchment and

the 970 km^2 Gers catchment, located in the same Gascogne region as the Save catchment and with the same climatic conditions, geology (molasse) and agricultural landuse, also have similar specific sediment yields (63 and $41 \text{ t km}^{-2} \text{ y}^{-1}$, respectively) (Maneux et al., 2001). The Save sediment yield is also similar to that of the 900 km^2 Tordera catchment ($50 \text{ t km}^{-2} \text{ y}^{-1}$) in north-east Spain (Rovira and Batalla, 2006), but much lower than the $414 \text{ t km}^{-2} \text{ y}^{-1}$ reported for the 445 km^2 Isábena catchment (Southern Central Pyrenees), which is highly erodible and experiences frequent floods (López-Tarazon et al., 2009).

3.3. POC simulation and yield

Based on this relationship between suspended sediment and particulate organic carbon, POC was computed from simulated sus-

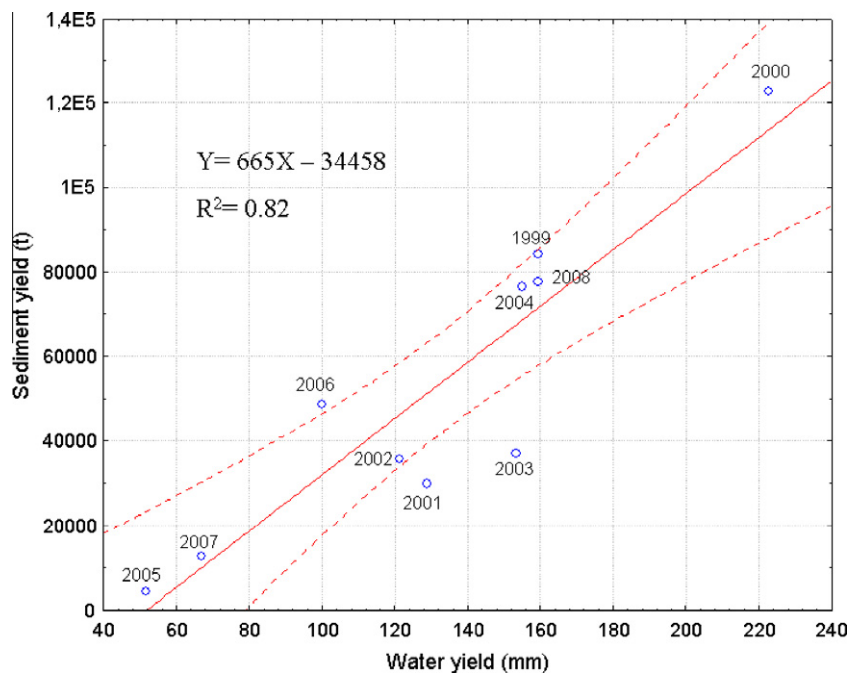


Fig. 7. Empirical correlation between annual water yield and annual sediment yield with 95% confidence interval for the Save catchment.

pendent sediment data for the period January 1998–March 2009 (Fig. 6A). Annual yield of particulate organic carbon ranged from $0.1 \text{ t km}^{-2} \text{ y}^{-1}$ to $2.8 \text{ t km}^{-2} \text{ y}^{-1}$ (annual mean of $1.2 \text{ t km}^{-2} \text{ y}^{-1}$). The 2008 value of 1948 t was statistically similar to the observed annual value of 2060 t (Fig. 6C). The annual POC yield showed strong variability due to the variability in sediment yield within the catchment. The average specific POC yield of 1.2 t km^{-2} in the Save catchment is similar to that of the Garonne River ($1.47 \text{ t km}^{-2} \text{ y}^{-1}$) (Veyssy et al., 1999) and that of other rivers in Europe (mean $1.10 \text{ t km}^{-2} \text{ y}^{-1}$) (Ludwig et al., 1996). However, it is lower than that of the Amazon River ($2.83 \text{ t km}^{-2} \text{ y}^{-1}$) (Richey et al., 1990).

3.4. Identification of critical areas of soil erosion

Using the total simulation results, it was possible to identify areas of significant soil erosion based on the average annual sediment yield for the total hydrological period within each sub-basin. The rate of soil erosion ranged from 0.10 to 6 t ha^{-1} (Fig. 8). Among the 91 sub-basins within the catchment, numbers 91, 89, 88, 87, 83, 81 were identified as areas with high soil erosion (up to 3 t ha^{-1}). These are several possible reasons for this. These sub-basins are located high upstream, have steep slopes, are subjected to tillage and experience many major rainfall events, while downstream areas are mostly flat and experience fewer major rainfall events, resulting in less soil erosion although these areas are intensively cultivated. Therefore, appropriate strategies should be devised to protect these critical areas where soil erosion is most serious.

4. Conclusions

Parameterisation of the model to achieve good simulations of daily flow and sediment transport for long hydrological periods proved to be a laborious task in the Save agricultural catchment. The simulation of daily discharge was better than that of sediment transport. Although the model underestimated and overestimated daily discharge and suspended sediment for some flood events, predictions were within acceptable limits. The hydrological assessment showed that more than two-thirds of the total rainfall received was removed from the Save catchment as evapotranspiration. The water balance component in SWAT proved very useful for examining water management in the catchment, which is dominated by intensive agriculture. An empirical correlation between annual water yield and annual sediment yield was developed for this agricultural catchment. This relationship can be used for generating long-term sediment yield for the Save catchment in the future, reducing the need for expensive field work. SWAT can be a useful tool for assessing hydrology and sediment yield over long periods. Moreover, the model allowed contributing erosion areas at the catchment scale to be identified. Based on historical flow and climate data, SWAT can generate sediment yield values, which

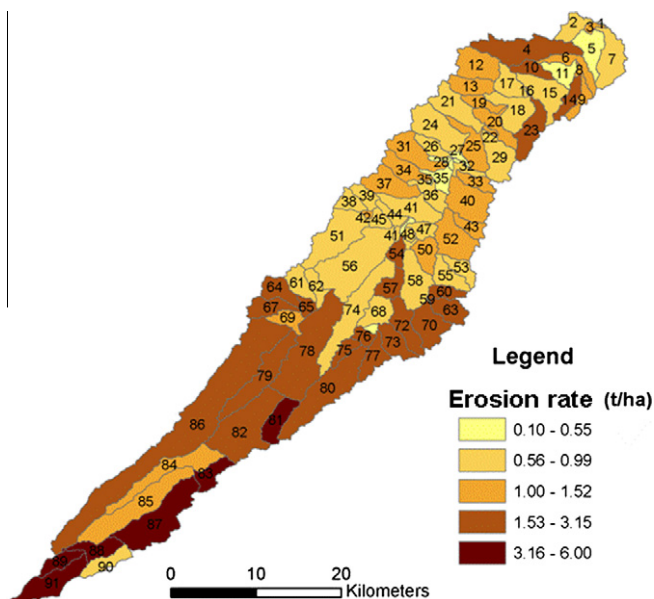


Fig. 8. Simulated contributing erosion areas within the 91 sub-basins, based on average sediment yield (1999–2008).

are crucial in identifying soil erosion patterns within a catchment. Prediction of discharge and soil losses is important for assessing soil degradation and for determining suitable land use and soil conservation measures for a catchment. The results obtained can be used to mitigate environmental problems within intensively farmed agricultural catchments.

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