

Supplementary materials

Modeling the Effectiveness of Sustainable Agricultural Practices in Reducing Sediments and Nutrients Export from a River Basin

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Supplementary material S1. Supplementary tables

Table S1. SWAT data variables for model setup and calibration/validation.

Variables	Source	Description
DEM	NASA Shuttle Radar Topography Mission (SRTM)	1 Arc-Second Global Land Elevation Map
Stream network	SNIAmb	Stream network according to the Water Framework Directive (WFD)
Land cover	DGT	COS 2010 (Land use map), 1 ha (minimum mapping unit). Classes were aggregated into seven main cover classes
Soil	Leitão et al. (2013)	Soil Ecological Value of Mainland Portugal, 1:50 000. Classes were aggregated into seven main soil classes
Precipitation and temperature	E-OBS	Mean daily precipitation (mm), maximum and minimum daily temperature (°C) from E-OBS gridded dataset, from 1970 to 2018
Climate (other variables)	SNIRH	Hourly values from 2003 to 2017 were converted to daily values of solar radiation (MJ), relative humidity (%), and wind speed (m/s) from climate 3 climate stations
River discharge	SNIRH	Daily observations of river discharge (m ³ s ⁻¹) at 1 hydrometric station. Calibration period: 1980–1982; Validation: 1983–1985
Water flow-in to reservoirs	SNIRH	Daily observations of water flow-in (m ³ s ⁻¹) to 6 reservoirs. Calibration period: 2004–2006; Validation: 2015–2017
Reservoirs	SNIRH, EDP	Location and input data for reservoirs
Water abstraction	SNIG, APA	Location of surface water abstractions and volume of water abstracted

Table S2. Soil classes used in SWAT .

Soil Classes	% in the Basin
Urban land	1.6
Water	2.3
Fluvisols dystric	2.9
Cambisols dydtric	7.6
Leptosols umbric on schist	10.1
Antrosols dydtric	23.2
Regosols umbric	25.9
Leptosols umbric on granite	26.3

Table S3. Land-cover classes used in SWAT.

SWAT Code	Land Cover Class	Major Vegetation Species
URHD	Residential-High Density	-
URMD	Residential-Medium Density	-
UIDU	Industrial units	-
UTRN	Transportation	-
URLD	Residential-Low Density	-
RYE	Non-irrigated arable land	Rye, potato
CTSR	Irrigated arable land	Corn
GRAP	Vineyard	Vineyard
ORCD	Orchard	Apple, orange and lemon tree
LAME	Pasture	
FOLH	Oaks and other broadleaved trees	<i>Quercus robur</i> , <i>Quercus pyrenaica</i> , <i>Castanea sativa</i> , <i>Betula celtiberica</i> , <i>Alnus glutinosa</i> , <i>Salix atrocinera</i>
RESI	Pine	<i>Pinus pinaster</i>
INVA	Eucalyptus and other invasive species	<i>Eucalyptus globulus</i> , <i>Acacia dealbata</i>
MATO	Atlantic shrubland	Heath and Gorse (<i>Erica australis</i> , <i>Calluna vulgaris</i> , <i>Pterospartum tridentatum</i>)
ZDPV	Baren rock and sparsely vegetated	Heath (<i>Erica</i> spp.) and dry perennial grasslands
WATR	Water bodies	-

Supplementary material S2. Additional methodological details regarding SWAT setup

Reservoirs setup

Reservoir outflow was modelled as simulated controlled outflow (IRESCO = 2). Monthly target reservoir storage (STARG), maximum daily outflow (OFLOWMX), sediment (RES_SED), nitrate (RES_NO3) and phosphorous (RES_SOLP) concentration were filled as monthly averages with observed data from SNIRH. Monthly target reservoir storage (STARG) was defined as the volume of water needed to fill the reservoir to the principal spillway (RES_PVOL) in Penide and Ponte do Bico, because there was no observed data. The number of days to reach target storage from current reservoir storage (NDTARGR) was set to 2 in run-of-rivers hydropower plants (i.e., Penide and Ponte do Bico) and 3 in the storage and pumped storage reservoirs.

Water transfer between tributaries and water pumping were simulated using the transfer command in the .fig file of SWAT. Since there was no observed data for water transfer between Alto Cávado and Alto Rabagão reservoirs, and between Vilarinho das Furnas and Caniçada reservoirs, 70% of water flow-in to Alto Cávado and 90% of water flow-in to Vilarinho das Furnas was transferred to Alto Rabagão and Caniçada reservoirs, respectively, according to an averaged value published in the report from APA [33]. Water transfer from small tributaries to Venda Nova and Paradelas reservoirs (Fig. 1) was simulated by transferring 70% of the water flow in the tributaries to the reservoirs, from October to June, according to EDP [32]. To simulate water pumping in Venda Nova and Alto Rabagão reservoirs, 30% and 20% of the water flow in the downstream subbasin was transferred to the upstream subbasin. The percentage of water transferred was selected based on the best agreement between observed and simulated values of reservoir flow-in.

Reservoir surface area when the reservoir is filled to the principal spillway (RES_PSA) was calculated by applying the proportion between reservoir surface area when the reservoir is filled to the emergency spillway (RES_ESA), the volume of water needed to fill the reservoir to the emergency spillway (RES_EVOL), and the volume of water needed to fill the reservoir to the principal spillway (RES_PVOL).

Reservoir water abstractions were included using the WURESN parameter of the reservoir database (.res), while river water abstractions were included using the WURCH parameter of the water use database (.wus). Annual data of water abstraction were converted to monthly data based on the percentage of water flow-in for each month.

Management operations

Crops and management practices of arable lands and pastures were different between the Barroso and the other parts of the basin. Crops and management practices commonly used in the Barroso region were used in the sub-basins located in the Barroso.

Corn is the dominant irrigated crop in the basin [25]. In the Barroso region corn is cultivated from May to September followed by winter vegetables, while in the mid and lower parts of the basin corn is followed by Italian regrass (*Lolium multiflorum*) [25]. Non-irrigated arable land in the Barroso region generally include rye rotating with potato and a fallow period during which the land is used for livestock grazing, while in the mid and lower parts of the basin corn is generally cultivated in spring and summer followed by poorly managed grass systems or winter pastures [22].

Traditional pastures in the Barroso region (“lameiros”) are very unique management systems essential for the production of hay and cattle grazing [22], while in the middle and lower part of the basin pastures mostly refer to unmanaged grass systems with some cattle occasionally grazing. Traditional pastures in the Barroso region are also called water meadows, because from autumn to spring they are permanently irrigated with water diverted from streams with traditional gravity irrigation systems, not to supply the water plants, but to avoid the formation of frosts that damage the vegetation cover [22]. Grazing does not take place from spring to summer so that hay can be produced for animal consumption in the following winter [23].

Fruit trees in the Barroso region are dominated by almonds and walnuts, while in the other parts of the regions by apple and citrus fruits [22], so walnuts were used as the crop

of fruit trees in the Barroso sub-basins while apple trees were used in the rest of the sub-basins

Management operations used in SWAT for irrigated (CTRS) and non-irrigated (RYE) arable lands, pastures (LAME) and fruit trees (ORCD) represent these differences in crops and management practices among regions in the basin.

The amount of livestock fertilizer applied in arable lands and pastures was estimated using data at the sub-basin scale from the Water Framework Directive (WFD), retrieved from SNIAmb. The amount of N and P reaching water bodies from livestock was determined, in the second river basin management plan [24], as 17% and 5% of the total N and P produced by livestock, which took into account the number of animals per farm and the amount of N and P produced by different livestock species. Data on N and P per sub-basin from the WFD was then divided by 17% and 5%, respectively, to determine the total amount of N and P produced. The amount of N and P produced by livestock per sub-basin was applied as fertilizers in arable lands and pastures, the former because livestock fertilizer is generally applied in the surrounding arable lands [25], and the latter due to direct fertilization during grazing. The polygons of these 3 land covers were then merged and intersected with the polygons of the sub-basins, in order to calculate the total fertilized area per subbasin, and finally determine the amount of N and P applied per hectare in every subbasin. The values of N and P from livestock applied per hectare agree with those reported in the literature [23,80].

Three fertilizers were added to the SWAT fertilizers database, two with the proportion of nitrate, ammonia, and organic nitrogen in leachate and manure of dairy and beef cows in Portugal, and the other with the proportion of mineral and organic P in the Dairy-fresh manure of the SWAT database, according to [81]. These fertilizers were used to add the N and P from livestock to irrigated and non-irrigated arable lands; the manure of beef cows was used to add N to the Barroso region and the leachate of dairy cows to add N to the other sub-basins. Two thirds of the of the N and P from livestock was applied before corn plantation, because corn has higher nutrient demands and is the main crop for cattle feeding where most of resources are invested, while the remaining one third was applied before Italian ryegrass plantation. Livestock fertilizers applied in arable lands are generally ploughed before crop plantation, so a tillage operation was used between fertilizer application and crop plantation for both spring and winter crops of arable lands. After spring and winter crop plantation of arable lands, auto-fertilization operation was used since livestock fertilization is generally not sufficient to meet crops nutrient demand [23,80]. For irrigated arable lands, a fertilizer with the proportion of N and P used in corn [82] was added to the SWAT database and used in auto-fertilization. Fertilization of vineyards and fruit trees was performed using an auto-fertilization operation with a fertilizer containing the proportion of N and P generally used in vineyards and fruit trees [82]. The nitrogen stress factor that triggers fertilization (AUTO_NSTRS), the maximum amount of mineral N allowed in one application (AUTO_NAPP), and the maximum amount of mineral N allowed to be applied in one year (AUTO_NYR), for every auto-fertilization that was used were estimated from the literature [82,83]. Auto-fertilization was not used in non-irrigated arable lands of the Barroso region, because they include grazing that fertilize the soils and refer to the less intense cultivation systems where only local fertilizers are used [23].

For pastures, data of livestock fertilizer from the WFD were used as manure deposited from grazing (MANURE_KG (kg ha⁻¹ dia⁻¹)), which was calculated considering the number of days of grazing (GRZ_DAYS) and the proportion of N in Beef-fresh manure.

For irrigated arable lands, vineyards, and other fruit trees, the auto-irrigation operation was used with an irrigation efficiency (IRR_EFF) of 0.7, 0.9, and 0.75, according to [33]. For irrigated arable lands in the Barroso region the reach of the respective sub-basin was used as irrigation source, while for the remaining sub-basins the shallow aquifers of the respective sub-basins was used for irrigation, since water for irrigation is commonly diverted from rivers in the Barroso region, while it's commonly withdrawn from wells in

the lower parts of the basin [22,24]. For vineyards and fruit trees the shallow aquifer of the respective sub-basin was used as the irrigation source. The fraction of available flow that was allowed to be applied for irrigation was 75%, to avoid the reaches to get dry. The amount of irrigation applied each time auto-irrigation is triggered (IRR_MX) for every crop was estimated based on the literature [84]. Auto-irrigation was also used for pastures in the Barroso region (i.e. lameiros), from spring to summer according to the plant water demand because pastures are irrigated for hay production, while from autumn to spring auto-irrigation was used according to soil water content and with a higher amount of irrigation water applied each time auto irrigation is triggered (IRR_MX), because during this period a lot more water is diverted to the meadows to avoid the formation of frosts that damage the vegetation cover.

Planting and fertilization dates were assumed to be different among HRUs, with one third of the HRUs having planting and fertilization according to the average dates in the literature [25], one third having planting and fertilization 15 days before the average dates, and the other third 15 days after the average dates. This would avoid a simultaneous application of fertilizers, which is not realistic as the farmers in the basin are not likely to fertilize in the exact same day.

The dry weight of biomass consumed daily during grazing (BIO_EAT) was initially set as 2.76 kg ha⁻¹ day⁻¹ for all HRUs with pastures (“lameiros”) and winter pastures (rotating crop in non-irrigated arable lands), based on the literature referring that the mean weight of cows for meat production was 184 kg, that cows density in pastures was about 1 animal per ha, and that a cow consumed around 1.5% of its body weight per day (i.e. $184 \times 1.5\% = 2.76$ kg/day) [85]. However, this leads to very low biomass and high sediment yield in pastures with low livestock fertilization, and the opposite in pastures with high livestock fertilization. The approach that allowed to obtain a balanced and reasonable value of pasture biomass among sub-basins was by first setting BIO_EAT as 0.8 kg ha⁻¹ day⁻¹ for the sub-basin in the Barroso region with the highest livestock fertilization (sub-basins 2), and as 22 kg ha⁻¹ day⁻¹ for the sub-basin in the downstream areas with the highest livestock fertilization (sub-basin 51), and then determining BIO_EAT in the other sub-basins of the same region as a function of livestock fertilization (MANURE_KG, grazing operation). A different BIO_EAT value was calculated for the Barroso and the downstream area of the basin because pastures in the downstream areas has a higher cattle density that is then reflected in the amount of livestock fertilization. Therefore, the BIO_EAT value in the sub-basin 51 was calculated as $184 \text{ kg} \times 1.5\% \times 8 \text{ animals/ha}$, while in the sub-basin 2 was calculated as $184 \text{ kg} \times 1.5\% \times 0.3 \text{ animals/ha}$.

Supplementary material S3. Additional methodological details regarding LAI, evapotranspiration, and biomass calibration

Oaks, pines, eucalyptus, vineyards and fruit trees were set as mature trees at the beginning of the simulation (IGRO = 1), otherwise they will start growing from seedling and will have very low biomass at the end of the simulations. The number of days to bring plant to maturity (PHU_PLPT) was set to zero to start the simulation with mature forests. Initial dry weight biomass (BIO_INIT) for each plant species was defined according to the 6th National Forestry Inventory [36]. Maximum biomass for a forest (BMX_TREES) in the plant database was updated for oaks, pines and eucalyptus based on ICNF [36]. The default “Harvest and kill” operation was eliminated for non-crop vegetation.

Despite starting as mature forests, oaks, pines and eucalyptus biomass and evapotranspiration decreased considerably throughout the simulation years. The primary causes for the inadequate performance of the default SWAT model in simulating forest dynamics can be unrealistic radiation use efficiency (BIO_E), large leaf to biomass fraction (BIO_LEAF), and missing phosphorus supply from parent material weathering [86]. Subsequently, we changed the values of BIO_LEAF and BIO_E (Table 1 of the manuscript) according to Yang and Zhang [86], and the biomass and evapotranspiration of oaks, pines and eucalyptus were substantially improved.

The values used for the initial leaf area index (LAI_INIT) were adjusted to the maximum potential leaf area index (BLAI) of the respective species, otherwise the LAI of oaks, pine and eucalyptus was very low during the growing season. The parameters FRGRW1, FRGRW2, and ALAI_MIN of oaks were also changed (Table 1 of the manuscript) so that the LAI curves could be more similar to those reported in the literature [87]. The BLAI of vineyards in the crop database was also changed to 3 (Table 1 of the manuscript) according to Fraga et al. [88]. The ALAI_MIN of pastures in the upstream region was converted from 0 to 0.2, since SWAT also uses LAI for perennials, and pastures in the upstream region are irrigated from autumn to spring to avoid frosting and maintain vigorous vegetation.

The minimum temperature for plant growth (T_BASE) of pastures (LAME) was reduced to improve biomass estimations. The biomass and evapotranspiration of vineyards and apple trees were adjusted by increasing the harvest index for optimal growing conditions (HVSTI) and the fraction of tree biomass converted to residue (BIO_LEAF) (Table 1 of the manuscript). The harvest index override (HI_OVR) parameter was used to adjust the biomass of pastures.

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