Chapter 8

Modelling Agri-Environmental Measures for Minimizing Soil Erosion While Protecting Valuable Agricultural Land

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Additional information is available at the end of the chapter

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Abstract

Erosion processes in river basins and the consequent transport of sediment and sediment-bound pollutants to reservoirs cause hydromorphological changes and eutrophication, as well as the loss of reservoir storage capacity. This chapter deals with the optimal selection and implementation of agri-environmental measures in river basins to reduce sediment yield and load. The main aim of this was to contribute to more efficient river basin management by minimizing soil erosion, while protecting valuable agricultural land. This includes implementing measures at the most critical source areas, where they are most effective and necessary. The river Ledava basin was selected as the study area. It covers an area of 105 km^2 in northeast Slovenia and southeast Austria. The results of monitoring the river Ledava discharge reveal that the average annual concentration of sediment in the water body exceeded the recommended value of 25 mg/l by 46.7%. Using the Soil and Water Assessment Tool (SWAT), we were able to determine critical source areas and simulate the effects of eight different agri-environmental scenarios on sediment yield reduction. The results show that critical source areas comprise 12% of the river basin. Most of the scenarios reduced sediment load in the river Ledava where steeper slopes in the sub-basin prevail and where high average annual sediment transport from hydrologic response units (HRUs) has been identified. The impact of the scenarios on the average annual sediment load (ton/year) in the river was lower than for the sediment yield (ton/ha) at the HRU level.

Keywords: erosion, sediment, agriculture, SWAT, agri-environmental measures

1. Introduction

Soil erosion has a significant impact regarding the degradation of valuable agricultural land, where a combination of rainfall, soil type, slope properties, and land management can result in extensive loss of soil and associated nutrients [1, 2]. At the same time, erosion processes in the river basin and the transport of sediment and sediment-bound pollutants cause hydromorphological changes and eutrophication of surface water [3, 4]. Although erosion is a natural process, the rate of soil loss is site specific and can significantly increase with inappropriate land management (e.g., removal of vegetation cover, overgrazing, fire, mineralization of organic matter, and compaction through mechanization) and climate change [5]. According to the Food and Agriculture Organization of the United Nations (FAO), erosion resulting from human activities is 100–700 times faster than the natural rate (0.1–1.0 ton/ha/year) [6]. Theoretically, soil erosion should be maintained at a rate that is equal to or below the natural rate at which new soil forms [5]. However, this balance is difficult to achieve because of differences in soil, slopes, land cover, and climate that are site dependent. Due to the Soil Strategy for England [7], estimated erosion rates in England and Wales range between 1 and 20 ton/ha/year for most agricultural fields. The mean soil loss rate in the European Union's erosion-prone land (agricultural land, forests, and semi-natural areas) has been found to be 2.46 ton/ha/year, resulting in a total soil loss of 970 Mt annually [8]. In Slovenia, about 4 ton/ha of soil are lost on average every year [9].

In order to mitigate the on-site and off-site effects of erosion processes, several control measures have been designed around the world. Measures adapted to specific farming systems to improve the environment are termed agri-environmental measures (AEM), adopted as the instrument of the Common Agricultural Policy. The introduction of the Water Framework Directive (WFD, 2000/60/EC) has increased interest in soil conservation, mainly because of the impact of runoff and associated sediment and pollutants on water quality [1]. Policy interventions (Good Agricultural and Environmental Condition, GAEC) over the last decade in Europe have reduced the soil loss rate by 9.5% on average and by 20% for arable land [8]. Many other studies report the positive effect of measures (rotation, conservation tillage, cover crops, contour farming, vegetative filter strips, terracing, etc.) on soil loss reduction at the field scale [1, 10–15] or the river basin scale [16–21]. As the performance of measures is highly dependent on local circumstances (e.g., soil type, slope, crop and climate), combining different measures can lead to a greater reduction of soil loss and sediment yield [16, 19, 22].

AEM can, however, also produce negative socioeconomic effects [20], because to achieve the water quality target under the WFD, the extent of arable land should be reduced from 77.2 to 46%, pasture increased from 4 to 15% and afforestation from 10 to 21%. Similar negative economic effects were reported by [23].

To avoid negative economic effects and to achieve the maximum possible benefit, the allocation of selected measures should focus on areas where they are most effective and necessary. The optimal locations for AEM are areas that contribute disproportionately high sediment and nutrient loads, which are often referred to as critical source areas (CSAs). These areas have a particular type of soil, land use, land management, and slope and represent an overlap with areas prone to generating high volumes of runoff and erosion [24]. The use of river basin

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models, such as the Soil and Water Assessment Tool (SWAT) [25], can help in identifying CSAs and prioritizing areas for the cost-effective implementation of AEM [26–28].

Many studies worldwide have used SWAT to evaluate the impact of land-use scenarios and mitigation measures on water quality and sediment yield reduction [16, 17, 19, 29–32]. The assessment of AEM using SWAT can ensure the most cost-effective allocation of measures, minimizing sediment yield, while protecting valuable agricultural land.

This chapter deals with the optimal selection and implementation of AEM in a river basin, in order to reduce sediment yields from land surfaces and sediment loads in the river. The main aim of this study was to contribute to more efficient river basin management by minimizing soil erosion while protecting valuable agricultural land. This includes the identification of CSA, where AEM are most effective and necessary.

2. Materials and methods

2.1. Study site

The river Ledava basin was selected for the study. It covers an area of 105 km^2 in northeast Slovenia and southeast Austria (**Figure 1**). Some 33.7 km^2 lies in Austria and 71.6 km^2 in Slovenia. The highest elevation on the Austrian side is 598 m above sea level, in Gleichenberger Kogel, and on the Slovenian side, 418 m above sea level at the Sotinski breg. Over a third of the basin comprises arable land (37.8%), followed by forests (36.7%), meadows (12.1%), orchards (3.4%), and other land use (10%). The otherwise homogenous hilly landscape is steeper in the upper part of the river basin. Inclinations between 0–11, 11–24, 24–35, 35–50, and over 50% represent, respectively, 35.5, 37.0, 16.1, 7.9, and 3.5% of the study area. Poorly adhering tertiary and quaternary sediments, the topographical properties and the exchange of soils with low and high permeability increase the possibility of landslides and erosion processes. Landslides in this area are small in extent but numerous, with the majority (48.9%) occurring on inclinations at or above 9° or 15.4% [33, 34].

The basin area consists of higher and steeper terrain in the headwaters of the river Ledava in Austria, as a result of stiffer geological composition of phyllite carboniferous slates and basaltic tuff of volcanic origin, and homogeneous hills in Slovenia, dominated by tertiary marlstone and claystone. The bottom of the valley is covered with alluvial clay and sandy clay sediments. Almost a third (27.07%) of the area's soil consists of pseudogley district brown soils and district brown soils on Pliocene sediments, which are washed out and not very fertile. Because the soil in the river valley is relatively impermeable, the density of the river channels network (**Figure 1**) is considerably higher (1.77–2.35 km/km^2) than the average in Slovenia (1.33 km/km^2). The river Ledava (Limbach in German) is a left tributary of the Mura River and originates in the village Pichl, Steiermark, (in the Kapfenstein municipality) at an altitude of 430 m. The length of the river to the mouth of the reservoir is 17.4 km, 8 km of which runs through Austria. The ecomorphological situation [35] of the headwater part of the river's network channels is evaluated as sustainably managed. In its central section, the river is channelized along agricultural areas, with fortified banks managed as grassland and with occasional shrub cover.

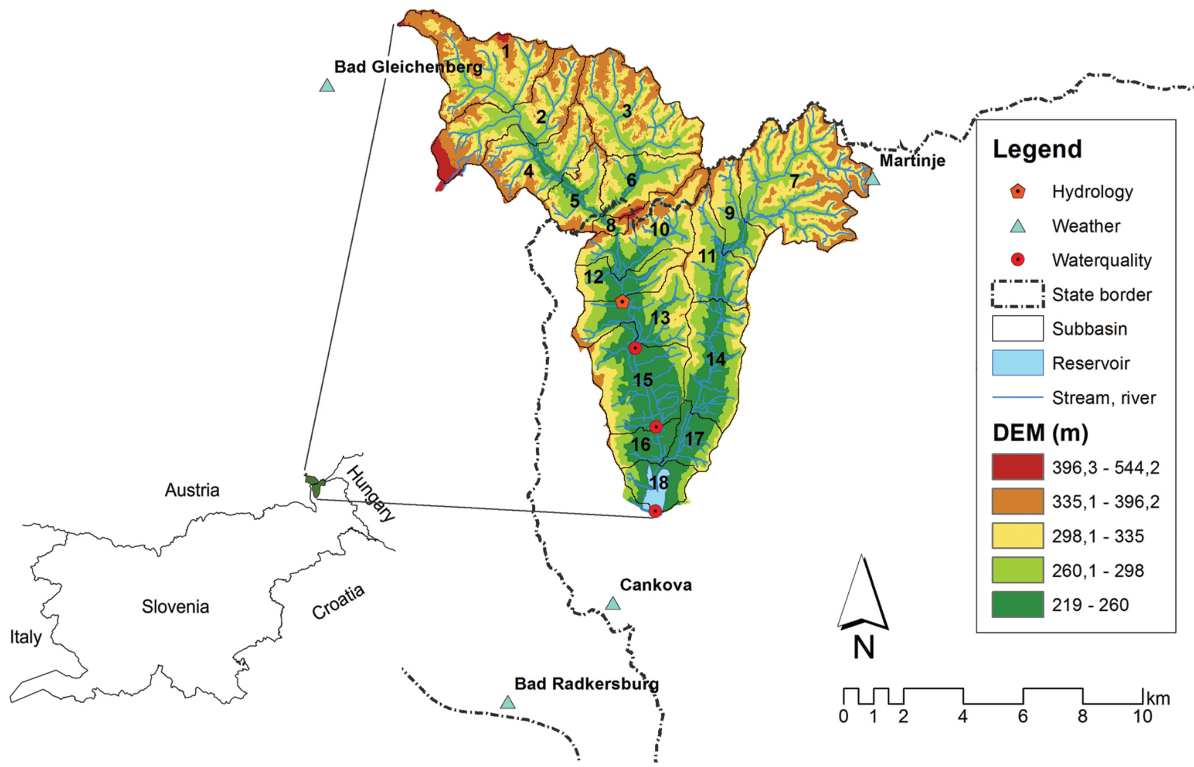

Figure 1. The river Ledava basin study site.

The river Ledava basin area has a continental climate, with average annual precipitation between 800 and 900 mm, falling mainly in the summer as showers and thunderstorms. The highest average temperatures (2003–2014) were measured in July (21°C) and the lowest in January (-0.1°C). The hydrological regime of the river is characterized by a rain–snow mixture, with the highest flows in early spring and late autumn. Low flows in the summer are the result of higher temperatures, higher evapotranspiration, and rainfall interception by vegetation. The maximum average monthly river flows (1993–2013) were measured between December and March (-0.47 to 0.42 m^3/s), with the highest river flow recorded in August 2005 (29.3 m^3/s). Due to the rapid hydrological response in the basin, the river Ledava flooded regularly. In order to protect the city of Murska Sobota and the cultivated land along the river, the Ledavsko jezero reservoir was built in 1977.

The results of simultaneous monitoring from June 2013 to May 2014 on the Ledava river and the Ledavsko reservoir reveal that the average annual concentration of sediment in both water bodies exceeded the recommended value (Fish Directive, 2006/44/EC) of 25 mg/l by 46.7% in the river and by 73.3% in the reservoir.

2.2. Model description

We selected the SWAT to evaluate the effects of different AEM on sediment yield and to evaluate CSAs in the river Ledava basin. SWAT is a physically based, spatially distributed basin scale model developed by the Agricultural Research Service (ARS) of the US Department of Agriculture (USDA) [36]. The main objective of the model development was to support river basin managers in evaluating the effects of alternative management decisions concerning water resources and nonpoint-source pollution in large river basins over a longer time span [25]. In SWAT, a river basin is divided into sub-basins based on topography and river networks. Sub-basins are further divided into hydrologic response units (HRUs), based on unique land cover, soil, slope, and management practice combinations. Processes such as surface runoff and sediment yield are simulated for each HRU, and the contributions of each HRU are then aggregated for the sub-basin by a weighted average. Water is then routed to the outlet of the river basin. For this study, we used the SWAT 2012 model version, ArcGIS 10.0 software and the ArSWAT 2012.10_0.15 interface.

Erosion and sediment yields were estimated for each HRU using the modified universal soil loss equation (MUSLE). Whereas USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yields. This increases the prediction accuracy of the model, eliminates the need for a delivery ratio, and provides an estimation of single storm sediment yield [37]. MUSLE is represented by Eq. (1):

$$sed = 11.8 \times (Q_{surf} \times q_{peak} \times area_{hru})^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG \tag{1}$$

where *sed* is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor [(0.013 ton/m^2/h)/(m^3-ton/cm)], C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and *CFRG* is the coarse fragment factor.

Each of these factors can be adjusted to represent the adoption of AEM such as slope terracing, contour farming, field crop strip sowing, and residue management. Overland flow routings in SWAT model are controlled by curve number (*CN*) and coefficient of Manning's roughness (*n*). AEM can be represented by modifications of CN and *n* values affecting decrease in surface runoff by increasing infiltration (e.g., contour farming, slope terracing, and field crop strip sowing) and flow rate decrease by runoff interception (e.g., crop residue management, and field crop strip sowing), respectively, [38]. The effectiveness of vegetated filter strips (*VFS*) varies for different forms of sediments and nutrients. A single *VFS* is for modelling of concentrated flow split into two segments. In segment one, 90% of the *VFS* area obtains the least flow and segment two with 10% of area obtaining the major runoff (25–75%). Three parameters can be modified in the SWAT model to adapt modelled *VFS* design. The first one is drainage of the spatial area-to-*VFS* area ratio (*DAFSratio*), the second is percentage of the field drained by the most heavily loaded 10% of the *VFS* (*DFcon*), and the third is percentage of the flow through the most heavily loaded 10% of the VFS that is fully channelized (*CFfrac*) [28]. AEM can be simulated for specific dates and by explicitly defining the appropriate management parameters for each HRU.

2.3. Database and data analysis

Recently available geographical information system (GIS) maps for topography, land use, and soils for Slovenia and Austria were used to represent the area (**Table 1**). The stream network was defined based on a predefined stream network obtained from the Environment Agency of the Republic of Slovenia (ARSO). The topographic information was used for automatic delineation of the river basin. Land use and soil maps were superimposed over the basin.

Data type	Scale	Source	Data description
Topography (DEM raster)	Slovenia: 25 m Austria: 1 m	The Surveying and Mapping Authority of the Republic of Slovenia, GIS-Steiermark, and GIS-Burgenland	Elevation, overland and channel slopes, lengths
Soils	Slovenia: 1:25000 Austria: 1 km Raster	Ministry of Agriculture, Forestry and Food of the Republic of Slovenia; Biotechnical Faculty (University of Ljubljana) Austrian Research Centre for Forests	Spatial soil variability, soil types, and properties
Land use	Slovenia: 1 m Raster (Graphical Units of Agricultural Land) Austria: 1:5000	Slovenia: Ministry of Agriculture, Forestry and Food of the Republic of Slovenia Austria: GIS Steiermark, GIS Burgenland, and Municipalities (St. Anna am Aigen, Kapfenstein, Neuhaus am Klausenbach)	Land use, Land cover classification, and spatial representation
Land management information	/	Chamber of Agriculture and Forestry of Slovenia-Agricultural advisory service in Cankova	Crop rotations (harvesting, planting, management), fertilizer application (rates and time)
Weather	Slovenia 3 and Austria 2 stations	Environment Agency of the Republic of Slovenia (ARSO), Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Austria	Daily precipitation, Temperature (max., min.), relative humidity, wind, solar radiation from 2003-2014
River discharge	1 Point	Environment Agency of the Republic of Slovenia	Daily flow data (m^3/s) from 2003 to 2014
Waste water treatment plants	Slovenia: 3 Austria: 2	Environment Agency of the Republic of Slovenia; Land Steiermark-Amt der Steiermärkischen Landesregierung	Average daily discharge of orgP, sediment and orgN
Water quality	Two monitoring stations (Pertoča and Ledavsko jezero)	Bi-weekly monitoring	TSS, NO_3^-, NO_2^-, PO_4^{2-}TP, TN, temperature, dissolved O_2 (2013-2014)

Table 1. Model input data sources for the river Ledava sub-basin.

Data for 11 years (2003–2014) of daily observed precipitation, the temperature from five stations and the relative humidity, wind speed, and solar radiation data from two stations were obtained from the ARSO and Zentralanstalt für Meteorologie und Geodynamik (ZAMG) in Austria. In order to better understand the endpoint and transport of sediment and nutrients, data for typical management practices such as crop growth, fertilizer application, and tillage operations for different land use were gathered from the Chamber of Agriculture and Forestry of Slovenia—Agricultural Advisory Service, in Cankova.

Because the water quality data provided by ARSO were insufficient, bi-weekly water quality monitoring was carried out for 1 year (2013–2014). Concentrations of total suspended sediments (mg/l) were measured bi-weekly, from June 2013 to May 2014, at the sampling point of Pertoča (46°46′26,52" N 16°2′24,64" E), located on the river Ledava about 1.5 km upstream of the Ledavsko jezero reservoir. In total, 94 samples were taken and analyzed at the National Laboratory of Health, Environment and Food and Erico d.o.o.

2.4. Model setup and evaluation

For this study, the SWAT model was built up by dividing the river Ledava basin into 18 sub-basins (**Figure 1**) and 5758 HRUs. A warm-up period of 3 years (2003–2005) was used to initialize the model. For the calibration, data from 2006 to 2010 were used for flow calibration and from 2011 to 2013 for validation. For sediment calibration, data from 2013 to 2014 was used. Due to the small amount of measured sediment data over 1 year (June 2013–June 2014), validation for sediment was not performed.

The first step in the calibration and validation process in SWAT is to determine the most sensitive parameters for a given basin. Sensitivity analysis is helpful for identifying and ranking parameters that have a significant impact on specific model outputs, such as streamflow or sediment [39]. For the sensitivity analysis and calibration, special software called SWAT-CUP is used, which offers semi-automatic or combined manual/automatic calibration. Among the algorithms included in SWAT-CUP, the most efficient to calibrate a project is Sequential Uncertainty Fitting (SUFI-2), the use of which has been found to require fewer simulations to complete a calibration/uncertainty project [40] and is highly recommended for the calibration of SWAT models [25].

In this study, sensitivity analysis was performed using measured data for the river Ledava. The analysis was carried out for average daily flow and sediments. We used the default lower and upper bound parameter values for all parameters [37]. **Table 2** illustrates the parameters that have the greatest impact on the model when they are changed. The sensitivity analyses demonstrate the great importance of the parameters that are associated with surface runoff and snow (SFTMP, SMTM, TIMP, SOL_AWC, SURLAG, and CN2) and channel routing (CH_BNK_BD, CH_COV, SPEXP, and SPCON).

The most sensitive parameters were used to perform model calibration. Calibration is a process to better parameterize a model to a given set of local conditions, thereby reducing prediction uncertainty. During calibration, parameters are varied within an acceptable range until a satisfactory correlation is achieved between measured and simulated data [18, 25]. In this study, calibration of the model was performed for flow and sediment on a daily and monthly basis.

	Parameters	Definition	Process	Range	Sensitivity rank
Stream flow	CN2.mgt	SCS runoff curve number for moisture condition 2	Runoff	35-98	1
	SURLAG.bsn	Surface runoff lag time	Runoff	0-12	2
	SOL_AWC(...).sol	Available water capacity of the soil layer	Soil	0-0.3	3
	TIMP.bsn	Snow pack temperature lag factor	Snow	0.01-1	4
	SFTMP.bsn	Snowfall temperature	Snow	-5 to 5	5
	SMTMP.bsn	Snow melt base temperature	Snow	-5 to 5	6
Sediment	SPCON.bsn	Calculating maximum amount of sediment reentrained	Channel	0-0.01	1
	SPEXP.bsn	Calculating sediment reentrained in channel sediment routing	Channel	1-1.5	2
	CH_COV1.rte	Channel cover factor	Channel	-0.001 to 1	3
	CH_BNK_BD.rte	Bulk density of channel bank sediment	Channel	1.1-1.9	4

Table 2. Parameters identified during sensitive analysis to be sensitive to changes.

The model performance for river flow and sediment base simulation was tested with graphical comparison and with the help of objective functions commonly used in hydrological studies, such as the Pearson coefficient of correlation (R^2), Nash–Sutcliffe simulation efficiency (E_{NS}), and Percent bias (*PBIAS*) [41]. Several authors [20, 36, 42] provide further discussions regarding the strengths and weaknesses of using R^2, E_{NS}, and *PBIAS*.

2.5. Scenarios for AEM

In order to achieve “good ecological potential” in accordance with the Water Framework Directive (2000/60/EC) and Fish Directive (2006/44/EC), management measures have to be undertaken. Choosing measures often present a problem, because their effectiveness will depend on the type and source of pollution, as well as on the size and characteristics of the drainage area. At the same time, measures should be cost-effective, with minimum implementation and maintenance costs, with long-term effectiveness and without requiring major interventions in the area.

Based on a literature review [43], a list of 13 erosion AEM was proposed (cover crops, crop rotation management, conservation tillage, strip cropping, residue management, grassland conversion, vegetative filter strips, grassed waterways, riparian buffer strips, terracing, sedimentation basins, bank erosion protection, and check dams). Due to the heterogeneous characteristics of the study area, climatic conditions, ways of implementing the measures, different methods of measurement, capabilities of the model, and statements in relevant literature, we considered a set of measures as guidelines for the selection of scenarios. For the final selection of measures, we took into consideration the following five criteria:

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1. Land use, crop production management, and technologies;

2. Landscape characteristic (soil type, slope, and farmland area);

3. AEM already implemented in the river basin;

4. Model requirements;

5. Data availability.

Scenario/parameters	Used value	Default value	Range
S1-Vegetative filter strip on 0-11% slope			
VFSRATIO	60	10	0-300
VFSCON	0.5	0.5	0.25-0.75
VFSSCH	0	90	0-100
S2-Vegetative filter strip on 11-24% slope			
VFSRATIO	40	10	0-300
VFSCON	0.5	0.5	0.25-0.75
VFSSCH	0	90	0-100
S3-Vegetative filter strip on 0-24% slope			
VFSRATIO	60, 40	10	0-300
VFSCON	0.5	0.5	0.25-0.75
VFSSCH	0	90	0-100
S4-Conservation tillage			
EFTMIX	0.3	Equipment based	0-1
DEPTIL 150 (field cultivator)	150	Equipment based	0-750
DEPTIL 220 (field cultivator)	220	Equipment based	0-750
BIOMIX	0.4	0.2	0.2
OV_N	0.21	0.14	0.17-0.47
S5-Strip cropping or contour planting on 11-24% slope			
CN2	-3 units	HRU based	0-100
USLE_P	0.80	1	-1 to 1
S6-Terraces on 11-24% slope			
CN2	-6 units	HRU based	0-100
USLE_P	0.16	1	0-1
TERR_SL	15	20	0-100
S7-No cover crops in winter			
Winter cover crop has been removed from rotation			
S8-Cover crops every year			
After harvest in fall winter cover crops (red clover) was applied. In spring leftover was plough into a ground as green manure			

Table 3. Parameters and values used in the scenario simulations for the river Ledava basin.

From the 13 measures, we excluded those for which effectiveness increases in line with an increasing area of implementation (grassed waterways and sedimentation pools). Such measures are unsuitable for the study area, due to its scattered land parcel structure. Because of the important proportion of agricultural land on slopes >11%, we chose terraces, although they are not typical for this landscape and are rarely used. According to data from 2014 on the implementation of AEM in the Rural Development Program (RDP) under the EU Common Agricultural Policy (CAP) obtained from the Agency of the Republic of Slovenia for Agricultural Markets and Rural Development, three measures have also been implemented in the area to improve soil fertility and reduce soil erosion. These are cover crops, crop rotation management, and winterkill cover crop. We also selected vegetative filter strips, because the literature review indicates that these are among the most commonly used measures to reduce the effects of diffuse pollution. Five different measures were finally selected, from which eight modelling scenarios were built (**Table 3**).

We simulated measures for areas that are the most sensitive to erosion, such as arable land and drained arable land on slopes from 0 to 11% and from 11 to 24%. The aim of the scenarios was to find the most effective measure or combination of measures to effectively reduce soil erosion, sediment transport into the river and sediment flow into the downstream lake. Given the fact that orchards represent only 2.46% and vineyards 0.82% of the basin area, we decided to simulate the measures only for the arable land. This comprises the most critical areas in terms of soil erosion and covers 38.02% of the basin area. The current average arable land management practice in the basin involves a 7-year crop rotation.

3. Results and discussion

3.1. Calibration and validation

3.1.1. Hydrology calibration and validation

Objective functions show that the simulated total flow is within the acceptable range (**Table 4**; **Figure 2**). To achieve acceptable calibration and validation results, a list of model parameters was changed from default to final values (**Table 5**). **Table 4** lists the calibration and validation values for the model performance for flow. Values >0.5 for the coefficient of determination (R^2) are considered acceptable, while negative PBIAS values indicate a small overestimation of the simulated values. Nash–Sutcliffe efficiency (E_{NS}) on monthly and daily time steps are in the acceptable range [41]; however, the E_{NS} coefficient is very sensitive to values that stand out from the average [42]. SWAT simulated the streamflow trends very well, as simulated streamflow values do not exceed the measured streamflow data by more than 15% [41]. Comparing simulations run under different time steps shows that this element is important for understanding model performance [44]. Results show that on daily and yearly time steps, model simulations for streamflow are between good and very good in terms of correlating with measured values. The model simulations are weaker for monthly time steps. However, as our results will be presented as a yearly average, we can state that our model is calibrated

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sufficiently to be used for further scenario simulations. After the base model calibration was completed, the parameters remained fixed for further use in scenario modelling.

Objective function	Calibration (2005-2010)			Validation (2011-2013)
	Year	Month	Day	Day
E_{NS}	0.99	0.49	0.57	0.50
PBIAS	-5.29	-5.20	-5.30	14.08
R^2	0.70	0.62	0.57	0.53

Table 4. Statistical values for the annual, monthly and daily time step calibration for river flows of the river Ledava (2006-2010).

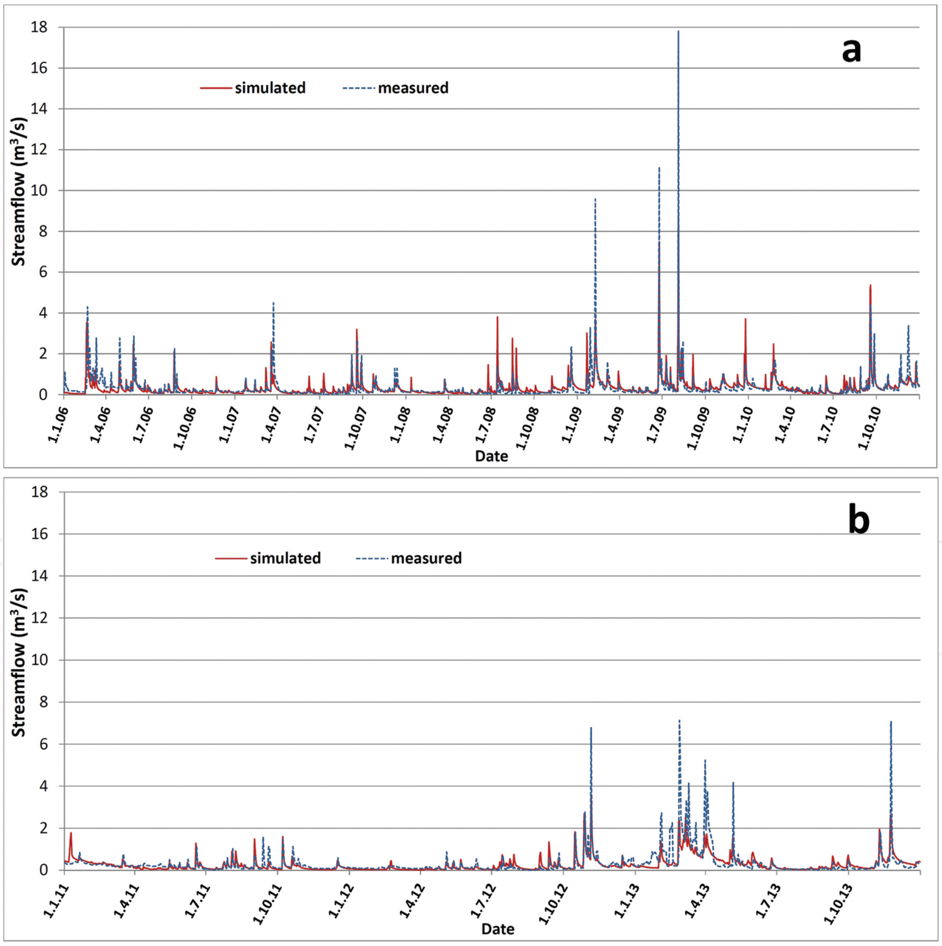

Figure 2. A comparison of simulated and measured values for river flow (m^3/s) in the river Ledava for (a) calibration period (2006–2010) and (b) validation period (2011–2013).

Parameters		Range	Default	Final
River flow				
ALPHA_BF	Baseflow alpha factor	0-1	0.048	0.5972
CANMX	Maximum canopy storage	0-100	0	-0.2017
CN2	SCS runoff curve number for moisture condition 2	35-98	Default	-0.0753
ESCO	Soil evaporation compensation factor	0-1	0.95	0.88
GW_DELAY	Groundwater delay	0-500	31	90.35
GW_REVAP	Groundwater "revap" coefficient	0.02-0.2	0.02	0.158
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	0-5000	1000	1400
SFTMP	Snowfall temperature	-5 to 5	1	1.66
SMFMN	Minimum melt rate for snow during the year (occurs on winter solstice)	0-10	4.5	1.397
SMFMX	Maximum melt rate for snow during year (occurs on summer solstice)	0-10	4.5	6.46
SMTMP	Snow melt base temperature	-5 to 5	0.5	1.5933
SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover	0-500	1	3.9767
SOL_AWC	Available water capacity of the soil layer	0-1	default	0.1917
SOL_K	Saturated hydraulic conductivity (mm/h)	0-2000	default	0.1883
SURLAG	Surface runoff lag time	0.01-24	4	0.2617
TIMP	Snow pack temperature lag factor	0-1	1	0.1321
Sediment				
ADJ_PKR	Peak rate adjustment factor for sediment routing in the sub-basin (tributary channels)	0.5-2	1	1.815
PRF_BSN	Peak rate adjustment factor for sediment routing in the main channel	0-2	1	2
SPCON	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	0.0001-0.01	0.0001	0.001197
SPEXP	Exponent parameter for calculating sediment reentrained in channel sediment routing	1-1.5	1	1.4
CH_COV1	Channel erodibility factor	-0.05 to 30	0	5.4
CH_COV2	Channel cover factor	-0.001 to 30	0	5.4
CH_ERODMO	Channel erodibility factor. Jan-Dec	0-1	0	0.3

Table 5. The parameters, range (min. and max. value), default and final values used in the model for the flow and sediment calibration and validation of the river Ledava basin.

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Due to the smaller volume of data covered, the performance results for the model validation period are often lower than for the calibration period [25]. Nevertheless, the results of the validation in this study are in line with the calibration results. E_{NS} values during calibration (0.57) and validation (0.50) indicate a good agreement between measured and simulated values, as demonstrated by the coefficient of determination ($R^2 > 0.5$). Only the *PBIAS* results vary between calibration and validation values. For calibration of the model, simulated values were overestimated, whereas for validation, the values were slightly underestimated. The *PBIAS* for validation is in the range of good to very good related to the calibration results.

3.1.2. Sediment calibration

Objective functions for a daily and monthly time step sediment calibration (**Table 6**; **Figure 3**) show that the model is acceptable for predicting sediment. Statistics significantly improve when only one outlier value is not included in the calculation. Due to the limited amount of data for sediment, with only 1 year of measurements, validation was not carried out. Sediment load was calculated as the product of the measured concentrations of sediment (mg/l) and the average daily and monthly flows (m^3/s). The coefficient of determination (R^2) indicates a moderate to strong positive agreement for daily and monthly time steps. The Nash–Sutcliff coefficient (E_{NS}) only exceeds 0.5 for monthly time steps when the outlier value (17. 2. 2014 amounted to 259.8 ton/day) is excluded. *PBIAS* describes the 18% deviation of the results for a daily time step, which is in the range for very good model performance [41]. The performance in simulation of trends with E_{NS} values (ranging from 0.26 to 0.11 for monthly and daily time steps, respectively) reveals that the simulation was unsatisfactory. However, this is because the efficiency coefficient is sensitive to extreme values and yields sub-optimal results when the dataset contains outliers [41]. The performance for R^2 and E_{NS} improves to a satisfactory level for daily time steps following the removal of outlier values. A better prediction of E_{NS} could be expected with a larger number of data samples over longer period of time [45].

Objective function	Sediment load (ton/day)			
	Monthly		Daily	
	All values	No outlier value	All values	No outlier value
E_{NS}	0.26	0.57	0.11	0.38
PBIAS	36.55	-14.09	53.04	17.69
R^2	0.37	0.64	0.22	0.39

Table 6. Objective functions for daily and monthly values of sediment concentration (mg/l) and sediment load (ton/day) in the river Ledava at the Pertoča observation station (June 2013 to March 2014).

Figure 3 shows the impact of one outlier value on the model statistical performance results for sediment. This value is a result of heavy precipitation (an average daily rainfall of 17.14 mm from the previous day to midnight at the nearby meteorological station at Cankova). This was a local storm with a local effect on sediment load. The impact of the outlier value is also evident from the difference in the coefficients of E_{NS}, R^2 and *PBIAS*. In all cases, the results were substantially improved when the outlier value was removed from the dataset, which is understandable considering the effect of this value on the average.

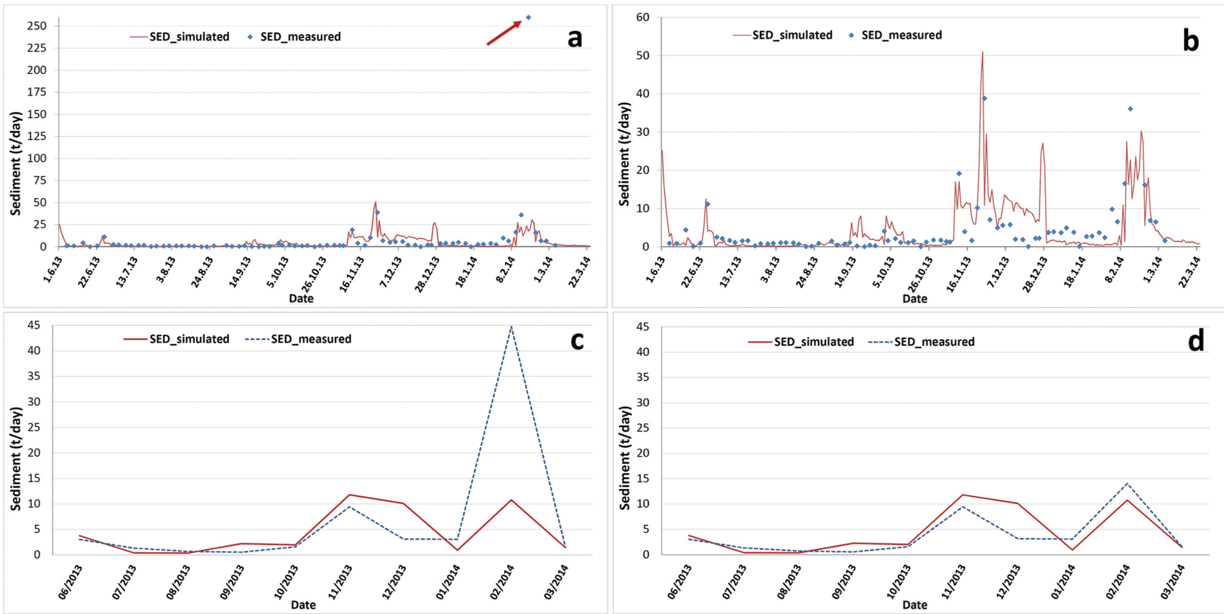

Figure 3. A comparison of the simulated and the calculated average daily (a, b) and monthly (c, d) sediment load (ton/day) in the river Ledava (Pertoča) between June 2013 and March 2014, with (a, c) and without (b, d) one outlier value.

3.2. Base scenario

Through analysis of the base scenario, we determined the CSAs, that is, where the source and transport areas that are connected to water bodies coincide. HRUs, where the annual average sediment yield exceeded 0.5 ton/ha, were considered to be CSAs (**Figure 4**). It turns out that CSAs represent only 12.2% of the entire river Ledava basin, whereas the most intense erosion occurs on arable land and encompasses 88.2% of all CSAs. These areas have unstable geology and soil types susceptible to soil erosion and for that reason are strongly subject to the action of weather forces [34]. The spatial variability of sediment yield is influenced by many factors, particularly land use, management practice, slope, and soil characteristics. The impact of land management and its graphical representations greatly depend on the accuracy of the spatial and attribute data used in the modelling process. The average annual sediment yield at the HRU level was divided into five classes (**Figure 4**).

The average annual sediment yield (0.28 ton/ha) in the river basin calculated with SWAT coincides with earlier calculations for this area based on land use and slope recalculations [34, 46]. The source of sediment in this river basin is spatially heterogeneous and on average amounts to between 0.3 and 0.9 ton/ha/year. This study shows that in certain HRUs, sediment yield can reach up to 4.10 ton/ha/year (**Table 7**; **Figure 4**). This value can be exceeded during periods of heavy rainfall, such as in 2009 when the highest value in the river reached 18.17 ton/ha. The most critical areas, with a sediment yield of 0.5 ton/ha, comprise an area of 1260 ha or

11.97%. They can be found on slopes between 11 and 24 and over 50%, and on all types of agricultural land. These areas contribute 60.9% of all the sediment transported from the HRUs into the river. The highest amount of sediment is transported from arable fields with drainage systems (0.60 ton/ha/year), other arable fields (0.40 ton/ha/year), and vineyards (0.37 ton/ha/year). Among the most erodible soil types are heavy gley and pseudogley soils. Sub-basins (1, 2, 4 and 5) with a maximum transport of sediment at the HRU level are located in Austria, where the area is characterized by intensive agricultural land, heavy soils, and steep topography. Soils with a high proportion of clay and without vegetation cover and steep topography are more erodible [5, 9, 34, 30].

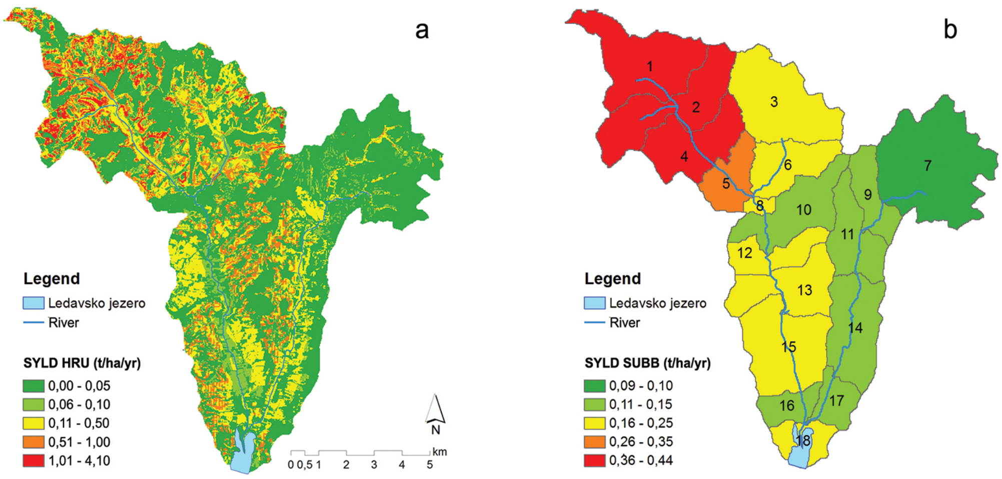

Figure 4. Average annual sediment yield (ton/ha/year) on the HRU level (a) and the sub-basin level (b).

Erosion class (ton/ha)	Area (ha)	Area from total (%)	Average sediment yield (ton/ha)
1.01-4.10	355.06	3.37	1.72
0.51-1.00	905.32	8.60	0.69
0.11-0.50	2245.50	21.33	0.23
0.06-0.10	855.62	8.13	0.08
0.00-0.05	6163.80	58.56	0.01
Sum/average	10,525.31	100.00	0.28

Table 7. Average annual values of sediment yield (ton/ha) at the HRU level presented with five classes (2006-2013).

3.3. Scenario evaluation

Evaluation of the measures used in the scenarios is dependent on achieving set goals and benchmarks. In the context of this research, the main objective was to reduce soil erosion and improve river water quality, which can be achieved by mitigating sediment yield and transport into the river Ledava.

New scenarios did not have any important impact on the predicted average annual flow in the river Ledava. The main reason lies in the configuration of the model parameters, because the modelling runoff curve CN was set at a uniform value for the entire river basin area. Among other things, the vegetation buffer zone in SWAT does not affect the surface runoff [37]. The small impact of measures used in the study on the river flow has also been confirmed in other studies [47, 48]. Whereas scenario S2 increased the simulated average flow rate, scenario S8 is the only one that decreased it. The review of average monthly values shows that scenarios S1, S2, S4, S5, and S6 reduce the river flow between May and October. This was influenced by increased evapotranspiration and intercepted precipitation by the vegetation canopy during the growing season [14]. Low flow rates between October and April result from the growth of cover crops on agricultural land (S8), which influences soil water retention. At the same time, cover crops can improve soil properties and can increase organic carbon content, soil stability, and the infiltration rate [49].

The sediment reduction efficiency of scenarios was estimated by comparing the simulation results of the base scenario with AEM scenarios (**Tables 8** and **9**). The efficiency (*r*) of the scenario was calculated according to [29] as follows:

$$r = \left(\frac{y_{base} - y_{scenario}}{y_{base}} \right) \times 100 \qquad (2)$$

where y_{base} represents the base scenario sediment transport (SYLD in tonnes/ha/year) and $y_{scenario}$ represents sediment transport (SYLD in tonnes/ha/year) according to the simulation results of the agri-environmental scenarios. The calculation is presented as a percentage change.

Sediment transport from the HRU is reduced in all cases, except for scenario S7 (**Table 8**; **Figure 5**). It is apparent that the sediment yield (ton/ha/year) reduction at the level of the HRU is most affected by vegetative filter strips (S2: 43.4% and S3: 56.1%) and terraces (S6: 42.4%), followed by conservation tillage (S4: 20.3%), contour tillage (S5: 18.9%), and cover crops (S8: 11.9%). A combination of vegetative filter strips (S3) on slopes up to 11% (S1) and from 11 to 24% (S2) is much more effective than any other measure. A very similar impact on sediment yield reduction at HRU level can be observed between scenarios S2 and S6, although they greatly differ in terms of financial and labor input. All the scenarios were most effective in the sub-basin dominated by agriculture land with slopes of up to 24%.

Most of the scenarios reduced sediment load in the river Ledava where steeper slopes in the sub-basin prevail and where high average annual sediment transport from the HRU was identified (**Table 9**). The impact of the scenarios on the average annual sediment load (ton/year) in the river was lower than at the HRU level. In this regard, scenarios S3 and S6 were also more effective than other measures (S4, S5, and S8): A highly similar order in the impact of the scenarios on sediment load in the river was achieved, although with less variation from the baseline scenario. Scenario S3 was the most efficient at reducing sediment load, followed by S2 and S6. Unlike S6, vegetative filter strips were more efficient in the lowland basin, with a smaller transport of sediment from the HRU. The importance of cover crops is observed in the S7 scenario, where cover crops were removed from rotation. Overall, negative changes appeared in comparison with the baseline scenario impacting on increase in the sediment yield at HRU level and sediment load in the river Ledava at the outlet of sub-basins.

Sub-basin	**Area**	**Sediment yield (ton/ha/year)**	**Scenarios percentage change in sediment yield (%)**							
	Ha	**Base**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
1	917.25	**0.42**	8.64	32.35	40.90	14.65	14.07	32.15	-8.59	8.98
2	827.44	**0.44**	12.84	41.75	54.59	19.56	18.09	41.34	-11.15	11.62
3	970.18	0.18	9.25	32.35	41.60	16.42	15.09	31.66	-8.23	8.16
4	650.81	**0.37**	9.86	43.79	53.65	19.37	18.72	43.01	-10.49	11.67
5	368.31	**0.28**	15.24	48.29	63.52	21.31	20.44	46.67	-12.58	13.69
6	480.25	0.20	16.40	50.93	67.34	24.81	22.77	49.24	-14.11	13.75
7	1414.75	0.09	10.55	41.09	51.64	22.97	19.26	39.44	**-22.26**	10.15
8	64.69	0.16	14.92	40.27	55.18	19.41	16.75	37.85	-18.13	13.13
9	351.44	0.10	**28.65**	53.43	**82.09**	29.67	23.74	50.34	**-19.47**	**18.61**
10	652.25	0.14	17.14	54.47	71.61	27.64	24.57	52.44	-17.07	14.15
11	507.63	0.12	**23.37**	**55.92**	**79.30**	**30.80**	**25.33**	**53.81**	**-21.20**	**16.69**
12	352.75	0.15	**21.60**	54.82	76.42	**30.22**	24.92	53.07	**-19.11**	15.10
13	603.69	0.16	20.16	54.16	74.32	**30.10**	24.51	52.28	-16.83	**16.87**
14	704.31	0.13	20.11	**57.10**	77.21	28.83	**25.78**	**54.65**	**-24.15**	15.37
15	879.56	**0.22**	20.06	**64.42**	**84.48**	**31.55**	**28.62**	**61.95**	-13.09	**16.46**
16	232.81	0.14	**21.42**	52.92	74.34	26.95	24.64	51.72	-9.42	16.08
17	255.25	0.11	**25.49**	**59.91**	**85.40**	**31.44**	**27.98**	**57.17**	-12.89	**18.75**
18	291.94	0.15	20.80	**57.13**	**77.93**	28.44	**26.55**	**54.99**	-11.18	14.80
Average	**105.31**	**0.28**	**12.78**	**43.36**	**56.13**	**20.33**	**18.94**	**42.41**	**-11.53**	**11.91**

The five largest changes in the scenarios are shown in bold.

Table 8. The impact of the agri-environmental scenarios (S) on the average annual sediment yield in the sub-basin level expressed as a percentage (%) change to the baseline scenario (2006-2013) for the river Ledava basin.

In sub-basins 1, 2, and 4, where erosion processes are most prominent, the simulated implementation of terraces on slopes between 11 and 24% decreased the amount of sediment in the river by 51, 51.4, and 54.1% (**Table 8**). By contrast, the effect of terraces on reducing the sediment transport from the HRUs (**Table 8**) was the largest in sub-basin 15 (62%), where average annual sediment transport was 0.76 ton/ha. The average annual sediment transport from the HRUs in sub-basins 11, 14, and 17 was relatively small (0.11–0.13 ton/ha), where the maximum amounts of sediment were transported from areas with slopes between 11 and 24%

(from 0.40 to 0.49 ton/ha/year). On average, scenarios S5 and S8 had the smallest impact on sediment load reduction in the river (**Table 9**). Results show that the effect of inferior non-construction measures, such as conservation tillage (S4) or contour or strip cropping (S5), achieve a smaller reduction effect than terraces (S6) or vegetation buffer zones (S1–3) [36]. Scenarios S7 and S8 show the importance of winter cover crops on soil erosion processes and sediment yield transport at the HRU level, as well as on simulated sediment load and concentration in the river Ledava.

Sub-basin	Scenario impact on sediment load at outflow								
	ton/year	Percentage (%) change from base							
	Base	S1	S2	S3	S4	S5	S6	S7	S8
1	569.16	13.06	30.36	39.92	27.07	23.69	51.40	-35.18	28.28
2	1013.30	10.88	30.00	36.45	25.63	23.32	50.97	-26.86	21.39
3	191.80	7.51	36.73	40.13	21.74	20.64	43.28	-17.48	10.55
4	1452.34	9.68	28.44	33.82	24.01	22.29	54.14	1.10	19.91
5	1259.76	-5.00	10.73	13.09	7.17	5.30	34.56	0.19	1.03
6	386.23	11.43	43.39	47.39	39.40	36.79	59.75	-41.70	30.03
7	29.42	25.77	15.54	30.29	32.15	21.09	43.06	-32.27	15.92
8	1270.28	10.30	-8.19	-11.79	-16.76	-13.90	16.07	0.13	-8.03
9	60.61	15.39	11.40	20.75	25.19	16.47	33.04	-23.26	14.43
10	1481.55	9.60	-6.31	-8.13	-11.47	-8.91	19.19	-0.83	-5.26
11	127.04	24.66	21.52	34.91	29.34	19.99	41.40	-25.39	15.86
12	1628.80	9.40	-5.46	-6.69	-8.79	-6.77	20.26	-2.53	-4.49
13	1771.26	9.14	-3.35	-3.93	-4.62	-3.26	22.28	-2.55	-2.45
14	222.31	22.58	20.04	33.23	29.94	21.06	43.80	-26.77	17.37
15	1969.03	9.53	-0.71	0.00	-1.87	-0.53	24.72	-5.41	-0.49
16	2160.74	12.36	4.70	5.03	4.87	6.13	28.41	-17.14	6.09
17	269.69	20.33	18.10	29.06	30.25	22.48	44.17	-86.39	20.23
18	2597.44	12.56	6.79	8.47	7.93	8.17	30.47	-24.68	7.73
Average	**933.14**	**12.74**	**14.32**	**19.20**	**14.70**	**12.11**	**36.91**	**-20.04**	**10.71**

The five largest changes in the scenario are shown in bold.

Table 9. The impact of the scenarios on the average annual sediment load (ton/year) at the outlets from the sub-basins and at the inflow into sub-basins 18, expressed as a percentage (%) change from the baseline scenario (2006-2013).

We conclude that the reduction in sediment transported at the sub-basin level was an effect of the proper placement of modelled AEM in CSAs where soil erosion and the sediment transport are highly evident, and also an effect of a higher proportion of forest, which may reduce

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excessive runoff [50]. The differences between the effect of terraces on the sediment transport at HRU level and the sediment yield in the river at the outlet from a sub-basin have also been reported in previous studies [20]. These situations, where AEM are more effective at the HRU level than at the sub-basin outlet or whole-basin outlet, are due to morphology of the terrain and soil properties [51–53].

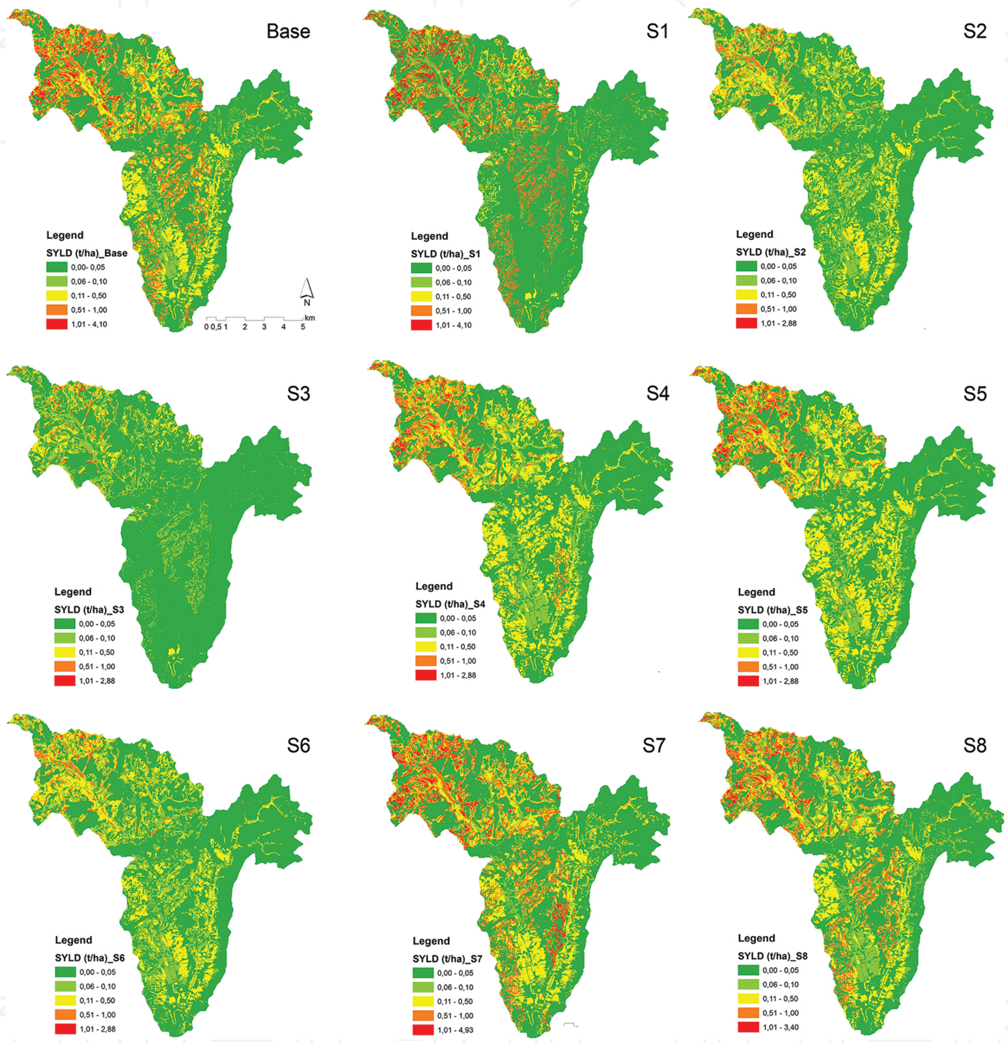

Figure 5. Changes in the average annual amount of sediment transported with surface runoff from HRUs as modelled by scenarios for the river Ledava basin.

4. Conclusions

According to the agricultural, environmental, and water policies in member states of the EU-28, AEM should be implemented according to need, the willingness of farmers to adopt the measures, existing management practice and the natural conditions in the relevant region. This study reveals the measures that are relevant to address the protection of agricultural soil in the selected river Ledava basin study area. The fact that the measures are more effective when they are introduced at a smaller scale (HRU level) and are necessary only in the CSAs, is important in terms of protecting valuable agricultural land in situ.

The main uncertainties in our research are connected with obtaining data and its comparability between two countries. The precision of all spatial layers varied greatly, as not one layer was at the same scale for the two countries. Wherever possible, we upscaled or downscaled the layers. To overcome this issue, countries in future should establish a common data protocol for transboundary river basins. One of the everlasting problems is state monitoring of water quality sampling. Monitoring is spatially rare, with wide time steps between sampling. There are frequent changes to the spatial position of the sampling point, river flow and water quality sampling points are often in different places, and in certain cases monitoring stops after few years. To overcome this, we carried out 1-year sampling of sediment concentrations at several points along the river. However, this required our own financial and working power resources, which are limited. We recommend that the relevant state environmental agency responsible for surface water measurements should pay more attention to the location of monitoring points and should ensure long-term, regular, and comparable time series. Calibration of the model results for soil erosion and sediment transport was done only with comparison to measured values in the river streamflow. Although we had three general maps representing erosion rates at a different spatial scale to previous studies [8, 9], actual soil erosion was never measured in the area. We propose a series of on-site field measurements of soil erosion at different slope, land usage, and soil types to evaluate the results of this and other similar studies.

One of the important factors for the effectiveness of AEM is climate change. Climate change already dictates differing land use, crop types, management, and production technology. This is already affecting the processes of mass transfer from catchment areas into water bodies, and we can expect that these processes will escalate in the future. These effects can only be determined with additional modelling of climate change impact. For example, currently foreseen AEM have been found to be less effective under future climate change scenarios, however not to the extent of being unnecessary.

The criteria for individual parameters that define the AEM in the model are necessary in order to assess, evaluate, and select alternatives with regard to the objectives of the decision-maker. Therefore, it is necessary to supplement the missing limit values for the water quality parameters, in particular those related to soil erosion, sediment yield, and sediment loads in surface water bodies.

The results show that CSAs occupy 12.2% of the river basin. Most of the scenarios predict reduced sediment in the river Ledava where steeper slopes in the sub-basin prevail and where high average annual sediment transport from the HRUs is identified. The impact of the scenarios on the average annual sediment load (ton/year) in the river was lower than at the HRU level. An extremely similar order in the impact of the scenarios on total sediment load in the river was achieved, although with less change from the baseline scenario. Overall, negative changes and or reductions appeared according to the baseline scenario in the sediment yield at HRU level and sediment in the river Ledava at the outlet of the sub-basin. This study enables us to better understand the processes of selecting environmentally effective

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measures and their contribution to the long-term improvement of the surface water bodies' ecological status in accordance with the Water Framework Directive. This also opens up the potential for selecting cost-effective and socioeconomically friendly solutions addressing the rural development programs of EU member states under the Common Agricultural Policy.

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