Towards climate-smart sustainable management of agricultural soils

SCALE

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ABSTRACT

Erosion models serve as valuable tools for studying and quantifying erosion and sediment transport across various scales, from local to landscape levels. However, the simulation of erosion management measures and sediment connectivity elements in agricultural environments on landscape scale remains underexplored and poorly exemplified. Integrating these measures and elements into simulations enhances the capacity of models to support erosion studies and practical erosion management efforts.

In this study, we investigated and demonstrated the implementation of erosion management measures and sediment connectivity elements across four modelling approaches, applied to simulate erosion management scenarios in six agricultural catchments across Europe. The modelling approaches encompassed RUSLE, RUSLE combined with the Index of Connectivity and Sediment Delivery Ratio methods, WaTEM/SEDEM, and a General Additive Model with topographical indices. The simulated erosion management measures and sediment connectivity elements encompassed different tillage practices, winter crops, buffer strips, grassed waterways, terraces, organic material dams, sediment retention ponds, and changes in vegetation cover.

From these simulations, we derived a guideline for practical implementation of the connectivity approach in modelling, intended for model users. The guideline is structured into eight categories following the general modelling process: problem identification, conceptual mapping of modelled processes, data availability, model selection, model setup, parameterization and evaluation, simulation scenarios, uncertainty management, and communication of simulation results.

The simulations themselves underscore the utility of models in erosion study and management, providing valuable insights into erosion and sediment connectivity, as well as the impacts of erosion management measures and sediment connectivity elements. However, they also highlight the considerable uncertainty inherent in simulating sediment connectivity and the challenges associated with model validation.

Overall, our work demonstrates that integrating erosion management measures and sediment connectivity elements into models suitable for landscape scale simulations enhances our understanding of erosion and sediment transport and management. Nonetheless, it also underscores the necessity for further advancements to improve the incorporation of sediment connectivity in modelling.

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1. Introduction

Erosion models are useful tools for studying and quantifying erosion and sediment transport from local to landscape scales (Borrelli et al., 2021), but their capacity to simulate and evaluate erosion management scenarios vary. This is due to varying possibilities to include erosion measures and connectivity elements that affect the transport and deposition of sediment in the landscape (Schmaltz et al., 2024; Baartman et al., 2020; Deproost et al., 2023). Inclusion of these measures and elements in the simulations further improves the capacity of models to support the study of erosion and practical erosion management.

Erosion, or detachment of soil particles from the soil surface, is affected by several factors, including rainfall and surface runoff, soil properties, topography, vegetation cover, and soil and erosion management (Renard, 1997). Sediment transport and deposition, in turn, depends on surface flow velocity, soil particle size distribution, soil surface roughness conditions, and landscape elements that influence the movement of soil particles. In agricultural environments these elements can include different soil cover types, agronomic measures, buffering measures, and other elements such as parcel borders, subsurface drainage, ditches, roads, etc. (Schmaltz et al., 2024; Deproost et al., 2023).

A concept of sediment connectivity has been developed to characterize the movement of sediment in the landscape, and to describe how different landscape elements influence the sediment movement (Hooke and Souza, 2021; Najafi et al., 2021; Heckmann et al., 2018; Bracken et al., 2015; Bracken and Croke, 2007). The connectivity is often differentiated between structural and functional connectivity, and lateral and longitudinal connectivity (e.g., Baartman et al. 2018). The structural connectivity aims to describe the physical coupling of system elements in the landscape, while the functional connectivity aims to include more dynamic aspects of the transport process, such as the effect of intensity and duration of rainfall event on connectivity. Lateral connectivity in turn describes the hillslope-to-channel connectivity, and the longitudinal connectivity describes the within-channel network connectivity. Altogether, the connectivity concept aims to characterise the continuity and strength of runoff and sediment pathways in the landscape, and it has been applied in various studies (e.g., Baartman et al., 2020; Keesstra et al., 2018; Heckmann et al., 2018).

Sediment connectivity is considered in models in different ways. In physically based models, the movement of sediments is described with physically based equations, that aim to describe the relevant processes in high detail (Merritt et al., 2003). In empirical models, the movement of sediment is described with statistical equations, and the connectivity approaches in these models include, for example, computation of connectivity indices and transport capacity coefficients (Heckmann et al., 2018). The consideration of sediment connectivity elements as part of landscape scale erosion management simulations is not, however, well explored and exemplified.

Therefore, in this report we explore the inclusion of the connectivity approach in model simulations with the objective *to develop guidelines for model users on the practical use of the connectivity approach in modelling*. The guidelines were developed based on simulation of erosion mitigation scenarios for different agricultural catchments with a selection of models. These simulations covered different erosion and connectivity conditions, a range of erosion measures and connectivity elements, and different approaches to simulate connectivity. The simulations build upon the knowledge gained from previous SCALE tasks on model assessment and uncertainty sources (WP4-T1), implementation of erosion measures in models (WP4-T2) and improvement of connectivity representation in models (WP4-T3).

In the following sections we provide first the developed guidelines and the synthesis of the simulations, and then describe in detail the individual simulations, including the used models, the simulated erosion measures and connectivity elements, and the simulation results.

2. Guidelines

Guidelines on the practical use of the connectivity approach in modelling:

1. Problem identification

Identify the key problems that needs to be tackled with the model application. For example, is the problem related more to on-site (e.g., within or between fields) or off-site (e.g., loading to surface waters) impacts of soil erosion; and are there specific erosion management measures that are of interest, already prevalent or pre-specified. It is also important to recognize that problem identification and problem solving are often dependent to social, economic, and ecological aspects. Therefore, a participatory approach may also be needed, where experts and stakeholders from different fields are involved in the problem identification and planning of how the problems should be investigated and solved.

2. Conceptual mapping of the modelled processes

Perform a conceptual mapping of the erosion, sediment transport and deposition processes of the modelled system. Particularly, identify the sediment transport pathways and the landscape elements that influence the sediment connectivity. Identify the spatial and temporal scales and resolutions that are needed to address the problem of interest. For example, how large the modelled area is and what spatial resolution is needed to address the problem. Also, it is important to consider whether there are temporal dynamics such as rainfall patterns (i.e., functional connectivity) that are important for addressing the problem. Besides the structural landscape elements, these temporal dynamics may have a great impact on the connected area of runoff and sediment and the relative export of soil.

3. Data availability

Compile an inventory of available data for setting up modelling tools, parametrising the model, and evaluating the model performance. For example, in what detail and quality is the input data available for the model, and against which observation-based data the model (including the connectivity elements) can be parameterized and evaluated. A particular emphasis should be given for identifying the possibilities for evaluation of model prediction uncertainty in early stages of the modelling process. Simulation of connectivity involves typically high uncertainty. Also, involving experts and stakeholders for evaluating and complementing the available data may be beneficiary, especially concerning the presence of structural elements in the landscape which have a significant influence on the connectivity.

4. Model selection

Based on the problem identification, conceptual mapping of modelled processes, and data availability, select the modelling tools that adequately address the problem of interest. It is important that the modelling tools adequately represent the key processes of the simulated problem, but unnecessarily complex models may introduce additional uncertainty to model predictions. For example, if on-site problems or identification of high erosion areas are of interest, simpler models without explicit sediment transport simulation may be adequate. However, if off-site problems or sediment connectivity are of interest, the models that facilitate simulation of sediment transport and connectivity elements are needed. Models vary in their capacity to include different types of connectivity elements and erosion management measures and it is important to establish whether the model already includes the needed elements and measures or whether they must be added by the model users themselves. This may require additional expertise on which model parameters need alteration and on the effect of connectivity elements and management measures.

5. Model setup, parameterisation, and evaluation

Great emphasis should be given to model setup, parameterisation, and evaluation, as they directly determine the reliability and usefulness of the model predictions. The preparation of input data for model setup should aim for highest standards. In the case of sediment connectivity, emphasis should be given to prepare the data to accurately support the simulation of sediment movement in the landscape. For example, DEM plays an important role for the sediment movement, and therefore, selection of an appropriate DEM resolution, and appropriate strategy for treatment of inaccuracies (e.g., artificial sinks) in the DEM are highly important. The parameterisation of the model, including the parameterisation of erosion measures and connectivity elements in the model, should ideally be based on local empirical observations. The effect of erosion measures and connectivity elements may vary by local climatic and pedological conditions. Parameterisation should also consider a range of plausible parameter values for the simulations, particularly in the case of high uncertainty in actual parameter values. Ideally, critical parameters should be presented by probability distributions in the simulations, and the evaluation would be based on established assessment frameworks (e.g., Monte Carlo based methods, such as the Generalized Likelihood Uncertainty Estimation (GLUE)). The model predictions of sediment delivery, in turn, should be evaluated against adequate data of observed sediment delivery rates, for example from experimental fields or catchments. This evaluation should produce an estimate of prediction uncertainty and consider whether the model is scalable and if its predictions can be extrapolated to other locations. With the emphasis being on connectivity within the study area, it may also be beneficial to focus less on calibration of sediment at the outlet and more on spatial patterns of runoff within the fields and erosional vs. depositional areas (e.g., by acquiring DEMs of difference or tracer information), although this information may be sparsely available. Likewise, localized presence or absence of erosion features (e.g., gullying) can be used for calibration or validation instead of quantitative measurements. This gains more importance when moving away from off-site impacts. Qualitative evaluation of model output can also be part of a participatory approach with stakeholders and local experts.

6. Simulation scenarios

Formulate specific hypotheses or questions and simulation scenarios to answer them and to investigate the problem at hand, while considering the uncertainty in model predictions. A systemic approach where simulation scenarios are carefully developed to answer clearly defined hypotheses or questions provides an efficient simulation strategy. The scenario simulations should consider model uncertainty so that the uncertainty is reflected in the scenario simulation results. For example, results could be a range of model outcomes simulated with a range of plausible model parametrisations. Development of simulation scenarios to describe relative changes between scenarios or system responses may also be a good strategy to account for uncertainty, instead of focusing on prediction of absolute values of erosion or sediment delivery that are inherently uncertain. A participatory approach involving stakeholders in the formulation of hypotheses or questions and simulations scenarios will give the simulations more practical value and the results are likely to be better received.

7. Uncertainty management

Model predictions on sediment connectivity and delivery are inherently uncertain, and often suitable observational data for evaluating the model prediction are not available. These may result in irremediable uncertainties in the model simulations, which need to be managed. This uncertainty management starts from selection of appropriate model, model setup, model parameterisation, model evaluation, and continues to presentation and interpretation of the results. The uncertainty management should be a separate process that runs parallel to the whole simulation process and acknowledges the uncertainty sources and develops strategies for their management. The uncertainty management should inform the development of the conclusions, for example, to which extent the model simulations are able to answer the formulated hypotheses of the simulations. A participatory approach to include stakeholders in the management of uncertainties may also be needed.

8. Communication of simulation results

The presentation of simulation results should account for the uncertainties in the simulation process and outcomes. For example, presenting results as single deterministic absolute erosion or sediment delivery value (e.g., t ha^{-1} yr^{-1} or t yr^{-1}) without presentation of prediction uncertainty may be counterproductive. Instead, results should be presented in the context of their uncertainty, which is recognised during model evaluation and uncertainty management. The presentation of results as potential ranges, categories, or as relative differences between simulations scenarios may support more reliable drawing of conclusions from the simulations, as well as more responsible communication of simulation results. The modelling approach as a whole should also be well described and transparent for evaluation by broader audiences. Local erosion field trials can greatly improve credibility of the modelling results, but with inclusion of connectivity issues, they can become very difficult to perform.

3. Synthesis of simulations

Four modelling approaches were used to simulate erosion, erosion measures and connectivity elements at seven catchments or areas (Table 1). The modelling approaches included RUSLE (Renard, 1997), RUSLE combined with Index of Connectivity and Sediment Delivery Ratio (RUSLE/IC/SDR; e.g., Hamel et al., 2015), WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002) and a General Additive Model (GAM; Hastie and Tibshirani, 1986) with topographical indices (TI). The simulated erosion measures and connectivity elements included various tillage practices, winter crops, buffer strips, grassed water ways, terraces, dams in organic materials, sediment retention ponds, and vegetation cover changes. The simulation areas were in Slovenia, Finland, Belgium, and Spain, and their areas varied from 6 to 14,700 ha (0.06 to 147 km^2) (Table 1). The aim of all simulations was to simulate erosion measures and connectivity elements for reduction of erosion and/or sediment delivery. The simulations included scenarios that explored different configurations of erosion measures and connectivity elements at variable study area conditions (Table 1). The specific objectives of the simulations were:

- **RUSLE:** To evaluate the erosion at two catchments in Slovenia and estimate the reduction in erosion when applying agricultural measures.

- **RUSLE/IC/SDR:** To explore RUSLE/IC/SDR for simulating erosion management measures of no-till and buffer strips at two topographically differing catchments in Finland, and to assess the benefits of considering sediment connectivity in planning of erosion management at catchment and field parcel scale.

- **WaTEM/SEDEM:** Quantification and evaluation of the impact of the implementation of several connectivity elements/erosion control measures on erosion and sediment delivery to the water system at two catchments in Belgium.

- **GAM+TI:** Estimate the susceptibility of individual field areas to ephemeral gully (EG) erosion, which is one requirement for grassed waterway implementation. Five catchment areas in Belgium, Finland and Spain were investigated.

Table 1. Summary of the study areas, and erosion measures and connectivity elements of the simulations.

Models	Study areas	Erosion measures and connectivity elements in simulations
RUSLE	Slovenia: Drnica (29 km^2) catchment in Istria and Grosupeljščica cathment (36 km^2) in Dolenjska region.	Terraces, winter crops, no-till/reduced till measures (agricultural measures), weeding.
RUSLE/IC/SDR	Finland: Aura (147 km^2) and Mustio catchments (116 km^2) in Southern Finland.	No-till (winter-time stubble) and riparian grass buffer strips (30 m wide) in spring cereal (wheat, barley, oat) cultivation.
WaTEM/ SEDEM	Belgium: Maarkebeek (50 km^2) and Menebeek cathments (30 km^2), in southern part of Flanders.	Grass buffer strips (riparian and along ditches and sewers), dams in organic materials and sediment retention ponds, reduced tillage, conversion to permanent grassland on steep slopes, conservation of strategic grassland.
GAM + TI	Belgium: Maarkebeek (50 km2) and Molenbeek catchments (30 km^2), in southern part of Flanders. Finland: Aura (147 km^2) and Mustio catchments (116 km^2) in Southern Finland. Spain: small 0.06 km^2 catchment near Cordoba.	Grassed waterways (GWW) – perennial grass cover along ephemeral gully trajectories.

The used modelling approaches account for connectivity in different ways (Table 2). RUSLE was implemented in a distributed manner where computations are performed over gridded spatial units. As such RUSLE does not account for connectivity or sediment transport between the spatial units or in the landscape (Deproost et al., 2023). The RUSLE simulations provided examples on implementation of erosion measures on catchment scale and a comparison case for modelling approaches that include sediment transport or connectivity. RUSLE/IC/SDR accounts for structural connectivity and is based on post-processing of spatially distributed RUSLE erosion predictions. First an index of connectivity (IC; Borselli et al 2008) is computed from a Digital Elevation Model (DEM), which is then used to compute the Sediment Delivery Ratio (SDR; e.g., Hamel et al., 2015) for each spatial unit of the RUSLE prediction. The SDR is then used to compute the share of sediments that is delivered to a sink (e.g., surface water body) from each spatial unit of erosion prediction by RUSLE. WaTEM/SEDEM accounts for structural connectivity using a different method. The estimation of erosion is based on RUSLE factors, and the sediment transport is computed using a sediment routing algorithm and a transport capacity equation (TC) (Van Rompaey et al. 2001; Verstraeten et al., 2002). The sediments are routed from source areas to sinks, while considering the TC which describes the maximum amount of sediment that can be transported across a spatial unit. If the routed sediments exceed the TC of a computational unit, then deposition of sediments occurs in that spatial unit. The net soil erosion of a spatial unit is determined by taking into account the gross soil erosion (RUSLE), the influx of sediments from upstream computational units and the transport capacity (TC). The Sediment Delivery Ratio of a catchment can be calculated by dividing the modelled total sediment export to the water system by the total net erosion in the catchment. In the GAM approach, the sediment transport or connectivity is not simulated *per se*, but it was used to predict features of linear erosion with a set of topographical indices as predictors for the locations of linear erosion. Linear erosion features can be important connectivity elements in the landscape and indicate areas in need of erosion mitigation measures. The model does not calculate the magnitude of eroded or transported sediment, but the likely presence or absence of linear erosion. This typically occurs across several agricultural fields, unless field borders are designed to avoid this (e.g., in the Finnish catchments, fields are bordered by ditches).

Table 2. Summary of the connectivity methods, model parameterisations, and uncertainty assessments in the simulations.

Model	Connectivity method	Parameterisation of erosion and connectivity elements/measures	Uncertainty assessment
RUSLE	No connectivity method	RUSLE R, K, LS factors based on standard methods by Renard (1997) with customization in methods and national data used. Cf factor assessment largely taken from Panagos et al., 2015.	No uncertainty assessment
RUSLE/IC /SDR	Index of connectivity (IC; Borselli et al. 2008) and sediment delivery ratio (SDR; e.g. Hamel et al. 2017).	RUSLE R, K, LS factors based on standard methods by Renard (1997) and C factor by optimization against measured erosion rates (Räsänen et al 2023). IC/SDR parameterisation based on literature values (Tähtikarhu et al. 2022; Räsänen et al 2023).	Sensitivity analysis of IC/SDR parameterisation. RUSLE uncertainty evaluated earlier against erosion rates measured at experimental fields (Räsänen et al 2023).
WATEM/ SEDEM	Transport Capacity (TC) (Van Rompaey et al. 2001; Verstraeten et al., 2002) , Sediment Trapping Efficiency, Parcel Connectivity, routing algorithm	RUSLE factor values, Transport Capacity (TC), Parcel Trapping Efficiency (PTEF), parcel connectivity, transport capacity coefficient (kTC), Sediment Trapping Efficiency (STE) based on the methods of WaTEM/SEDEM (VAn Oost et al., 2000, Van Rompaey et al., 2001, Verstraeten et al., 2002). The transport capacity coefficients of the WaTEM/SEDEM model are calibrated by means of long-term sediment measurements in watercourses and retention ponds.	The sensitivity of the Transport Capacity, Sediment Trapping Efficiency and Parcel Connectivity was theoretically tested by a Morris Screening Sensitivity Analysis, while the uncertainty on these parameters was estimated using the Monte Carlo simulation approach (SCALE WP4-D1 report, in preparation)
GAM + TI	A set of 8 topographical indices (TI) are used as predictors. Some represent connectivity, but no explicit connectivity index (like IC) is included. Approach is similar but not identical to Conoscenti and Rotigliano (2020)	Parametrization happened during training of the model. By training the GAM to the training features, weights were assigned to the individual predictors to best represent the training features.	Different methods of spatial and non-spatial cross-validation; multicollinearity analysis of predictors used. These cover only the initial training areas, not those for application in this study.

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All simulations were based on computations over gridded spatial units that ranged from 1 to 30 m. The estimation of erosion required parametrisation of each computational unit with a range of data (Table 2). The implementation of erosion measures and connectivity elements required specifying their locations in simulation grid, as well as their parameterisation (Table 2). The parametrisations were performed using a range of approaches, including modelling approach specific parameter estimations methods (e.g., Renard 1997), optimisation and training against observations (e.g., Räsänen et al. 2023), sensitivity analysis (e.g., Tähtikarhu et al. 2022), and literature values (Table 2). The analysis of uncertainty in model predictions varied by modelling approach, but extensive uncertainty analysis frameworks were not implemented in any of the simulations. The methods used to estimate the uncertainty included evaluation against observations and sensitivity analysis.

The key findings of the performed simulations were:

RUSLE

The average soil erosion in the catchment area of Drnica river (Istra) is 16,1 t/ha per year and would be 17,6 t/ha per year if no measures would be applied. The erosion rates are significantly lower on catchment area of Grosupeljščica (central Slovenia) with 4,6 t/ha. If no measures would be applied the average soil erosion would be not significantly higher (4,6 t/ha). Agricultural mitigation measures have small effect on erosion reduction on the whole catchment scale.

Deeper analysis focusing only on parcels with measures implemented show significant impact of mitigation measures on soil erosion. If no cover crops on vineyards of Drnica catchment area would be implemented in 2022, average erosion would be 6 times higher (48,9 t/ha per year) than the current erosion which is estimated 8.1 t/ha per year. Cover crops on orchards (and olive groves) helped reduced tillage from 46.4 t/ha per year to current 15.5 t/ha per year on average. The farmers on Grosupeljščica who implemented reduced tillage practice and used crop residues in 2022 reduced erosion to 10.4 t/ha per year from 14.4 t/ha per year on average. Implementing cover crop practices on arable land reduced erosion from 12.8 t/ha per year to 10.7 t/ha per year. Average erosion rates of Grosupeljščica catchment are more similar to the average erosion estimated for Slovenia in 2020 3,68 t/ha (Bergant et. al., 2020).

When we compare the areas with difference in soil erosion between measures and no measures on catchment scale, we can see that differences appear on 130,0 ha (5 %) of Drnica catchment (Istria) and only on 59,5 ha (2 %) of Grosupeljščica catchment. On catchment of Drnica most of the areas (47 % or 61 ha) have difference in erosion higher than 20 t/ha and very small areas with erosion differences lower than 0 – 0,5 t/ha (0,1 ha or. 0 %). On the other hand, differences in soil erosion on catchment of Grosupeljščica are significantly lower. Most of the areas with different soil erosion have erosion difference in rank of 0,5 – 1 t/ha (15,3 ha or 26 %), following the rank of 0 – 0,5 t/ha on 14,1 ha (24 %).

RUSLE/IC/SDR

The RUSLE/IC/SDR simulates sediment connectivity via surface runoff, and the connectivity via sub-surface drainage cannot be considered. In the case of surface sediment connectivity, RUSLE/IC/SDR appeared to be a feasible approach for field parcel scale simulation of erosion measures and sediment connectivity elements, such as no till and buffer strips.

RUSLE/IC/SDR provided information on sediment connectivity characteristics and the effectiveness of no-till and buffer strips between field parcels and topographically varying catchments. For example, buffer strips were found to be more effective at Aura than Mustio River catchment, and their effectiveness varied by field parcel. In the catchment scale allocation of no-till and buffer strips to field parcels, the RUSLE/IC/SDR did not, however, bring substantial benefits compared to allocation with RUSLE. The magnitude of erosion at field parcels was a good predictor for the effectiveness of no till and buffer strips, and connectivity played a smaller role. This finding may not be generalisable to other agricultural areas. The field parcels of the case study areas are relatively small and isolated from each other by open ditches, in terms of sediment transport via surface runoff. At individual field parcels, the simulations showed how RUSLE/IC/SDR can support tailoring of erosion measures according to the local conditions. For example, the location and extent of buffer strips can be improved.

The parameterisation of IC/SDR, however, requires further research as it considerably affected the simulated absolute sediment delivery rates. The parameterisation had smaller effects on relative differences in sediment delivery rates between the field parcels, which suggests that uncertainties are smaller when results are interpreted in relative terms. Altogether RUSLE/IC/SDR expands and improves the RUSLE model framework by enabling the simulation of sediment connectivity at field parcels and the planning of erosion management according to local sediment connectivity characteristics.

WaTEM/SEDEM

For the purpose of local erosion mitigation planning, it is important to be able to test effectiveness of the proposed erosion control measures (ECMs) prior to their implementation in the landscape. An erosion model such as WaTEM/SEDEM is of great use for simulating erosion mitigation scenarios, by including planned ECMs in the model and comparing them to other possible scenarios.

In order to test the possibilities within the current WaTEM/SEDEM model, two case studies were done in the Maarkebeek (Province of East Flanders) and the Menebeek (Province of Flemish Brabant) catchments. In these catchments, several scenarios were modelled: on the one hand some general scenarios, based on standardised data and possible regulation, and on the other hand some specific scenarios, based on the stakeholder input. In these scenarios, the different ECMs that are used are: grass buffer strips, sediment buffers, conditional reduced tillage practices, and conditional conversion of arable land to grassland or vice versa.

From these case studies it is evident that WaTEM/SEDEM can be used to model these landscape changes, by converting data on these ECMs into the right model input, and to estimate the efficiency of the erosion mitigation scenario as compared to other scenarios. By calculating the Mean Erosion Rates (ER) and the Sediment Delivery Ratios (SDR) it is possible to classify different scenarios into on-site and off-site erosion mitigation scenarios. As the SDR is defined as the part of the eroded soil that reaches the water system, it reflects the sediment connectivity of a catchment as influenced by erosion control measures. If the SDR of a certain scenario decreases more than the ER compared to another scenario, this indicated a lowering of the sediment connectivity in the catchment, which indicates a stronger off-site erosion mitigation strategy for the scenario. The more ER is decreased, the more erosion is reduced on-site, which is the most sustainable and preferable strategy as soil quality is preserved. The difference in changes in SDR and ER for similar scenarios in different catchments can be indicative for the connectivity within the catchment between highly erodible parcels and the catchment's drainage system, as well. High changes in ER but low or inverse changes in SDR, are commonly expected in disconnected landscapes where on-site ECMs are applied, while a decrease in both ER and SDR corresponds with better connected erosion prone parcels and the catchment drainage systems, or more off-site ECMs.

When creating scenarios, a good understanding between modellers and stakeholders is needed to receive valid and reliable data that can be easily applied in the WaTEM/SEDEM model and to produce relevant output which has practical value for the stakeholder.

GAM+TI

While the model showed good performance in the original area of application (Austria), results of other areas were mixed. Predictions performed in the Belgian and Finnish catchments turned out very poor. In case of the Spanish catchment, the resulting prediction looks promising. Since no appropriate datasets of linear erosion features were provided for these catchments, no training of the model could be performed. The modelling approach is in fact only the first step of the proposed procedure. Only after likely locations for EG erosion have been identified, mitigation measures like GWW can be placed. Thus, this model approach can be useful in identifying EG risk areas and prompting the implementation of suitable mitigation measures. Other modelling approaches or measurements are needed in order to quantitatively estimate the impact of GWW implementation in terms of runoff or soil loss reduction.

These four types of simulations show altogether that models can facilitate simulation of erosion measures and connectivity elements in agricultural settings, but models vary in the methods and capacity to do so, and therefore, the model selection plays an important role in successful achievement of simulation goals. The four simulations also show that the simulation of connectivity is generally challenging, and the model predictions are inherently uncertain. This calls for careful consideration on uncertainty management, development of conclusions from simulations, and on presentation of simulation results to wider audiences. Key observed challenges in the simulations were that models do not always include or describe accurately all processes related to erosion, and that observational data for model parameterisation or evaluation are often not available. These can be addressed by further model development and collection of observational data to support modelling, and by performing simulations within a framework that considers these uncertainties in the model predictions. Particularly, in simulations where the effectiveness of erosion measures is analysed and compared in heterogenous landscapes, the appropriate implementation and parameterization of these measures in the models require specific attention. Despite the observed uncertainties, the simulation strengthened the view that models are efficient tools for exploring the complex phenomena such as erosion and sediment connectivity, and they can positively contribute to practical erosion management by providing valuable information on erosion management and its efficiency from field parcel to catchment scales.

4. Simulations

4.1. RUSLE

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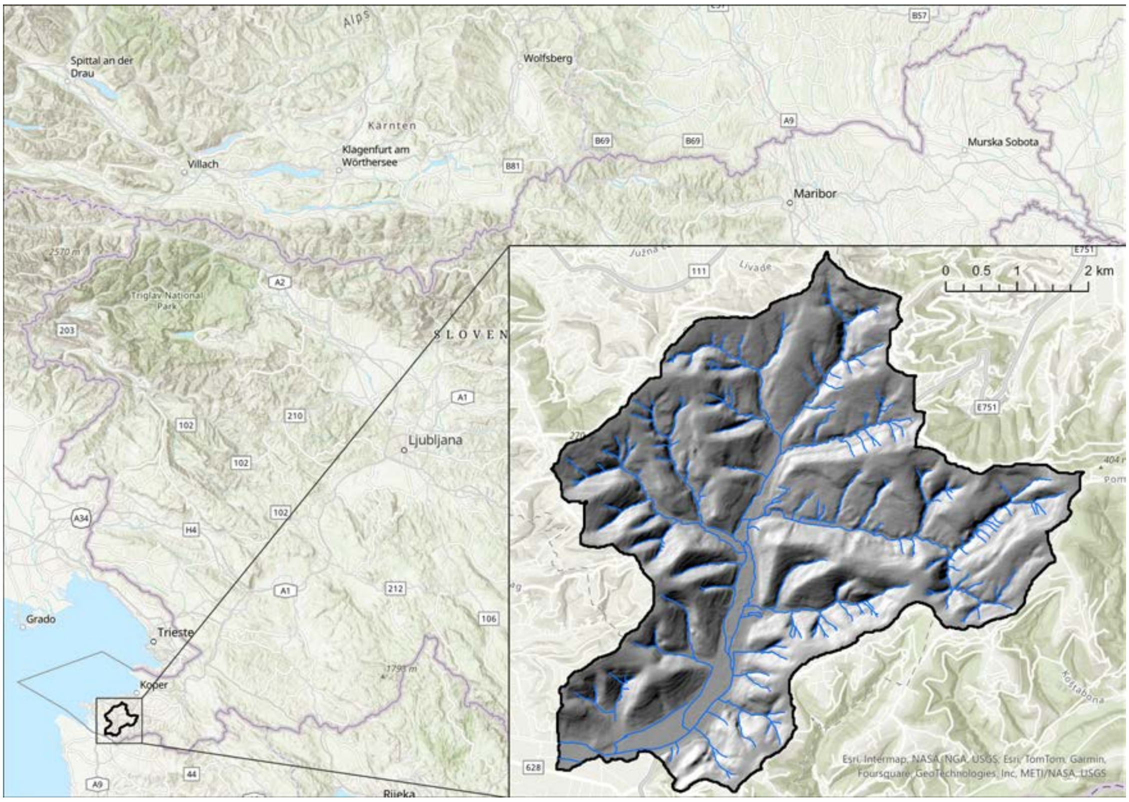
4.1.1. Introduction

Erosion was often an overlooked environmental threat in Slovenia, mainly due to the small parcels, the abandonment of farming and some agri-environmental measures, which helped reducing soil erosion (Zorn, 2015). Nevertheless, measurements of two events near Straža pri Novem mesto, Komac and Zorn (2007) estimated soil erosion to 22 t/ha per year (Komac and Zorn, 2007b). 10.76 t/ha was eroded from a vineyard near Limbuš near Maribor (inclination 14.9°) (Vršič et al. 2000). Soil erosion in the hop field at a slope of 0.18° was estimated to be 5 t/ha per year using the GLEAMS 2.1 method (Zupanc, Pintar, Mikoš 2000). According to the modified Gavrilović equation, erosion was calculated to be 22 t/ha in vineyards and 11 t/ha on arable fields per year, and according to the RUSLE method, 51 t/ha per year in vineyards and 22 t/ha per year on arable land (Petkovšek 2002). Between 2005 and 2006, measurements were made on eight micro-erosion fields (1m^2 area) in the Rokava basin (Slovenian Istria); bare ground in an olive grove (2 fields), overgrown meadow (2 fields), forest (4 fields). Total erosion in an olive grove with a slope of 5.5° was 90 t/ha, on a meadow with a slope of 9.4° 1.68 t/ha, in a forest with a slope of 7.8° 3.91 t/ha and in a forest with with a slope of 21.4 ° 4.15 t/ha (Zorn and Mikoš, 2009). Calculation using the USLE method predicted an average erosion of 6.4 t/ha per year for Mirnska Dolina (Topole, 1998; adapted from Zorn and Komac, 2005). Mikoš and Zupanc (2000) note that in Slovenia we lose an average of 5-10 mm of fertile soil on agricultural land annually due to erosion, which means between 80 and 100 t/ha per year (summarized from Zorn and Komac, 2005).

During the SCALE project two catchments in Slovenia were included in the RUSLE modelling of soil erosion. One catchment is Drnica in Slovenian Istria (Figure 1), and the other catchment is the Grosupeljščica (Figure 2) in Dolenjska region. The catchments differ in terms of climate type (submediteranean vs. subcontinental) and soil erodibility. At the Drnica catchment area eutric brown soils with a nutty texture, characterised by a high soil erodibility are very common. The Grosupeljščica river basin is located on post-carbonate brown soils with a polyhedral structure, which is theoretically characterized by lower soil erodibility.



Esri, Intermap, NASA, NGA, USGS, Esri, TomTom, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

Figure 1. The location of Drnica catchment in Slovenian Istria.

The objectives of simulation were to calculate the soil erosion on two geographically different catchment areas and to test our hypothesis that erosion is higher on catchment of Drnica since the dominant soil types there are known to be more erodible than soil types common at Grosupeljščica catchment.

The other objective was to calculate the erosion using RUSLE method and 1x1 m DEM from LIDAR data. Consequently, terraces as one of the important connectivity elements of erosion mitigation was included in RUSLE model through calculation of LS factor. Also, with running RUSLE model in different scenarios we wanted to access the effect of management mitigation measures on reduction of soil erosion on agricultural land of two catchment areas.

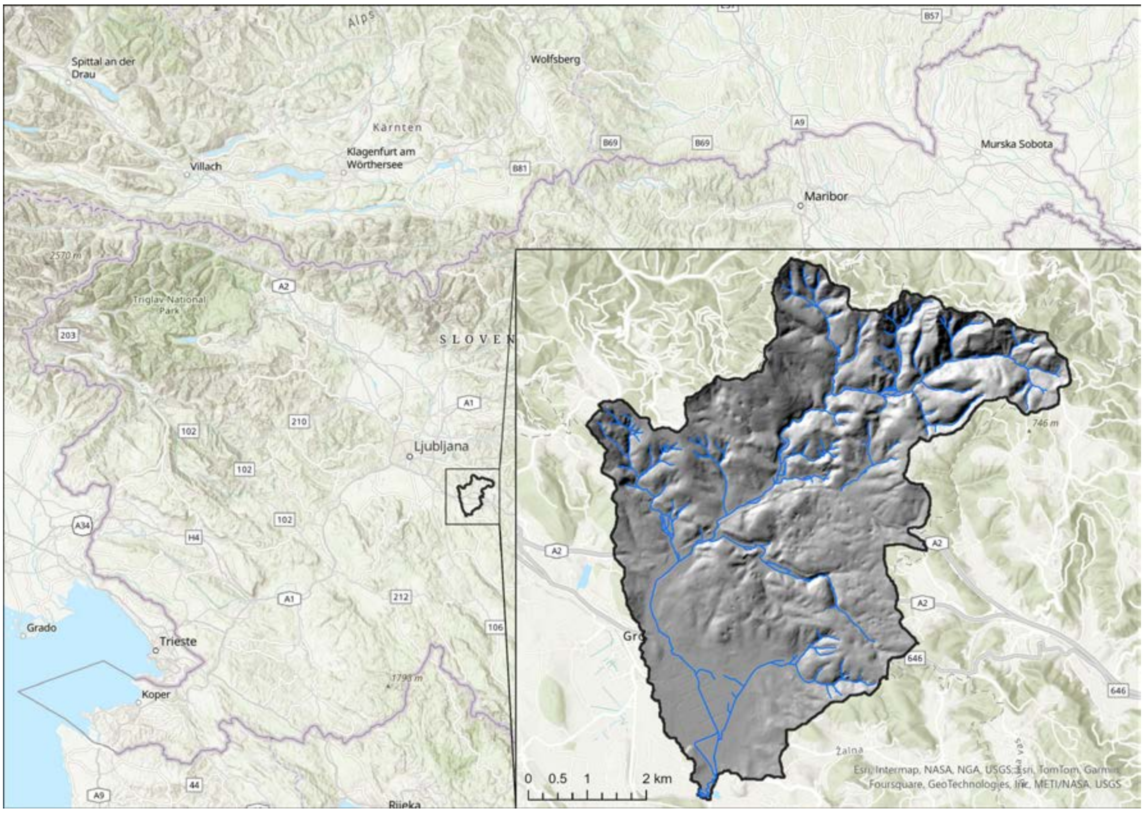


Figure 2. The location of Grosupeljščica catchment in Slovenian Dolenjska region.

Most of the river Grosupeljščica area is covered by forest (1885 ha) and permanent grassland (868.4 ha). Forest is also covering most of the river Drnica area, whereas a lot of area is also covered by olive trees and vineyards as seen on the Figure 3 below.

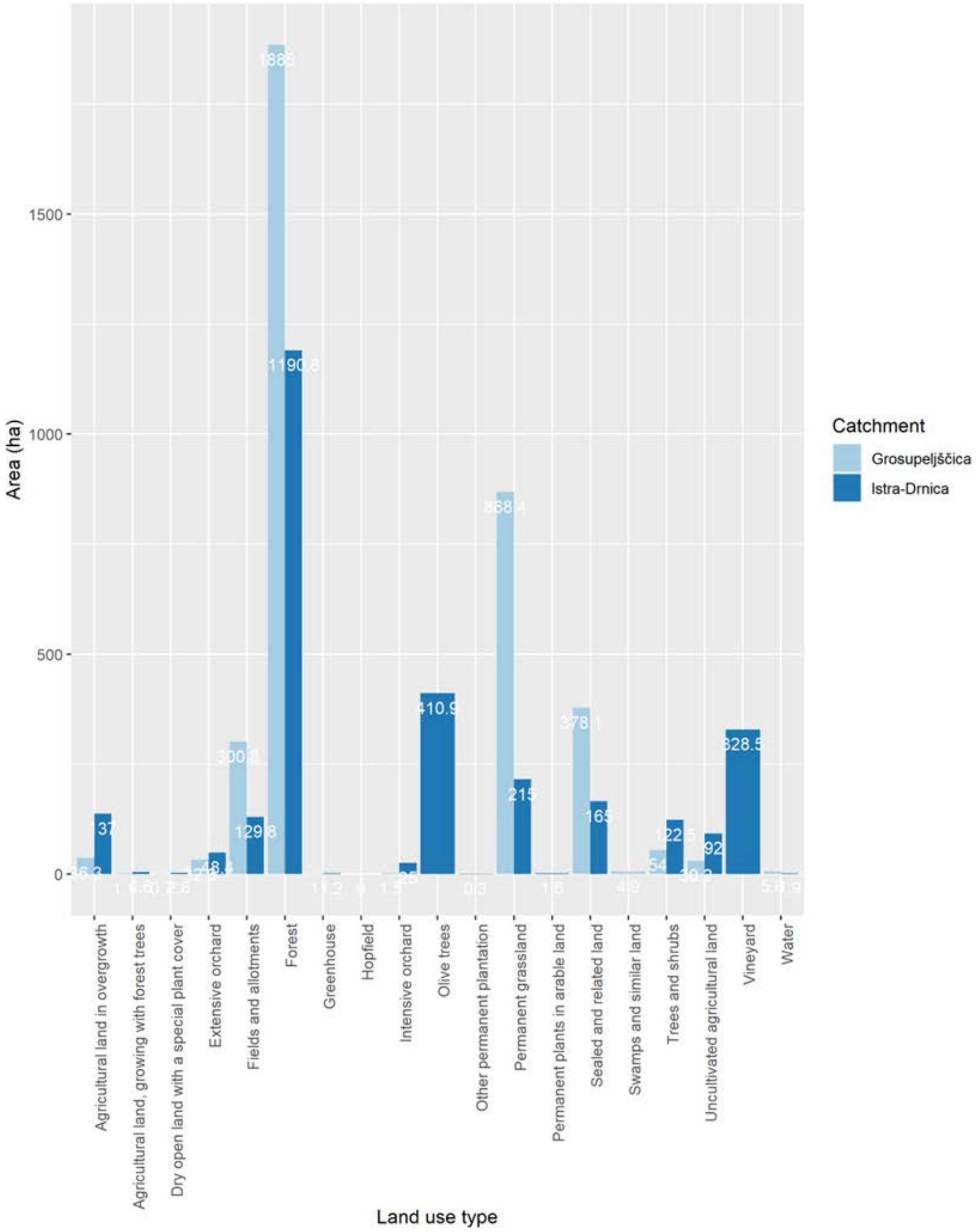


Figure 3. Dominant land use types in catchment of Drnica and Grosupeljščica.

As we can identify on the Figure 4 below by far dominant soil type on Istra-Drnica is Calcaric Cambisol (1733.6 ha), followed by Eutric Cambisols (700.6 ha) which both occur on flysch rock, sandstone or marlstone. Both soil types are commonly known as highly erodible. Catchment of Grosupeljščica river is pedologically different. Most common soil types are Chromic Cambisol (1247.6 ha) and Renzic Leptosol (1086 ha). Especially Chromic Cambisols have higher percentage of clay and polyhedral structure. Soils form strong organo-mineral bonds which makes soil more stable and resistible to soil erosion.

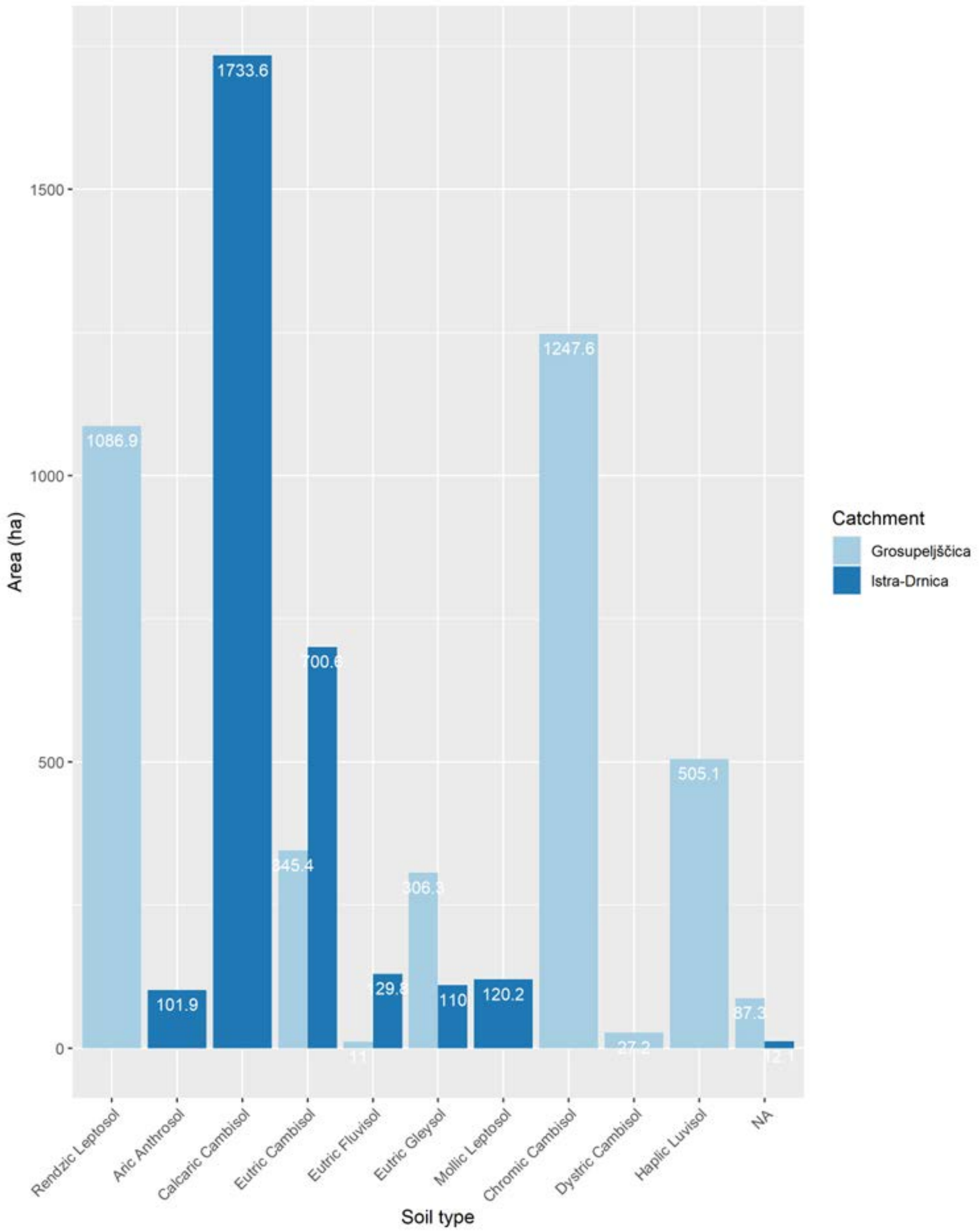


Figure 4. Dominant soil types in catchment of Drnica and Grosupeljščica.

4.1.2. Data and methods

4.1.2.1. Revised Universal Soil Loss Equation (RUSLE)

RUSLE (Renard et al., 1997) is an empirical model for predicting sheet and rill erosion by water and it is the revised version of USLE (Wischmeier and Smith, 1978). The equation was originally developed for assessing soil loss at field slope/plot scale but has been later widely used as a spatially distributed model. The RUSLE equation is:

$$A = R \times K \times L \times S \times C \times P$$

where A is the annual average erosion (t ha^{-1} yr^{-1}). R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}) describing effect of rainfall and overland flow on erosion, and it is defined by the energy intensity of rainfall events. K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}) describing the propensity of soil to detach by the energy of the rainfall and overland flow, and it is affected by soil properties, including particle size fractions, organic matter content, soil structure, soil permeability and soil freezing. L and S are the topographic factors (dimensionless) describing the effect the slope length (L) and steepness (S) on erosion. C is the cover-management factor (dimensionless) considering the effects of different cropping and tilling practices on erosion, and it is described by the energy intensity of rainfall, prior-land-use, canopy cover, surface cover, and the surface roughness. P is the support practice factor (dimensionless) accounting for the effect of various support practices on erosion, including contouring, strip cropping, terracing and subsurface drainage. For more detailed description of RUSLE factors, see Renard et al. (1997).

The original field slope/plot scale RUSLE predicts soil loss, or the amount of sediment transported to the end of the slope (Renard et al., 1997), whereas the spatially distributed RUSLE predicts soil loss at a spatially discrete unit, such as a grid cell, but does not account for sediment transport between the spatial units. Therefore, the predictions of spatially distributed RUSLE over a landscape are considered gross erosion predictions. The spatial units are, however, connected in the spatially distributed computation through the LS factor accounting for the effect of slope length and steepness on erosion rate at each spatial unit. The lack of sediment transport between the computational units in spatially distributed RUSLE considerably reduces the capacity to include erosion measures and sediment connectivity elements in the computations.

4.1.2.2. Simulations

We used different data and methodology for each of the input factor of the RUSLE equation. Most of our modelling was done in R using Rstudio and packages such as terra, sf, tydiverse. For managing large database tables, we used SQL language. For cartography purposes we used ArcGIS pro.

For C factor (Cf) we used the logic of the Land use and management model (LANDUM) (Panagos, et. al, 2015) which we adopted to Slovenian available datasets. We used crop type dataset and national land use map to join the literature-based C factor values to create „ccrop“ (Table 3) and „clanduse“ spatial raster layers. We prioritized ccrop over clanduse dataset to create layers of basic Cf for each year in period from 2019 – 2022. We also derived Cmanagement rasters for each year in period 2019 – 2022. We took Cmanagement values from literature (mostly from the study of Panagos et al., 2015) which were attributed to most common agricultural practices. The closer Cmanagement is to 0 the more it reduces the basic erosion. We assigned basic Cmanagement values to the national dataset of agro-environmental measures as shown in the Table 4 below and multiply it with the minimum fraction of area on which measure needs to be implemented in order to receive subsidies. This was made on the parcel level and rasterized to create Cmanagement rasters (Table 4). Erosion management measures implemented in our model where:

- reduced tillage practices: conservation tillage, requires minimum tillage to maintain soil structure and fertility and prevent erosion. It must be carried out over the entire area of the main crop land. Using the reference from Panagos et. al., 2015 the soil erosion is reduced by 75 %, therefore these areas received Ctill = 0.35.
- Crop residues: The conservation tillage measure requires that at least 30% of the land area of the main crop be left in harvest residues after harvest. Cresidues in this study is set to 0.8.
- Crop cover measures are implemented through measures:
  - Proportion of the area of the plot covered by green overwintering cover where at least 70 % of the area must be covered with green cover. The measure is applied on the overwintering crop. Value set to 0.8.
  - Proportion of the area of the parcel covered by non-winter crops (coverage from 15th of August till 16th of October the same year) It shall be claimed as a non-winter crop on at least 70 % of the area of the parcel. We set the value to 0.934.

  - The proportion of the area of a parcel sown after the main crop has been harvested and ploughed in no later than 15.11. of the current year. No minimum crop presence is defined. The measure is applied as a non-winter crop. We set the value to be 0.934.
  - The proportion of the area of the hop-growing area covered by crops in the interrow space from 25.7 to at least 25.10 of the current year. Part of the main crop. We set the value to 0.9.
- Cover measures on vineyards are implemented through measures:
  - Cover of inter-row space with cultivated fallow. Set to value of 0.16.
  - Soil cover over winter in vineyards where the interrow space is not covered by cultivated fallow land. We set the value to 0.79.
- Cover measures on orchards and olive trees: Coverage of inter-row space by cultivated fallow land in orchard or olive grove. We set the value to 0.324.

We carried out two versions of final Cf calculation:

- RUSLE erosion if no measures would be implemented by farmers (Cmanagement equals 1 = no reduction).
- RUSLE erosion with current measures included. In this case final Cf raster was calculated by multiplying basic Cf with Cmanagement raster.

Table 3. C crop values from literature assigned to Slovenian dataset of selected crop types (only few are shown in this table).

Plant	Latin name	Ccrop	Reference
Wheat (spring)	*Triticum aestivum L.*	0.2	Panagos et. al, 2015
Buckwheat	*Fagopyrum esculentum Moench*	0.2	Panagos et. al, 2015
Maize for grain	*Zea mays L.*	0.38	Panagos et. al, 2015
Maize for silage	*Zea mays L.*	0.38	Panagos et. al, 2015
Triticale (spring)	*X Triticosecale Wittmack (Triticum x Secale)*	0.2	Panagos et. al, 2015
Oats (spring)	*Avena sativa L.*	0.2	Panagos et. al, 2015
Barley (spring)	*Hordeum vulgare L., spring barley*	0.2	Panagos et. al, 2015
Millet	*Panicum miliaceum L.*	0.2	Panagos et. al, 2015
Cereal mix. (spring)	*Mixture of cereals (spring)*	0.2	Panagos et. al, 2015
Sunflowers	*Helianthus annus L.*	0.28	Panagos et. al, 2015
Oil pumpkin	*Cucurbita pepo var.pepo*	0.28	Panagos et. al, 2015
Oilseed rape (spring)	*Brassica napus var.napus*	0.3	Panagos et. al, 2015
Potatoes (early)	*Solanum tuberosum L.*	0.34	Panagos et. al, 2015

Table 4. C management values assigned to Slovenian dataset of agri-environmental measures.

Area of implementation	Group of measures	Erosion mitigation measure	Measure description, practice	Plot share	Share of the reduction or C management	References
ARABLE LAND	C till	POZ_KONZ	Conservation tillage, or conservation tillage, requires minimum tillage to maintain soil structure and fertility and prevent erosion. It must be carried out over the entire area of the main crop land.	100%	0.35	Panagos, 2015
	C residues	POZ_KONZ.	The conservation tillage measure requires that at least 30% of the land area of the main crop be left in harvest residues after harvest.	30%	0.88	Panagos, 2015
	C cover	POZ_ZEL ali VOD_ZEL	Proportion of the area of the plot covered by green overwintering cover. Where POZ_ZEL or VOD_ZEL, at least 70 % of the area must be covered with green cover. The measure is applied on the overwintering crop.	70%	0.8	Panagos, 2015
		POZ_NEP ali VOD_NEP	Proportion of the area of the parcel covered by non-winter crops (coverage from 15th of August till 16th of October the same year) It shall be claimed as a non-winter crop on at least 70 % of the area of the parcel Panagos et. al. 2015 does not have this.	70%	0.934	AIS assessment, POZ_ZEL value converted to 2 months duration (15.8 - 16.10.)
		POZ_POD ali VOD_POD	The proportion of the area of a parcel sown after the main crop has been harvested and ploughed in no later than 15.11. of the current year. No minimum crop presence is defined. The measure is applied as a non-winter crop. Panagos et. al. 2015 does not have this.	70%	0.934	AIS assessment, value of POZ_ZEL converted to 2 months duration (15.9 - 15.11.)
		HML_POKT	The proportion of the area of the hop-growing area covered by crops in the interrow space from 25.7 to at least 25.10 of the current year. Part of the main crop. Panagos et. al. 2015 does not have this.	100%	0.9	AIS assessment, value of POZ_ZEL converted to 3 months duration (25.7 - 15.10.)
VINEYARDS	C cover	VIN_POKT	Cover of inter-row space with cultivated fallow.	100%	0.16	AIS assessment, proportion of reduction in vineyard value to approach the grassland result of 0.0405 + 20% (0.0486). The intercropping cover is very similar to permanent grassland, but slightly more prone to erosion due to the herbicide belt.
		VIN_MEDV	Soil cover over winter in vineyards where the interrow space is not covered by cultivated fallow land.	100%	0.79	AIS assessment, see VIN_POKT, except that conversion to 3 months (winter period) coverage.
INTENSIVE ORCHARDS AND OLIVE GROVES	C cover	SAD_POKT	Coverage of inter-row space by cultivated fallow land in orchard or olive grove.	100%	0.324	AIS assessment, proportion of reduction in the value of the orchard to approach the grassland result of 0.0405 + 20% (0.0486). This is because the interspace cover is very similar to permanent grassland, but slightly more exposed to erosion due to the herbicide belt.

We used the rainfall erosivity made by Petan (2010) and resampled it to the resolution (using bilinear interpolation). Petan used the Brown and Foster (1987) and Renard et al. (1997) equation to calculate average annual rainfall erosivity. Petan (2010) calibrated the calculation of E (rainfall kinetic energy) based on 3 reference stations with continuous data and calculated the E for 31 pluviographic stations (1999 – 2008). The final Petan‘s R factor map is the interpolation of the measured data over Slovenia using kriging and kriging residuals.

We used the Desmet and Govers (1996) equation for calculating the LSf. We used different tools and combinations of values for input optional parameters in SAGA software. As the input we used the DEM (1 x 1 m) we created from LIDAR data. We derived 6 LS factor maps. After visualizing and reviewing we decided to choose the one that best detects the terraces. Those were the LSf created using Desmet and Govers (1996), one step procedure using fill sinks by Wang and Liu method.

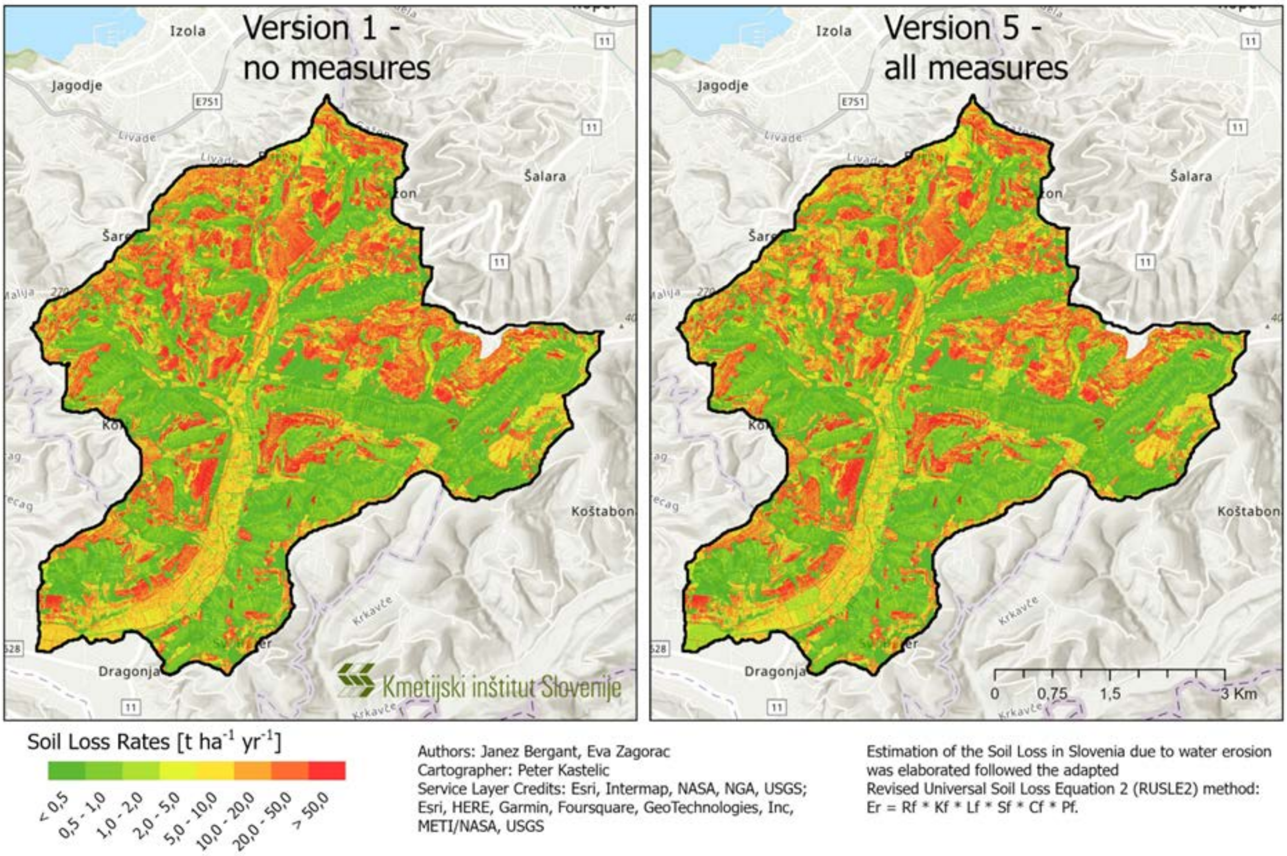
We calculated the Kf factor using equation also used by Wischmeier & Smith (1978) and Renard et al. (1997), Panagos et al. (2015b).

$$Kf = \{[2,1 \times (10-4) \times M1,14 \times (12 - OS)] + [3,25 \times (s - 2)] \times (p - 3)]\} / 100 \times 0,1317$$

We used the soil profiles of Slovenia (1681 profiles) and derived the needed soil properties recalculating it to 0 – 20 cm depth. We interpolated the Kf factor to soil map of Slovenia (1:25.000) using representative soil profiles and using weighted average of Kf from soil typological units.

4.1.3. Results

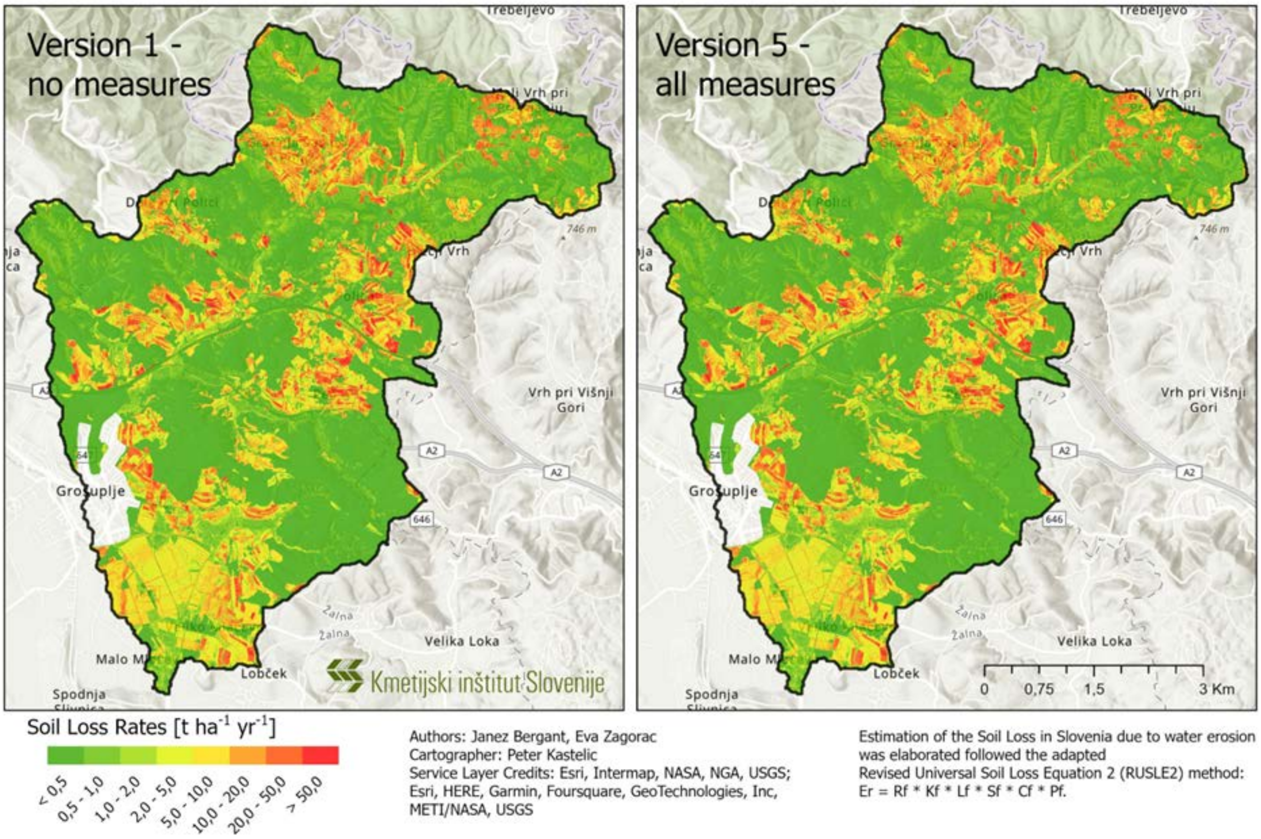
The average soil erosion in the catchment area of Drnica river (Istra) is 16.09 t/ha and would be 17.61 t/ha if no measures would be applied (Figure 5). The erosion rates are significantly lower on catchment area of Grosupeljščica (central Slovenia) with 4.55 t/ha (Figure 6). If no measures would be applied the average soil erosion would be not significantly higher (4.59 t/ha). We can conclude that measures on Drnica have larger impact on soil erosion reduction then on river of Grosupeljščica. Average erosion rates of Grosupeljščica catchment are more similar to the average erosion estimated for Slovenia in 2020 3.68 t/ha (Bergant et. al., 2020).



Authors: Janez Bergant, Eva Zagorac
Cartographer: Peter Kastelic
Service Layer Credits: Esri, Intermap, NASA, NGA, USGS; Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

Estimation of the Soil Loss in Slovenia due to water erosion was elaborated followed the adapted Revised Universal Soil Loss Equation 2 (RUSLE2) method: Er = Rf * Kf * Lf * Sf * Cf * Pf.

Figure 5. RUSLE erosion map of Drnica catchment with no measures implemented (left) and all the management measures implemented (right).



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Estimation of the Soil Loss in Slovenia due to water erosion was elaborated followed the adapted Revised Universal Soil Loss Equation 2 (RUSLE2) method: Er = Rf * Kf * Lf * Sf * Cf * Pf.

Figure 6. RUSLE erosion on Grosupeljščica catchment with no measures implemented (left) and all the management measures implemented (right).

When we compare the areas with difference in soil erosion between RUSLE (measures implemented) and RUSLE (if no measures were implemented) on catchment scale, we can see that differences appear on 130.0 ha of Drnica catchment (Istria) and only on 59.5 ha of Grosupeljščica catchment (Figure 7).

On catchment of Drnica most of the areas (47 % or 61 ha) with different soil erosion have average difference in erosion higher than 20 t/ha per year and very small areas with erosion differences lower than 0 – 0.5 t/ha (0,1 ha or 0 %) (Figure 8). On the other hand, differences in soil erosion on catchment of Grosupeljščica are significantly lower. Most of the areas with different soil erosion have erosion difference in rank of 0.5 – 1 t/ha (15,3 ha or 26 %), following the rank of 0 – 0,5 t/ha on 14,1 ha (24 %) (Figure 8). This being said, we conclude that mitigation measures on Drnica catchment have higher impact on total erosion reduction than mitigation measures on Grosupeljščica catchment.

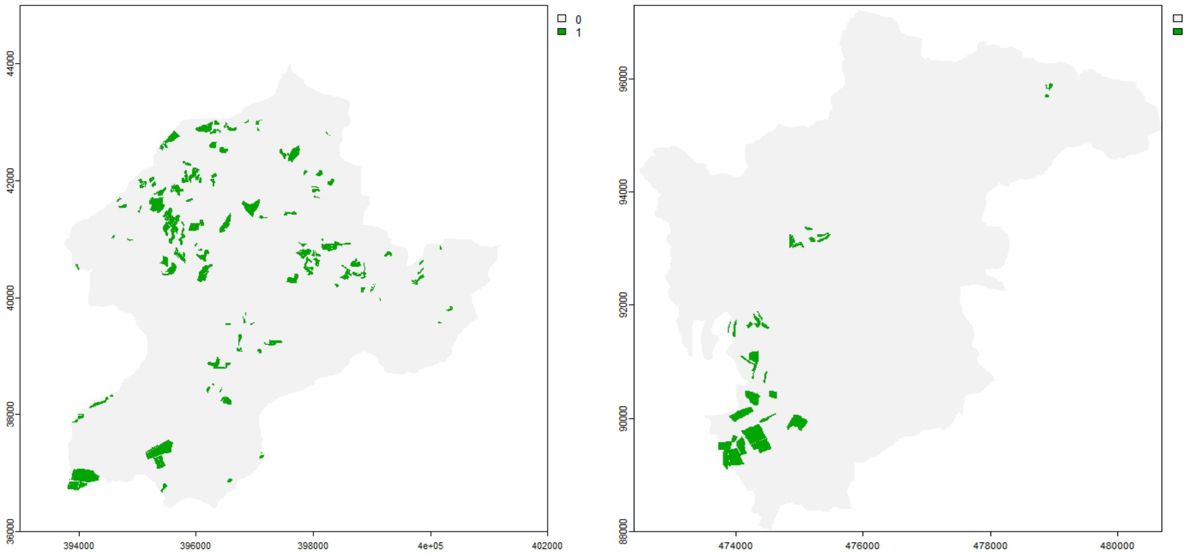

Figure 7. The areas with different soil erosion if management practices would not be implemented (rusle_v1 vs rusle_v5) on Drnica catchment (left) and Grosupeljščica catchment (right).

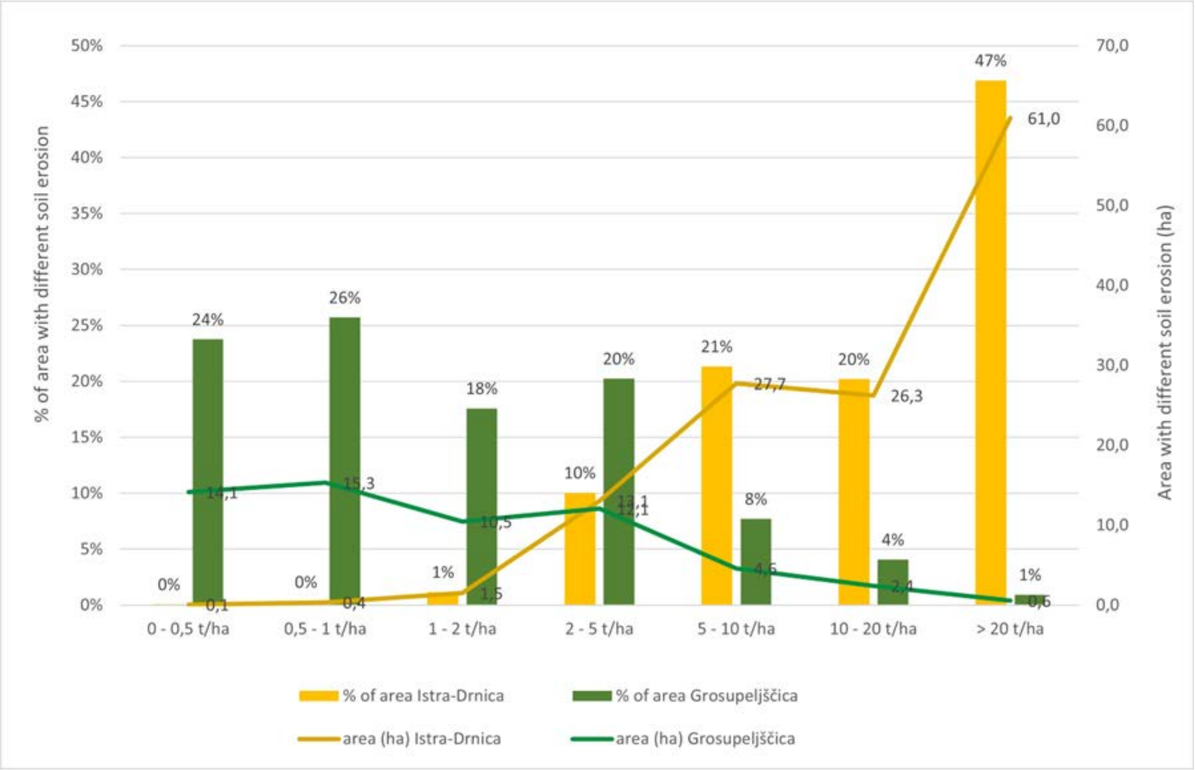

Figure 8. Areas (expressed as ha and %) by soil erosion differences (as ranks) between measures vs no measures scenario.

After analysing the results of RUSLE erosion on the agricultural land where mitigation measures were implemented by farmers in 2022, we can see that on Drnica catchment farmers implemented only cover crop practices (60.6 ha) on vineyards and orchards (including olive grove) (56.9 ha). There were no farmers that would implement reduced tillage, crop residues or cover crop practices on arable land. If no cover on vineyards would be implemented, average erosion would be much higher (48.9 t/ha per year) then the current which is 8.1 t/ha per year. Cover crops on orchards (and olive groves) helped reduced tillage from 46.4 t/ha per year to current 15.5 t/ha per year on average (Figure 9).

The farmers on Grosupelščica have different land-management practices. They have implemented the reduced tillage and crop residues practices and also cover crop practices on arable land. No cover crop practice on vineyards and orchards were implemented in 2022. With implementing reduced tillage and crop residues on 25,8 ha they reduced erosion according to RUSLE to 10.4 t/ha per year from 14.4 t/ha per year on average. Implementing cover crop practices on arable land on 16.7 ha average erosion according to our RUSLE model was reduced from 12.8 t/ha per year to 10.7 t/ha per year (Figure 10).

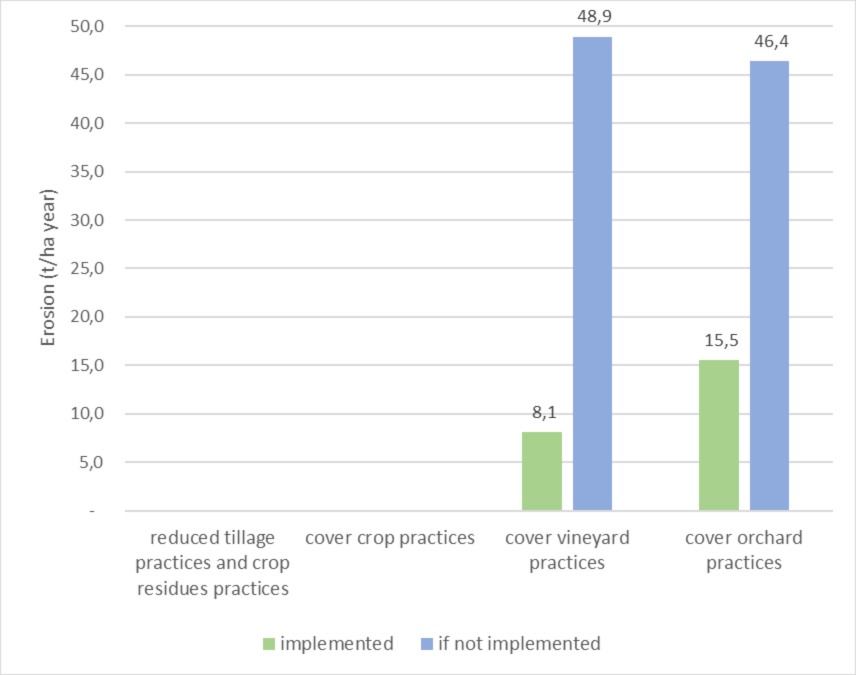

Figure 9. RUSLE erosion (t/ha per year) by management mitigation measures on Drnica catchment.

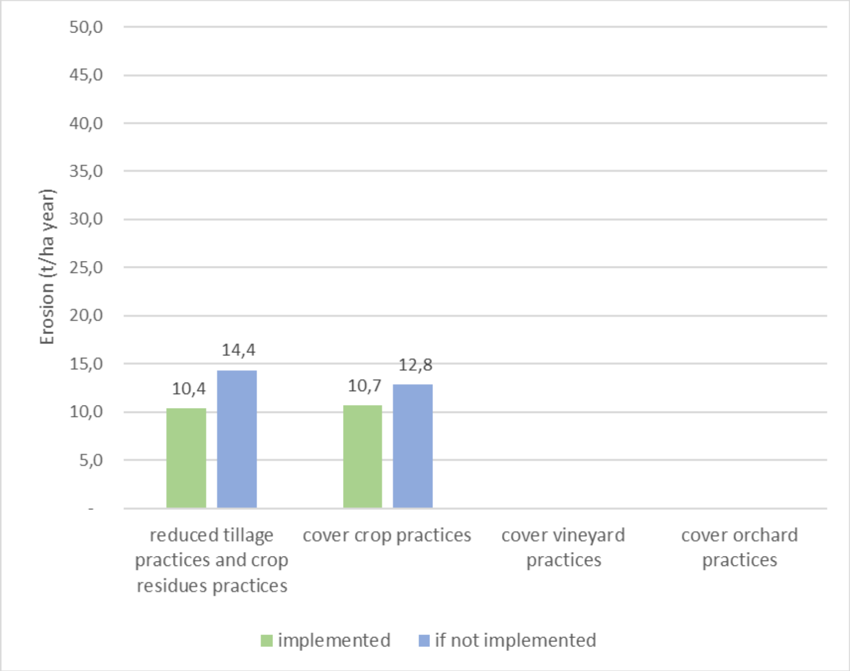

Figure 10. RUSLE erosion (t/ha per year) by management mitigation measures on Grosupeljščica catchment.

There are significant differences in soil erosion rates by land use and soil types.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 862695

Figure 11 shows that there is no major difference in average erosion rates on Drnica catchments when comparing land use types with erosion measures vs. no erosion measures applied. Average erosion in vineyards without erosion measures applied is 48,2 t/ha, whereas the average erosion rate in vineyards with measure shows lower average erosion rate of 40,4 t/ha. Slightly higher erosion rate was found in olive trees 53,9 t/ha than in olive and with measures 49,8.

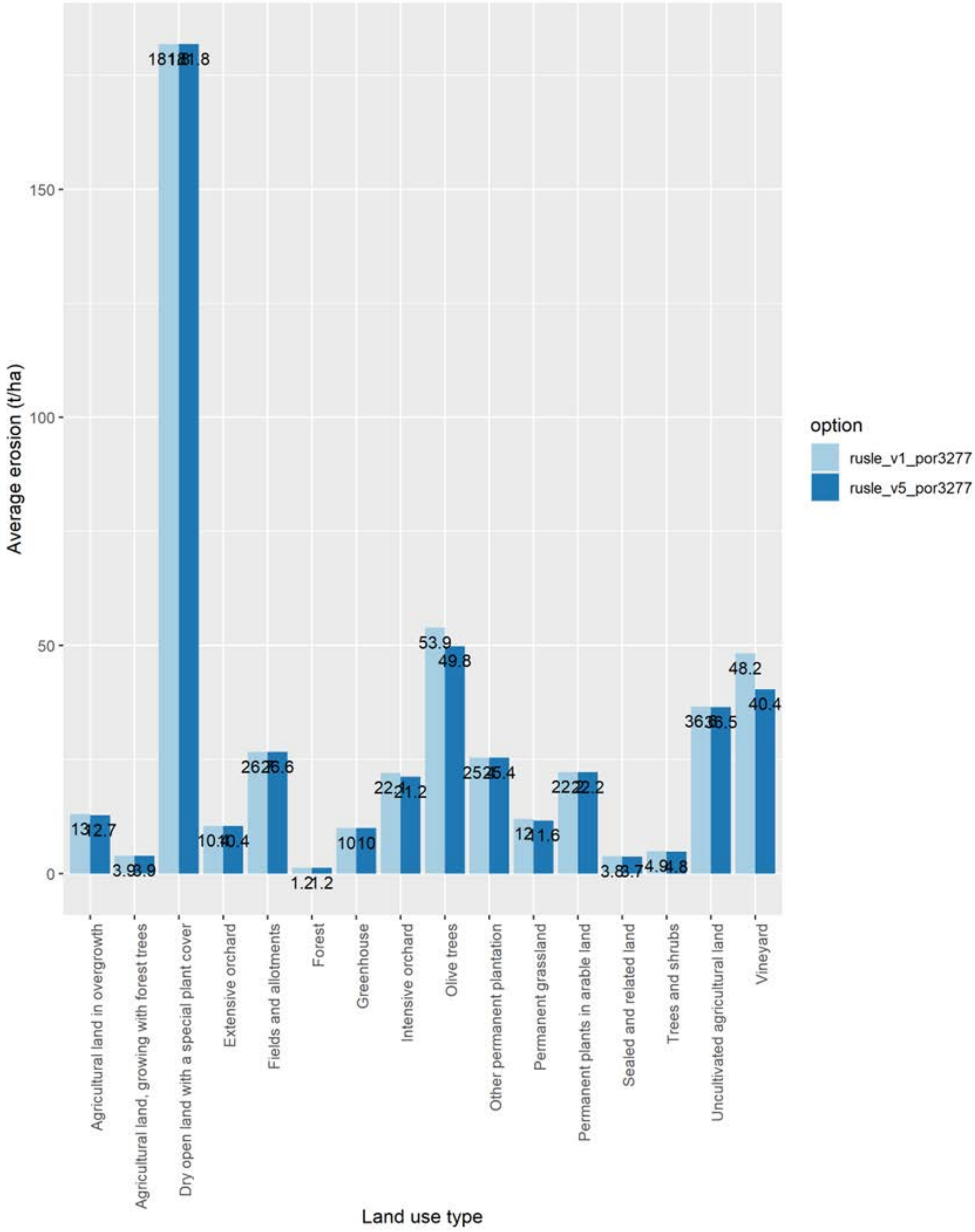

Figure 11. Erosion on Drnica catchment by land use types between no measures (rusle_v1…) vs measures (rusle_v5…).

When looking at soil types in connection with erosion measure vs. no measures on the catchment Drnica, results showed that the most erodible soil type on Drnica catchment are Aric Anthrosols. The average erosion on this soil type when no measures were applied is 27.1 t/ha and 25.4 t/ha when the measures were applied. The least erodible soil type on Drnica catchment is Mollic Leptosols (Figure 12).

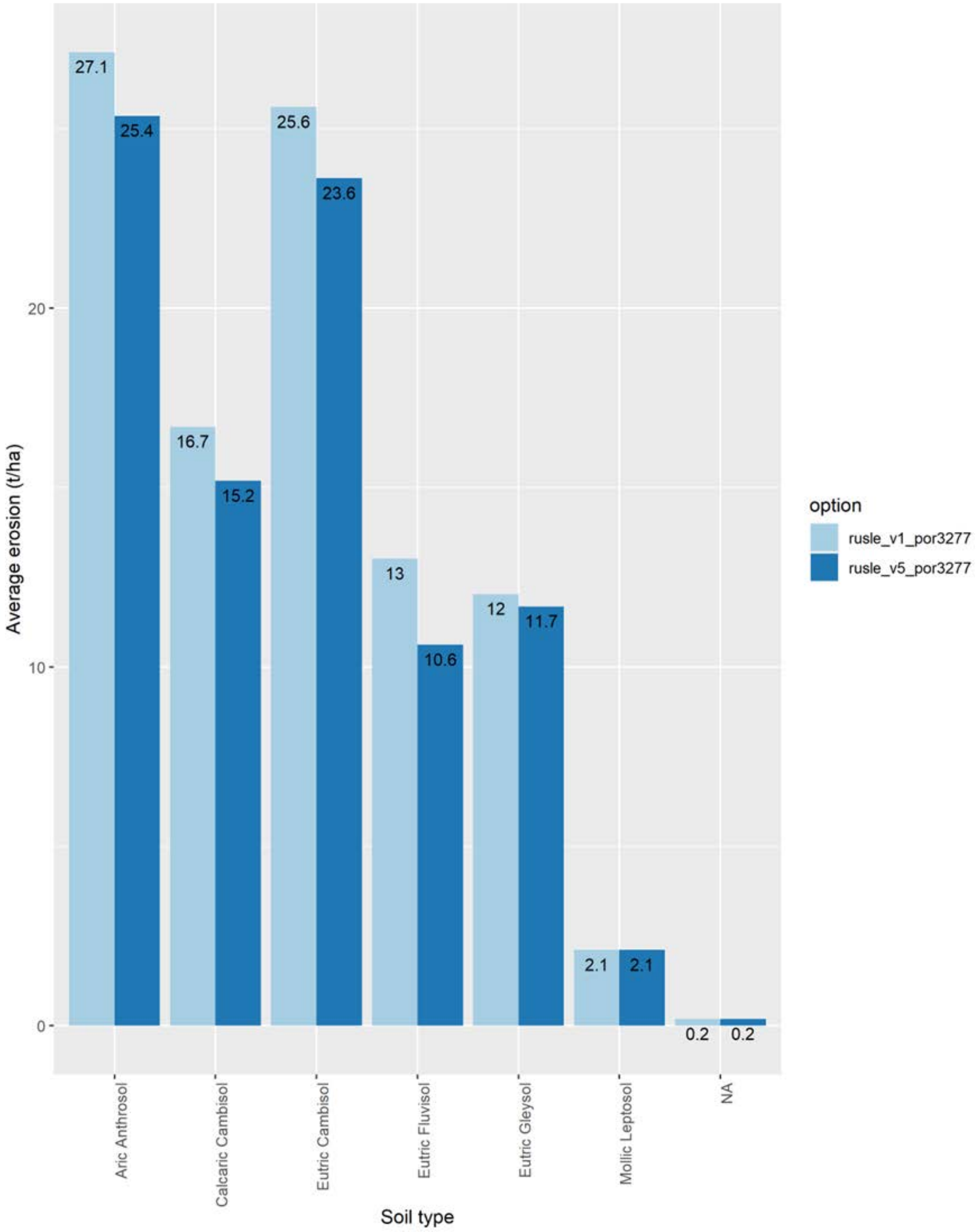

Figure 12. Erosion on Drnica catchment by soil types between no measures (rusle_v1…) vs measures (rusle_v5…).

Figure 13 shows the results of comparison of average erosion rates on different land use types on Grosuplejščica catchments between no measures vs measures. No major difference in average erosion rate was detected whether the measures were applied or not.

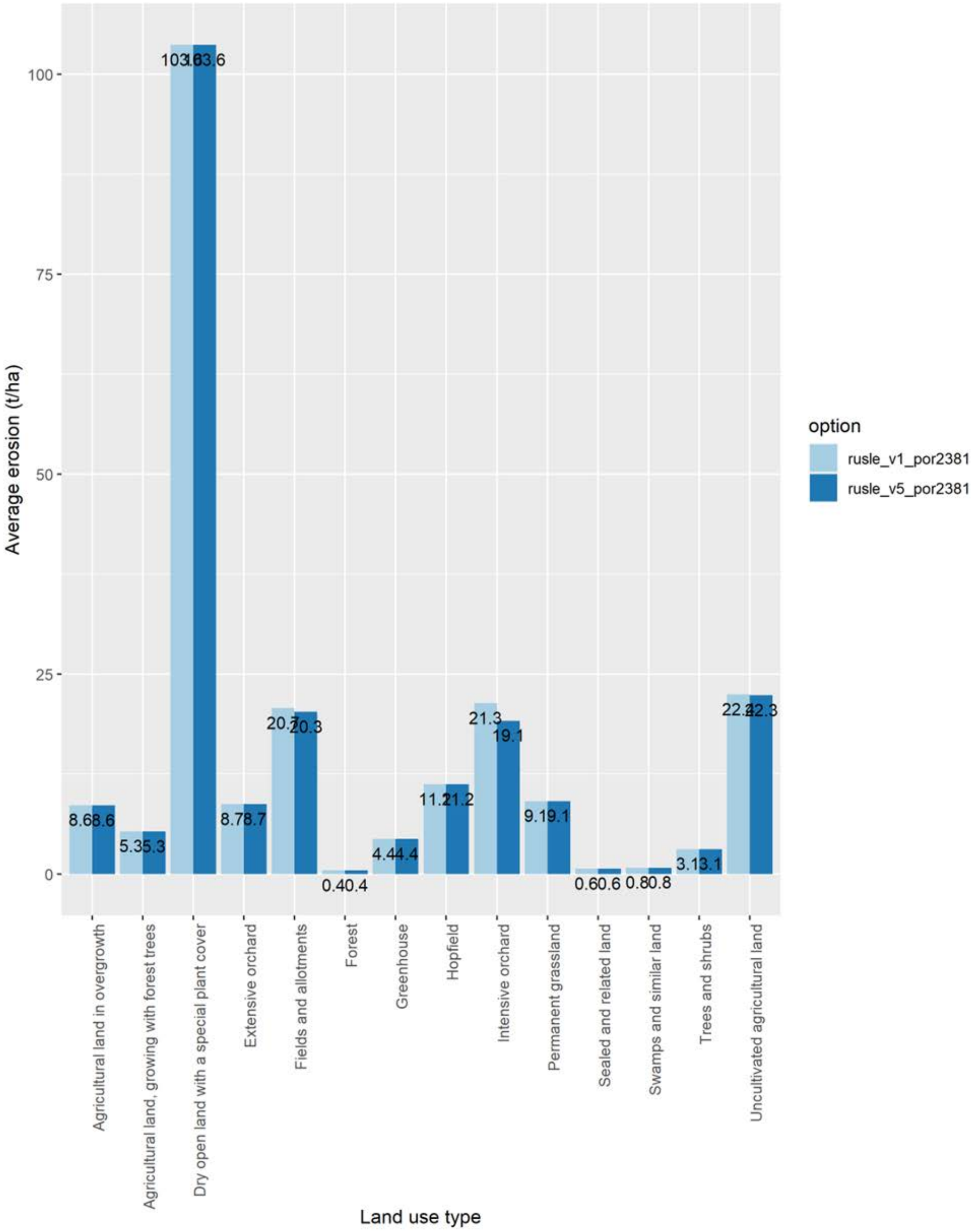

Figure 13. Erosion on Grosupeljščica catchment by land use types between no measures (rusle_v1…) vs measures (rusle_v5…).

The most erodible soil type on Grosupeljščica catchment are Haplic Luvisols, where the average erosion rate without measures applies is equal to 7.2 t/ha and 7.1 t/ha when the measures are applied (Figure 14).

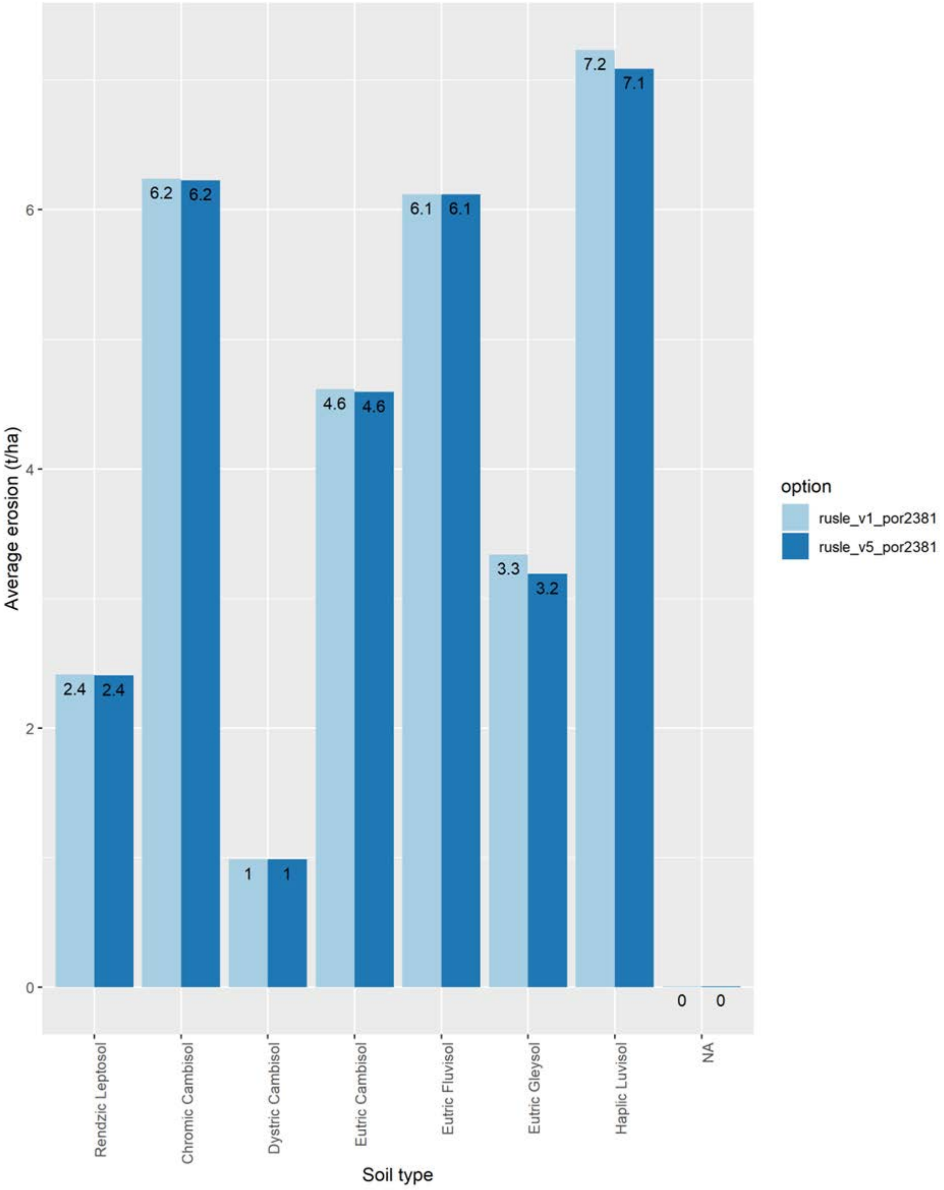

Figure 14. Erosion on Grosupeljščica catchment by soil types between no measures (rusle_v1…) vs measures (rusle_v5…).

Figure 15 and Figure 16 show the difference in erosion on cropland field on Grosupeljščica catchment and Drnica catchment between no measure applied vs. measures applied. The redder the figure is the higher soil loss rate was detected.

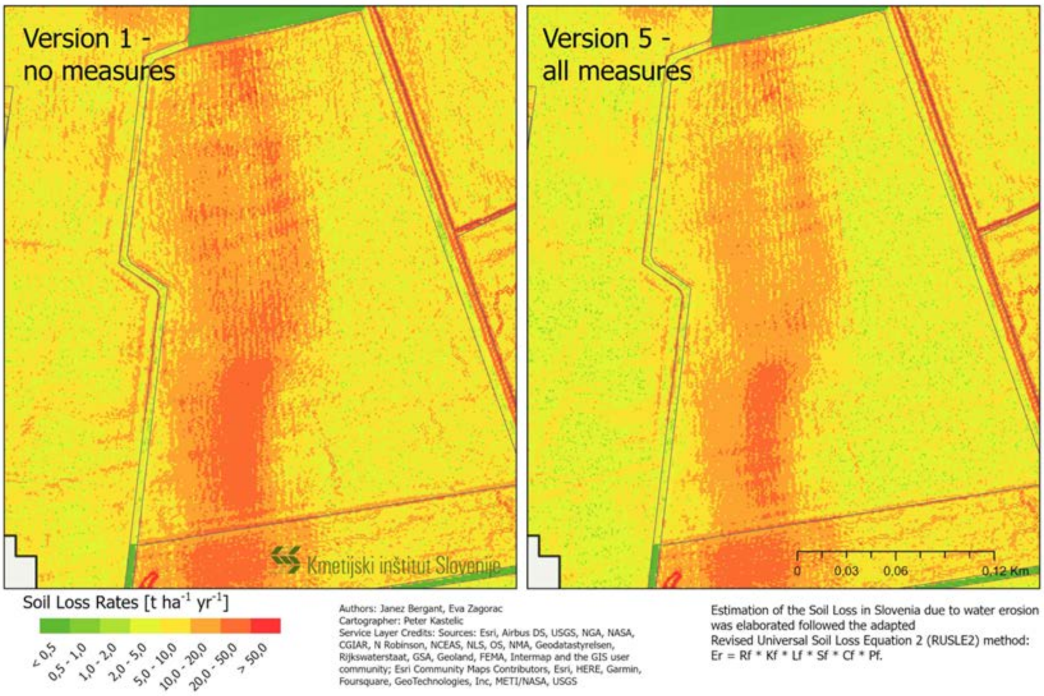

Figure 15. Difference in erosion on cropland field on Grosupeljščica catchment between no measures (left) vs measures (right).

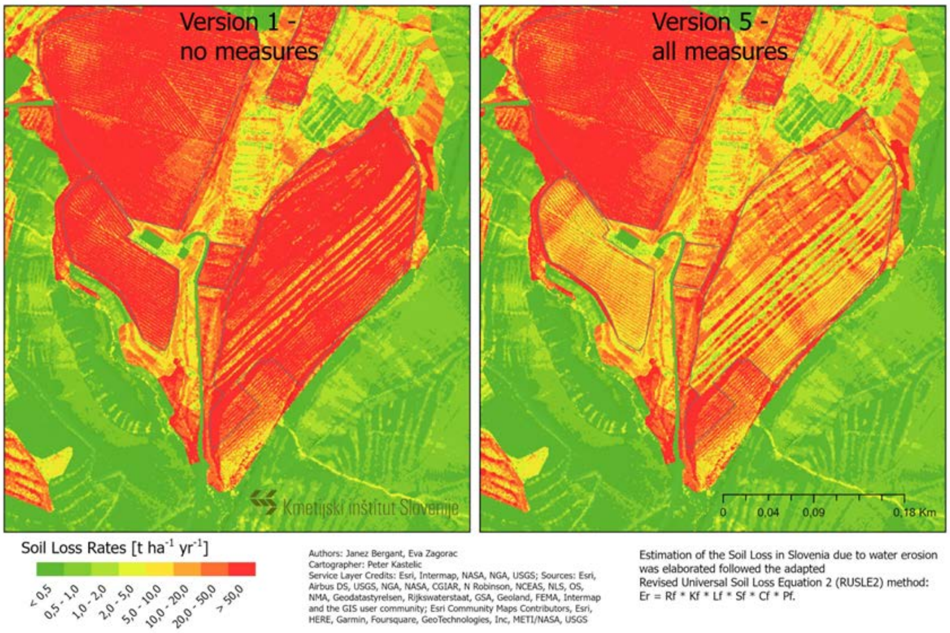

Figure 16. Difference in erosion rate on vineyard on Drnica catchment between no measures (left) vs measures (right).

4.1.4. Discussion

Drnica catchment has higher average erosion rates than Grosupeljščica catchment which is what we expected in one of our objectives. The main reason is that C factor representing land use and the land management practices iis significantly higher on Drnica catchment. Just the fact that Grosupeljščica catchment has 52 % of area covered with forest and 24 % with permanent grassland it is expected that the C factor would be lower than on Drnica catchment where forests cover 41 % and grasslands 7 % of catchment area and vineyards cover 11 % and olive grove 14 %. The other reason is that on Drnica catchment most common soil types are known to be more erodible than soil types common at Grosupeljščica catchment. If we compare the soil types with highest erosion rate on Drnica catchment these are Aric Anthrosols with average erosion rate 25.3 t/ha per year and Eutric Cambisols with average erosion rate of 23.6 t/ha per year. For comparison two soil types with the highest erosion rate in Grosupeljščica catchment have three times lower erosion rates; Haplic Luvisol with 7.1 t/ha per year and Chromic Cambisols with 6.2 t/ha per year. The third reason is that the catchment of Drnica has steeper slopes than Grosupeljščica catchment.

The average RUSLE erosion with all measures implemented for Drnica catchment is 16.09 t/ha per year and on Grosupeljščica catchment 4.55 t/ha per year. Both erosion rates are higher than the average erosion estimated with RUSLE for Slovenia in 2020 with 3,68 t/ha per year (Bergant et. al., 2020) but erosion on Grosupeljščica is very similar. On the other hand, erosion on Drnica catchment is significantly higher. The erosion results from our RUSLE model on vineyards with average 40.4 t/ha per year is comparable with estimation of erosion on vineyards carried out by Petkovšek 2002 (51.31 t/ha per year). Zorn and Mikoš, 2009 measured the soil erosion on bare soil olive grove in Rokava river (near Drnica catchment) to be 90.13 t/ha per year, our RUSLE model estimates lower average values 49.8 t/ha per year.

The terraces are one of the important connectivity mitigation measures. Since the RUSLE model does not enable connectivity mitigation measures by default, the terraces were not included in the model directly but through calculation of slope length factor (LS factor). Using high resolution 1x1m DEM derived from LIDAR data terraces (which are common on steep slopes of Drnica catchment) were visually detected from DEM. Using the parameterization and iterating of LS factor calculation we chose LS factor results which best showed the differences of LSf between the flat and steep part of the terraces.

The effect of management mitigation measures/practices on reduction of soil erosion on agricultural land is not significant. Applying agricultural measures show small differences in average erosion reduction (for Drnica on average 1,52 t/ha, on Grosupeljščica only 0,04 t/ha). But if we take a look at the erosion rates only on areas where the mitigation measures were implemented, we found out that mitigation measures did have significant effect on reduction of soil erosion. After analysing the results of RUSLE erosion on the agricultural land where mitigation measures were implemented by farmers in 2022, we can see that on Drnica catchment if no cover crops on vineyards would be implemented, average erosion would be much higher (48,9 t/ha per year) then the current erosion which is 8.1 t/ha per year. Cover crops on orchards (and olive groves) helped reduced tillage from 46.4 t/ha per year to current 15.5 t/ha per year on average. The farmers on Grosupeljščica which implemented reduced tillage practice and used crop residues in 2022 reduced erosion to 10.4 t/ha per year from 14.4 t/ha per year on average. Implementing cover crop practices on arable land reduced erosion from 12.8 t/ha per year to 10.7 t/ha per year.

The results of RUSLE model on high resolution are useful for estimating soil erosion rates on small catchment areas but have certain limitations. The one is that RUSLE calculates the average long term erosion rates. But most of the erosion happens in several erosion events. Therefore, we are aiming to model erosion on smaller time scale (e.g., months). The other limitation of RUSLE is disability of calculating the erosion flow direction and deposition areas. Nevertheless, the results of our RUSLE model can be used to estimate the erosion rates and has a potential to become a decision support for government which agricultural practices effect erosion more efficiently and where should be more encouraged.

4.2. RUSLE/IC/SDR

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4.2.1. Introduction

In Finland, the main problem of erosion is considered to be its negative impacts on surface water quality and aquatic ecosystems. The erosion rates are relatively low in European context, but the effects of erosion on surface waters are nevertheless significant. The impact of soil erosion on agricultural soil productivity has not received similar attention as the impact of surface waters.

Most of the erosion in Finland occurs outside the growing season during spring, autumn and early winter, when the fields have less protective vegetation cover, and the soil is more exposed. According to measurements from experimental fields under different cultivation practices, the long-term erosion is estimated to vary from 50 to 2,100 kg ha^{-1} yr^{-1} and vary on annual basis at least up to 4,600 kg ha^{-1} yr^{-1} (Räsänen et al 2023).

The agriculture in Finland is dominated by spring and winter cereals (wheat, barley, and oat; 60% of the field area), and perennial grass and hay type crops (Finnish Food Authority). The spring crops are planted in April-May and harvested in August-September. The ploughing is typically in the autumn by conventional moldboard plough or with reduced tillage. The winter-time vegetation cover (e.g., winter crops, stubble cover) has increased in recent years and can be in some regions well over 50% of the total field area.

The erosion is typically managed with winter-time vegetation cover, reduced tillage, and riparian grass buffer strips. The fields are mostly well-drained and surrounded by open ditches isolating the field parcels from each other in terms of surface runoff and sediment transport. The ditches effectively drain and transport sediments towards streams, rivers, and lakes. Artificial subsurface drainage is also a common practice.

The agricultural erosion management is less studied in Finland in the context sediment connectivity. Particularly, how the connectivity affects the effectiveness of commonly applied erosion measures in varying agricultural landscapes and between individual field parcels. Therefore, model simulations were setup using RUSLE/IC/SDR approach for two topographically differing agricultural catchments to explore the effect of connectivity on erosion management and to exemplify their simulation. The specific objectives were to:

1. Explore the suitability of RUSLE/IC/SDR for simulation erosion and connectivity elements at field parcel scale.
2. Estimate the effect of erosion and connectivity measures at two topographically differing catchments.
3. Evaluate the benefits of considering connectivity in catchment scale allocation of erosion and connectivity measures to field parcels.

The simulated erosion measures included no till (winter-time stubble) and riparian buffer strips (30 m wide) in spring cereal cultivation, and the simulations were performed at the riparian field parcels of the Aura and Mustio River sub-catchments in Southwestern Finland (Table 5 and Figure 17; hereafter catchments). Both are the lowest catchments of coastal river catchments draining to the Baltic Sea with less than 80 km distance between them. The two catchments were selected as case study areas as they both are intensive agricultural areas, with nationally high erosion rates, and they represent topographically different agricultural environments, while having similar climatic conditions. The simulation focused only on riparian field parcels (≤ 10 m from surface water bodies).

The work presented here is based on a scientific article, which was under peer-review during the writing of this report (Räsänen et al., under review).

Table 5. Characteristics of the Aura and Mustio River catchments and their riparian field parcels.

	Aura River catchment	Mustio River catchment
Catchment area [km^2]	146.6	116.2
Average annual precipitation [mm]	690	710
Field area of catchment [%]	34	30
Topography at field parcels	Generally flat, with steep slopes near rivers and streams	Gently undulating
Dominating soil types at field parcels	Vertic Luvic Stagnosols (clay soil)	Vertic Luvic Stagnosols (clay soil), Stagnic Regosols (siltic and loamic soils)
Number of field parcels	514	232
Average size of field parcels [ha]	4.6	6.3
Average field parcel slope [°]	2.3	2.7

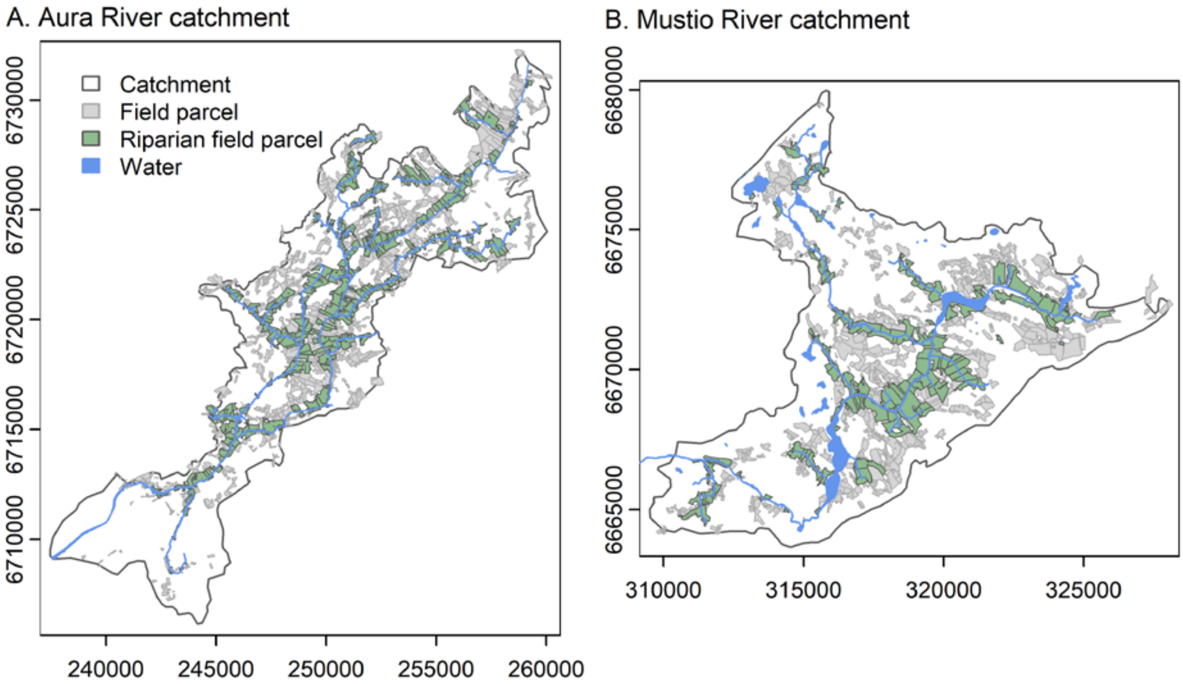

Figure 17. A) Aura and B) Mustio River catchments and their riparian field parcels.

4.2.2. Data and methods

4.2.2.1. RUSLE, Index of Connectivity, and Sediment Delivery Ratio (RUSLE/IC/SDR)

The spatially distributed RUSLE (Renard et al. 1997) has been combined with IC (Borselli et al., 2008) and SDR (e.g., Hamel et al. 2017) computations to include sediment transport and delivery via surface runoff. The approach is mostly used at catchment scale, but its use at field parcel scale has also been explored (e.g., Borselli et al., 2008; Hamel et al., 2017; Tähtikarhu et al. 2022). A benefit of the approach is that it can be implemented together with RUSLE with low amount of additional data.

The IC is computed based on landscape structural elements (elevation and roughness) as follows:

$$IC = \log_{10}\left(\frac{D_{up}}{D_{down}}\right),$$

where D_{up} [-]and D_{down} [-] are the upslope and downslope factors, respectively. D_{up} is calculated as:

$$D_{up} = WS\sqrt{A}$$

where W [-] is the mean weighing factor of the upslope area, S [m m^{-1}] is the mean terrain slope (upslope area) and A [m^2] is the upslope area. D_{down} is calculated as:

$$D_{down} = \sum_{i=1}^{n} \frac{d_i}{W_i S_i}$$

where d_i [m] is the length of i^{th} pixel, W [-] is the weighing factor and S_i [m m^{-1}] is the slope of i^{th} pixel along the downslope flow path. W describes the effects of land use and vegetation (due to roughness) on the IC. High and low IC values describe areas high and low degree of connectivity, respectively.

Sediment delivery rate (SDR) from a pixel to a chosen location is described with a sigmoid-type function (e.g., Hamel et al., 2017):

$$SDR_i = SDR_{max}(1 + \exp\left(\frac{IC_0 - IC_i}{K_{IC}}\right))^{-1}$$

where SDR_{max} [-] is the maximum SDR (ranging from 0.0 to 1.0), IC_i [-] is the IC value of the i^{th} pixel, IC_0 [-] and K_{IC} [-] are empirical parameters. SDR described the share of eroded sediment that is transported from a pixel to a defined downstream location.

Sediment delivery from spatially distributed RUSLE is thereafter computed as:

$$Q_i = E_i SDR_i$$

where Q_i [t ha^{-1} yr^{-1}] is the sediment delivery, E_i [t ha^{-1} yr^{-1}] is the RUSLE erosion in the i^{th} grid cell, as described in the previous section.

5.2.2.2. Simulations

The simulation methodology consists of six parts. First the erosion measures were defined for the riparian field parcels. Second, erosion rates of the field parcels under erosion measures were estimated with RUSLE. Third, the sediment delivery rates under erosion measures, as well as the sediment delivery reduction rates by the erosion measures were estimated with RUSLE/IC/SDR. Fourth, erosion measures were allocated on catchment scale to the riparian field parcels using RUSLE and RUSLE/IC/SDR approaches. Fifth, the catchment scale total sediment delivery reductions resulting from the allocated erosion measures by the two approaches were compared. Sixth, RUSLE/IC/SDR were further evaluated at two case study field parcels with implementation of erosion measures. These parts are explained in detail in the following sections and are summarised in Table 6.

Table 6. Summary of the methodology for evaluating the implementation of erosion measures and connectivity elements in RUSLE/IC/SDR and its benefits in catchment scale allocation of these measures and elements compared to RUSLE.

Methodological parts	Description
1. Erosion measures	Erosion measures for spring cereal cultivation: • No measure: Conventional autumn moldboard ploughing (plough depth 20-30 cm) • No till: Seed drill and zero till (winter-time stubble cover) • Buffer strip: 30 m wide riparian grass buffer strips
2. Estimation of erosion at field parcels	Erosion by RUSLE with: • No measure • No till • Buffer strip
3. Estimation of sediment delivery from field parcels and its reduction by erosion measures	Sediment delivery by RUSLE/IC/SDR with: • No measure • No till • Buffer strip Sediment delivery reduction by erosion measures: • Sediment delivery with no till - (minus) sediment delivery with no measure • Sediment delivery with buffer strip - (minus) sediment delivery with no measure
4. Catchment scale allocation of erosion measures to field parcels	Allocation of erosion measures: • RUSLE approach: to highest ranking field parcels by erosion rate with no erosion measures • RUSLE/IC/SDR approach: to highest ranking field parcels by sediment delivery reduction by erosion measure Allocations were based on two field parcel ranking units, four erosion measure allocation rates, and three IC/SDR parameterisations: • Ranking units: kg ha^{-1} yr^{-1} and kg yr^{-1} • Allocation rates: 20 %, 40 %, 60 % and 80 % of field parcel/potential buffer strip area • IC/SDR parameterisations: P1, P2, and P3
5. Evaluation of erosion measure allocation approaches	The RUSLE and RUSLE/IC/SDR approaches were evaluated by comparing the catchment scale total sediment delivery reductions resulting from the two allocation approaches with two ranking units, four erosion measure implementation rates, and three IC/SDR parameterisations.
6. Evaluation erosion measures at case study field parcels	The effectiveness of erosion measures was further evaluated at two case study field parcels with implementation of no-till, buffer strip, and extended buffer strip.

Erosion measures

The erosion measures were considered only for the riparian field parcels, that were defined as being, or partially being, within 10 m distance from surface water bodies, such as perennial streams, rivers, and lakes, which is the distance used in the Finnish regulations for implementing riparian buffer strips. The simulated erosion measures included no till and riparian grass buffer strips in spring cereal cultivation. No till corresponded to use of seed drill and zero tillage and winter-time stubble cover. Riparian grass buffer strips corresponded to 30 m wide grass buffers strips that are moved every autumn. No erosion measures, in turn, corresponded to conventional autumn moldboard till with tillage depth of 20-30 cm.

Estimation of erosion at field parcels

The erosion at each field parcel was estimated with RUSLE at 2 m × 2 m resolution for spring cereals with autumn moldboard till, no till, and riparian grass buffer strip. The erosion was calculated as average for each field parcel in kg ha^{-1} yr^{-1} and kg yr^{-1}. The latter was calculated by multiplying the kg ha^{-1} yr^{-1} rate by the surface area of the respective field parcel.

For RUSLE, the R, K and LS were taken from Räsänen et al. (2023). The R is from a 1 km resolution gridded European scale dataset, where R for Finland was calculated from hourly precipitation data measured at 64 stations during the years 2007–2013 (Panagos et al., 2015). The R-values for Aura and Mustio River catchments are 360 and 314 MJ mm ha^{-1} h^{-1} yr^{-1}, respectively.

The K factor is based on the Finnish Soil Database (Lilja et al., 2017a) that was supplemented with soil specific K values (Lilja et al., 2017b, 2017c). The soil database contains a vector map (1:200.000) describing the Finnish soils according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022) with the smallest spatial feature of 6.25 ha. Aura and Mustio River catchments the dominating soil types Vertic Luvic Stagnosol (clay soil) and Stagnic Regosol (siltic and loamic soils) were given values of 0.040 and 0.057 t ha h ha^{-1} MJ^{-1} mm^{-1}, respectively.

The LS is based on two-meter resolution digital elevation model derived from LiDAR measurements (National Land Survey of Finland, 2020), and it was calculated for the field areas using Desmet and Govers (1996) method (rill/inter-rill erosivity ratio = 1) and multiple flow direction algorithm (Quinn et al., 1991). The average LS values for the fields of Aura and Mustio River catchments are 0.470 and 0.830, respectively.

The C factor values used for RUSLE were also taken from Räsänen et al. (2023). For no measure a C value of 0.211 was used, for no till a C value of 0.075 was used, and for grass buffer strip a C value of 0.065 was used. These values are based on calibrations against erosion measurement data from seven experimental fields in Finland with 20 different crop and management cases (Räsänen et al. 2023). The R^2 of calibration was 0.76. The P factor was not considered.

The resulting RUSLE data for the field parcels of Aura and Mustio River catchments were raster data with two-meter resolution, and they are summarized in Table 7. The RUSLE computations in this paper were done using R (R Core Team, 2022) and terra package (Hijmans et al., 2021).

The RUSLE prediction uncertainty was evaluated earlier in Finland against measurements at seven experimental fields by Räsänen et al., (2023). The 90 % prediction error interval was -711 and 218 kg ha^{-1} yr^{-1} with underestimation at heavy clay fields. The evaluation is limited by low number of experimental fields and short measurement periods.

Table 7. Summary of the data used for RUSLE.

RUSLE factor	Description	Source
R	European gridded 1 km dataset. For Finland, data from 64 stations with hourly precipitation data from 2007–2013.	Panagos et al. (2015)
K	Finnish Soil database with soil map (1:200 000) supplemented with K values.	Lilja et al. (2017a, 2017b, 2017c)
LS	Calculated from two-meter resolution LiDAR elevation model using Desmeth and Govers (1996) method	Räsänen et al. (2023)
C	C factor values for spring cereals with moldboard autumn ploughing, spring cereals with no till, and perennial grass estimated from data from seven experimental fields in Finland	Räsänen et al. (2023)
P	Not used	-

Estimation of sediment delivery from field parcels

The sediment delivery from each field parcel was estimated with RUSLE/IC/SDR at 2 m × 2 m resolution for no measure, no till, and riparian grass buffer strip. The sediment delivery rate was calculated both in kg ha^{-1} yr^{-1} and kg yr^{-1}, similarly to erosion. The sediment delivery reduction by no-till was calculated as the sediment delivery difference between no till and no measure. Likewise, the sediment delivery reduction by buffer strip was calculated as the sediment delivery difference between no measure and buffer strip.

The IC/SDR were setup following Tähtikarhu et al. (2022), who explored the RUSLE/IC/SDR approach at the same catchments as in this study. IC_i, SDR_i and Q_i were computed within each field parcel. The downslope flow path was described as the distance from a pixel to the ditches or surface water bodies surrounding the field parcel. Similarly, SDR_i and Q_i described the share and amount of sediment delivered from a pixel to the ditches or surface water bodies, respectively.

The IC_i computations were done using the same two-meter resolution digital elevation model (National Land Survey of Finland, 2020) as for the LS factor of RUSLE. The elevation model was treated for artificial sinks to prevent the artificial discontinuity of flow paths by filling sinks up to 0.15 m, which was found to be a realistic fill level at the study areas (Tähtikarhu et al., 2022). Fields have also natural depressions and filling of sinks fully would remove these discontinuity features.

W_i was parameterized based on the C values of RUSLE, as suggested by Borselli et al. (2008). For no measure, the W_i value of 0.211 was used, for no till a W_i value of 0.075 was used, and for grass buffer strip areas a W_i value of 0.065 was used, following the C values used for RUSLE and estimated by Räsänen et al. (2023).

The uncertainty in SDR_i were explored with sensitivity analysis by applying three parameterisations P1, P2 and P3 for IC_0 and K_{IC} based on earlier work by Tähtikarhu et al. (2022) in the same catchments as in this study. The true IC_0 and K_{IC} parameter values have not been evaluated for Finnish agricultural conditions and the used parametrisation range is intended to reflect general the sediment transport levels via surface runoff that has been observed at experimental fields. The parameterisation of SDR is known to affect the absolute SDR values but less the relative comparison of SDR values between areas and field parcels (Hamel et al., 2015; Tähtikarhu et al., 2022). The used parameterizations P1, P2 and P3 are shown in Table 2.

The Q_i was the estimated using the erosion estimate from RUSLE as E_i. The sediment delivery from each field parcel was calculated as the sum of Q_i for every pixel within a field parcel.

The IC/SDR parametrisation is summarised in Table 8 and the computations were done using the standard tools of ArcMap 10.6.1 (ESRI, 2019).

Table 8. Parametrisation of IC/SDR.

Parameter	Description	Source
W	No measure: 0.211 No till: 0.075 Grass buffer strip: 0.065	Räsänen et al. (2023) following Borselli et al. (2008)
SDR_{max}	1	Tähtikarhu et al. (2022)
IC_0	P1: 0.5 P2: 0.5 P3: -3.3	Tähtikarhu et al. (2022)
K_{IC}	P1: 2.0 P2: 3.5 P3: 1.0	Tähtikarhu et al. (2022)

Catchment scale allocation of erosion measures to field parcels

The erosion measures were allocated at catchment scale to field parcels with two allocation approaches, two erosion and sediment delivery ranking units, and four erosion measure allocation rates (Table 9). The first approach was based on A. allocation of measures to highest ranking field parcels by erosion rate under no measure estimated with RUSLE. The second approach was based on B. allocation of measures to highest ranking field parcels by highest sediment delivery reduction by the erosion measures of no till and buffer strip estimated with RUSLE/IC/SD. The ranking of field parcels was made using field parcel specific erosion and sediment delivery allocation units of kg ha^{-1} yr^{-1} and kg yr^{-1}. The allocation rate of no till was 20, 40, 60 and 80% of riparian field parcel area, and for buffer strip the rate was 20, 40 60 and 80% of potential buffer strip area of the riparian field parcels. Potential buffer strip area refers to 30 m wide strip at the riparian side of the field parcels.

Table 9. Catchment scale total sediment delivery reduction estimates A1-A24 and B1-B24 with different erosion measure allocation approaches, ranking units, erosion measure allocation rates and IC/SDR parametrisations for each erosion measure.

Allocation approach	Ranking unit for ranking field parcels	Allocation rate for allocating erosion measures	Parameterisation of IC/SDR	Catchment scale total sediment delivery reduction by RUSLE/IC/SDR
A. RUSLE (Erosion under no-measures)	kg ha^{-1} yr^{-1}	20%	P1	A1
			P2	A2
			P3	A3
		40 %	P1	A4
			P2	A5
			P3	A6
		60 %	P1	A7
			P2	A8
			P3	A9
		80%	P1	A10
			P2	A11
			P3	A12
	kg yr^{-1}	20%	P1	A13
			P2	A14
			P3	A15
		40 %	P1	A16
			P2	A17
			P3	A18
		60 %	P1	A19
			P2	A20
			P3	A21
		80%	P1	A22
			P2	A23
			P3	A24
B. RUSLE/IC/SDR (Sediment delivery reduction by no-till and buffer strip)	kg ha^{-1} yr^{-1}	20%	P1	B1
			P2	B2
			P3	B3
		40 %	P1	B4
			P2	B5
			P3	B6
		60 %	P1	B7
			P2	B8
			P3	B9
		80%	P1	B10
			P2	B11
			P3	B12
	kg yr^{-1}	20%	P1	B13
			P1	B14
			P2	B15
		40 %	P1	B16
			P2	B17
			P3	B18
		60 %	P1	B19
			P2	B20
			P3	B21
		80%	P1	B22
			P2	B23
			P3	B24

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 862695

Evaluation of erosion measure allocation approaches

After the allocation of erosion measures to field parcels by RUSLE and RUSLE/IC/SD, the catchment scale total sediment delivery reductions resulting from the allocations were estimated using RUSLE/IC/SD for both erosion measures at both catchments. This included the estimates of total sediment delivery reductions with ranking units of kg ha^{-1} yr^{-1} and kg yr^{-1}; allocation rates 20, 40, 60 and 80 %; and the parameterisations P1, P2 and P3. This resulted in of 24 total sediment delivery reductions estimates for both allocation approaches (A1-A24 and B1-B24) that were compared to determine whether the RUSLE/IC/SD allocation approach results in greater total sediment delivery reductions (Table 6).

Evaluation of erosion measures at case study field parcels

The implementation erosion measures in RUSLE/IC/SDR and their effectiveness were further evaluated at two case study field parcels. The parcels were selected so that they have high erosion rates, and the standard location of the buffer strips does not result in ideal sediment delivery reduction due to large share of sediment flows bypassing the buffer strip. In addition to the no till and buffer strip, an extended buffer strip (30 m wide) was considered to capture the major sediment flows from the fields.

4.2.3. Results

4.2.3.1. Erosion and drainage

At the riparian field parcels of the Aura River catchment the erosion rate is on average 25% higher than at Mustio River catchment (Table 10). The high erosion areas are also distributed differently between the catchments. At Aura River catchment, high erosion areas are concentrated near rivers and streams, whereas at Mustio River catchment high erosion areas are more scattered in the landscape and often further away from rivers, streams, and lakes (Figure 18). The average erosion rate at the riparian buffer strip areas of Aura River catchment is, in turn, 155% higher than at Mustio River catchment (Figure 18, Table 10). The total area draining over the potential buffer strip areas is on average 63 % and 69% of the field area at Aura and Mustio River catchments, respectively, but these rates vary considerably between field parcels (Table 10).

Table 10. Characteristics of the riparian field parcels at Aura and Mustio River sub-catchments. Erosion rates are reported for spring cereals with conventional autumn till. Values in brackets are 25. And 75. percentiles.

	Aura River sub-catchment	Mustio River sub-catchment
Field parcel slope [˚]	2.3 (0.9-2.9)	2.7 (1.5-3.8)
Buffer strip slope [˚]	3.6 (1.2-5.1)	2.3 (1.0-2.9)
Field parcel erosion [kg ha^{-1} yr^{-1}]	1,939 (649-2,586)	1,762 (783-2,176)
Buffer strip erosion [kg ha^{-1} yr^{-1}]	3,774 (924-5,572)	1,715 (547-1,894)
Field parcel area draining over buffer strip areas [%]	63 (53-89)	69 (49-91)

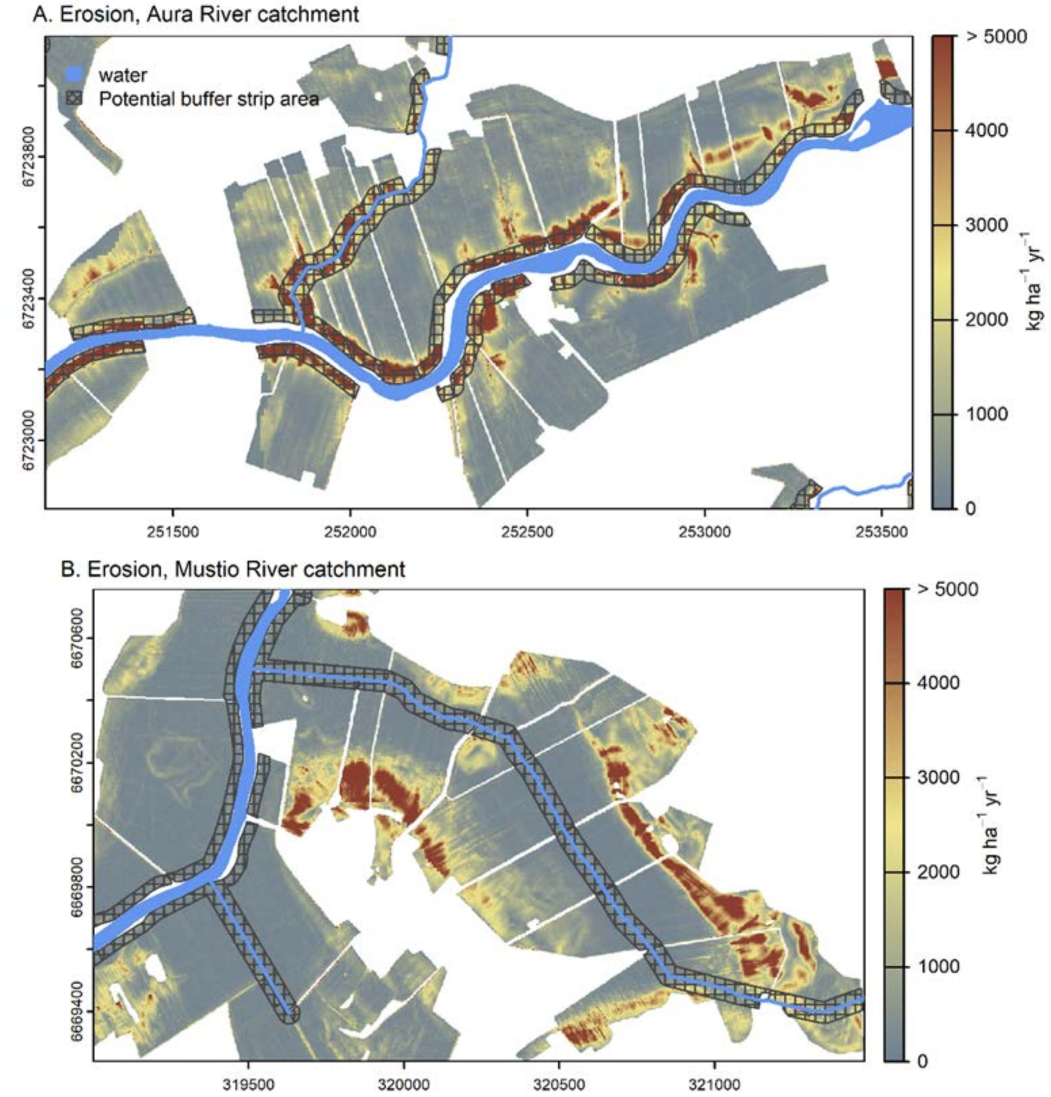

Figure 18. Estimated erosion (kg ha^{-1} yr^{-1}) at the riparian field parcels of A) Aura and B) Mustio River catchments. For erosion estimate, all fields are assumed to have the same crop and management (no measure).

4.2.3.2. Sediment delivery reduction by no-till and riparian buffer strips

At field parcel scale, the assessment with RUSLE/IC/SDR and parameterisation P1-P3 suggest that no till has similar effect on sediment delivery at both catchments, and buffer strips reduce sediment delivery more efficiently at Aura than at Mustio River catchment (Table 11). No till was found to reduce sediment delivery of individual field parcels on average by 71-83 % (P1-P3) at both catchments, and the differences between individual field parcels in the reduction percentage were small (≤ 2 %). The sediment delivery reduction by the buffer strips, in turn, varied more by the catchments and field parcels (Table 11). At Aura River catchment, the riparian buffer strips reduced sediment delivery at individual field parcels on average by 39-55 % (P1-P3), with a quarter of the parcels having lower reduction than 22-40 % (P1-P3). At Mustio River catchment, the reduction at individual field parcels was on average by 23-34 % (P1-P3), with a quarter of the parcel having lower reduction than 7-13 % (P1-P3). The parameterisation P3 resulted in the largest and the parameterisation P2 in the lowest sediment delivery reductions.

On catchment scale, the same allocation rates of erosion measures resulted in larger total sediment delivery reduction at Aura than at Mustio River catchments, similarly as on field parcel scale. For example, no till with 40 % allocation rate reduced the total sediment delivery at Aura River catchment by 52-73%, and at Mustio river catchment by 38-68%. Similarly, riparian buffer strips with 40 %

allocation rate reduce the total sediment delivery at Aura River catchment by 33-53%, and at Mustio river catchment by 10-27%.

The erosion measures were found to have greatest impact on total sediment delivery in the catchments at lower allocation rates and their effectiveness was reduced towards higher allocation rates. For example, in the case of no-till, the increase of allocation rate from 60 % to 80 % resulted only in additional total sediment delivery reduction of 1-6% at Aura River catchment and 4-15 % at Mustio River catchment. In the case of buffer strips, the increase of allocation rate from 60 % to 80% resulted only in additional total sediment delivery reduction of 1-3 percentage points (pp) at Aura River catchment and 1-4 pp at Mustio River catchment.

Table 11. Catchment scale total sediment delivery reduction by erosion measures according to the RUSLE and RUSLE/IC/SDR allocation approaches, two ranking units, four allocation rates and three parameterisations at the riparian field parcels of Aura and Mustio River sub-catchments.

		Aura River catchment								**Mustio River catchment**							
Ranking unit		kg ha^{-1} yr^{-1}				kg yr^{-1}				kg ha^{-1} yr^{-1}				kg yr^{-1}			
Allocation rate [%]		20	40	60	80	20	40	60	80	20	40	60	80	20	40	60	80
Erosion measure: No till																	
A. RUSLE: Total sediment delivery reduction (A1-A24) [%]	P_1	-47	-66	-73	-75	-36	-58	-67	-72	-41	-57	-68	-74	-23	-42	-55	-68
	P_2	-41	-59	-66	-69	-32	-52	-61	-67	-34	-50	-61	-68	-21	-38	-51	-63
	P_3	-53	-73	-79	-81	-40	-64	-73	-78	-50	-66	-76	-81	-25	-46	-59	-74
B. RUSLE/IC/SDR: Total sediment delivery reduction (B1-B24) [%]	P_1	-47	-66	-73	-75	-37	-62	-72	-74	-42	-58	-68	-74	-32	-47	-61	-72
	P_2	-41	-58	-66	-69	-32	-54	-63	-68	-35	-50	-61	-68	-23	-40	-54	-65
	P_3	-54	-73	-80	-81	-44	-69	-79	-80	-51	-68	-76	-81	-40	-60	-71	-80
Difference in sediment delivery reduction [pp]	P_1	0	0	0	0	-1	-4	-4	-2	-2	0	0	0	-9	-5	-7	-4
	P_2	0	1	0	0	0	-2	-2	-1	-1	0	0	0	-3	-2	-3	-2
	P_3	-1	0	0	0	-4	-5	-6	-2	-2	-1	-1	0	-15	-14	-12	-6
Erosion measure: Buffer strip																	
A. RUSLE: Total sediment delivery reduction (A1-A24) [%]	P_1	-27	-43	-49	-50	-27	-42	-47	-50	-14	-18	-22	-23	-8	-15	-19	-22
	P_2	-21	-34	-39	-40	-21	-33	-37	-40	-9	-13	-15	-16	-5	-10	-13	-16
	P_3	-33	-53	-59	-60	-33	-51	-56	-60	-20	-26	-30	-32	-11	-21	-26	-31
B. RUSLE/IC/SDR: Total sediment delivery reduction (B1-B24) [%]	P_1	-29	-43	-49	-50	-30	-44	-49	-50	-14	-19	-22	-23	-14	-19	-22	-23
	P_2	-22	-33	-39	-40	-23	-34	-39	-40	-9	-13	-15	-16	-10	-13	-15	-16
	P_3	-35	-52	-60	-61	-37	-53	-60	-60	-20	-27	-31	-32	-21	-27	-31	-32
Difference in sediment delivery reduction [pp]	P_1	-2	0	0	0	-3	-2	-3	-1	0	-1	0	0	-7	-5	-3	-1
	P_2	-1	1	0	0	-2	-1	-2	-1	0	0	0	0	-5	-3	-2	-1
	P_3	-2	1	0	0	-4	-2	-3	-1	0	-1	-1	0	-10	-7	-4	-2

5.2.3.3. Evaluation of erosion measure allocation approaches

The simulations show that the allocation of erosion measures with RUSLE/IC/SDR approach resulted in from zero to modest improvements compared to RUSLE, in terms of total sediment delivery reduction in the catchments (Table 11). In the case of no till, allocation with RUSLE+IC+SDR approach resulted at Aura River sub-catchment in 0-6 pp and at Mustio river sub-catchment in 0-15 pp higher total sediment delivery reduction than allocation with RUSLE approach. In the case of buffer strip allocation with RUSLE/IC/SDR approached resulted at Aura River sub-catchment in 0-4 pp and at Mustio river sub-catchment in 0-10 pp higher total sediment delivery reduction than allocation with RUSLE approach. The level of improvement depended on the used ranking unit, allocation rate, and parameterisation of IC/SDR (Table 11).

The use of ranking unit kg ha^{-1} yr^{-1} resulted generally in larger or similar total sediment delivery reduction in the catchments than the use of unit kg yr-1 (Table 11). In the case of no till, the use of unit kg ha^{-1} yr^{-1} resulted at Aura River catchment in 1-13 percentage points (pp) and at Mustio River catchment 1-25 pp larger total sediment delivery reduction than the use of unit kg yr^{-1}. In the case of buffer strip, the use of unit kg ha^{-1} yr^{-1} resulted at Aura River sub-catchment in similar (-2 - +3 pp) and at Mustio River sub-catchment 0-10 pp larger total sediment delivery reduction than the use of unit kg yr^{-1}. The difference in the sediment delivery reduction between the two ranking units were commonly higher with lower erosion measure allocation rates. The two units also emphasized the size of field parcels differently in the of allocation of erosion measures. The use of unit kg yr^{-1} tends to prioritize larger field parcels with large drainage areas, whereas the use of unit kg ha^{-1} yr^{-1} does not consider the size of field parcel or drainage areas and accounts only for the erosion or sediment delivery rate per surface area.

The improvements of RUSLE/IC/SDR allocation approach compared to RUSLE approach varied also by erosion measure implementation rate (Table 11). The improvements of by RUSLE/IC/SDR approach were commonly higher at lower implementation rates compared to RUSLE approach, but not in all cases.

It was also observed that parameterisations P1-P3 of the IC/SDR had only a small effect on allocation of erosion measures to field parcels. When the field parcels were ranked according to the sediment delivery reduction by the erosion measures estimated with the parameterisations P1-P3 the rankings between the parameterisations were very similar. The Spearman rank correlations between the rankings was 0.97-1.00 ($p<0.000$).

5.2.3.4. Erosion measures at case study field parcels

Both case study field parcels at Aura and Mustio River sub-catchments (Figure 19) are large field parcels, and they have high erosion rates. The Aura parcel is 13.5 ha with erosion rate of 2970 kg ha^{-1} yr^{-1} (no measure), and the Mustio parcel is 16.2 ha with erosion rate of 2108 kg ha^{-1} yr^{-1} (no measure).

The no till measure has similar effect on sediment delivery reduction at both parcels, but the effect of buffer strips is different. In both parcels, no till reduces sediment delivery by 71-82 %, but at Aura parcel the buffer strip reduces sediment delivery by 36-52% and at Mustio parcel 4-6% (Table 12).

The drainage area of buffer strips is larger, and more sediment is transport over the buffer strip area at Aura than at Mustio parcel (Figure 19). At Aura parcel, 53 % of the field area drains and 64-71 % (P1-P3) of the sediments are estimated to flow over the buffer strip area. The parcel has a gully (non-cultivated area, formed over long time) in the centre of the field, with high sediment source areas associated to it, and the sediment flows from these areas flow directly to the gully and not over the buffer strips. The gully then acts as a sediment transport pathway to the mainstream of the Aura River.

Whereas at Mustio parcel, 29 % of the field area drains and only 10-16 % (P1-P3) sediments flow over the buffer strip area (Figure 19). The high sediment source areas are located far away from the buffer strip, and the sediments from these areas flow directly to a ditch and not over the buffer strip. The ditch then acts as a transport pathway to a small tributary of Mustio River.

The implementation of extended buffer strips provides additional sediment delivery reductions (Figure 19). At Aura parcel, the extended buffer strip is located around the gully, and it reduces the sediment delivery by an additional 13-17 pp (Table 12). At Mustio parcel, the extended buffer strip is located next to the ditch draining the high erosion areas and it reduces the sediment delivery by an additional 21-40 pp (Table 12).

Altogether at the Aura parcel, the buffer strip results in 32-46 pp larger sediment delivery reduction than at the Mustio Parcel. In the case of the extended buffer strip, the sediment delivery reduction is still 23-24 pp larger at the Aura than at the Mustio parcel.

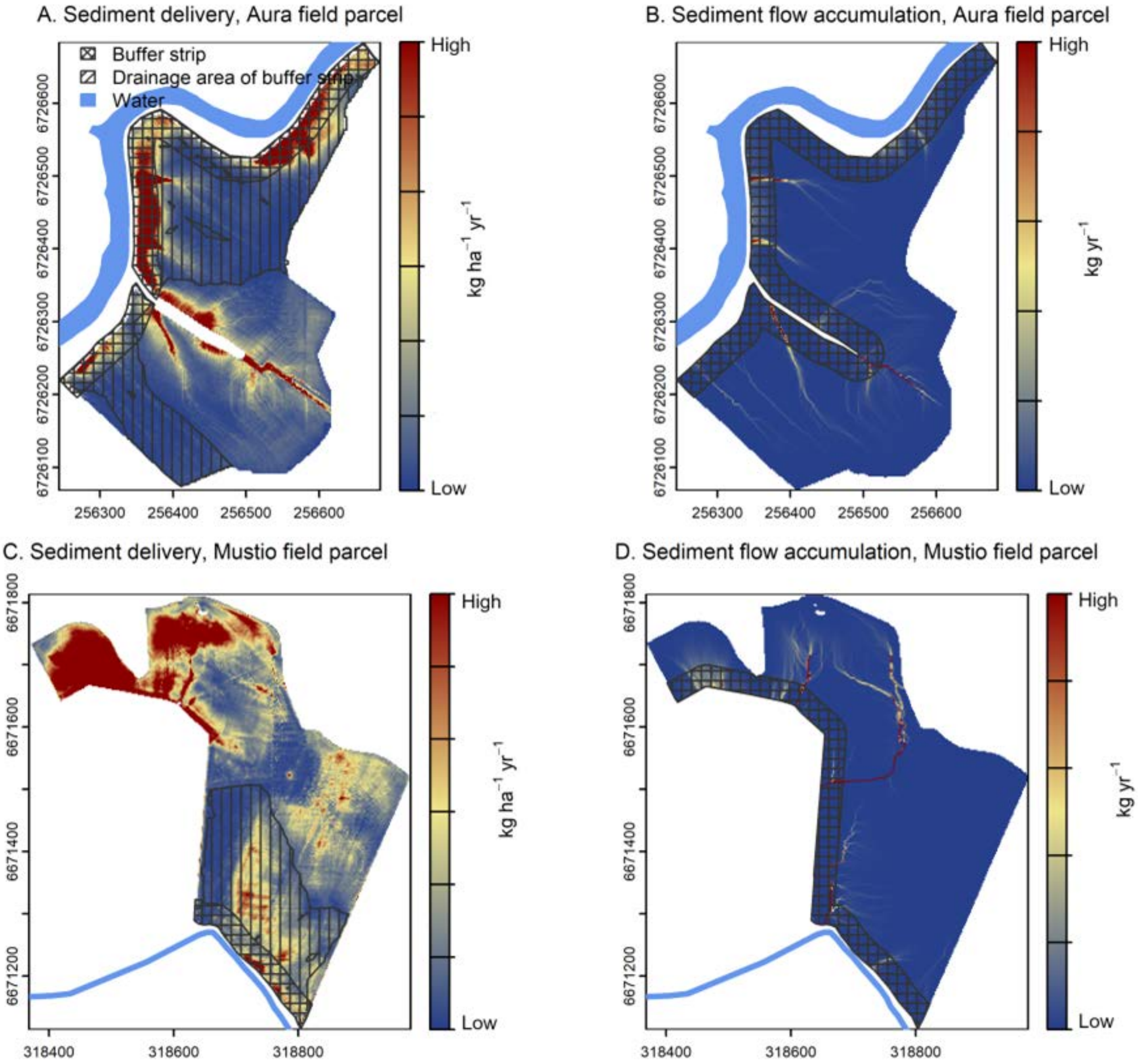

Figure 19. Sediment source areas (A, C) and sediment flow accumulation (B, D) at Aura field parcel (13.5 ha) of the Aura River sub-catchment (A, B) and at the Mustio field parcel (16.2 ha) of the Mustio River sub-catchment (C, D) estimated with RUSLE/IC/SDR. Buffer strip width 30 m. Note that sediments can exit the from any side of the field parcel and the case study parcels are surrounded by open ditches that are connected to perennial streams and rivers.

Table 12. Estimated reduction in erosion and sediment delivery by no till, buffer strip, and extended buffer strip at the Aura field parcel (13.5 ha) of the Aura River catchment and at the Mustio field parcel (16.2 ha) of the Mustio River catchment.

		Aura field parcel Reduction [%]	**Mustio field parcel Reduction [%]**
No till	Erosion reduction	-64 %	-64 %
	Sediment delivery reduction, P1	-77 %	-77 %
	Sediment delivery reduction, P2	-71 %	-71 %
	Sediment delivery reduction, P3	-82 %	-82 %
Buffer strip	Erosion reduction	-32 %	-3 %
	Sediment delivery reduction, P1	-44 %	-6 %
	Sediment delivery reduction, P2	-36 %	-4 %
	Sediment delivery reduction, P3	-52 %	-6 %
Extended buffer strip	Erosion reduction	-41 %	-15 %
	Sediment delivery reduction, P1	-59 %	-36 %
	Sediment delivery reduction, P2	-49 %	-25 %
	Sediment delivery reduction, P3	-69 %	-46 %

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4.2.4. Discussion

4.2.4.1. Implementation, model structure, and parametrisation of IC/SDR

The implementation of IC/SDR as post-processing method for RUSLE had low data input requirements. The main input data was a 2 m × 2 m resolution DEM that was treated for artificial sinks, while trying to maintain real depressions that occur at fields (see e.g., Tähtikarhu et al., 2022). The computation of IC/SDR, in turn, can be easily implemented with standard libraries and algorithms of commonly used software, such as ArcGIS, R or Python, or by using the InVest model (Hamel et al., 2015).

The inclusion of IC/SDR to RUSLE expanded the model structure to account for the sediment delivery from the field parcel and the sediment retention by variable vegetation cover at the field parcel, which the distributed RUSLE alone is not capable of. The RUSLE/IC/SDR thus enables the simulation of the effect of a set of erosion measures that are area-based on the sediment delivery for the field parcels, such riparian buffer strips, grass strips, vegetated water ways, winter-time vegetation cover.

The model structure has also important limitations, particularly, it accounts only for sediment delivery via surface runoff and not via artificial subsurface drainage. The eroded soil particles are known to be transported from the soil surface through cracks and macropores in the soil matrix to the subsurface drainage pipes (Foster et al., 2003; Øygarden et al., 1997, 1997; Turunen et al., 2017), and the observations at the Finnish experimental fields show that 33-98% of the total sediment load from the field can be via sub-surface drainage flow (Finnish Environment Institute, 2019; Kukkonen et al., 2004; Nurminen et al., 2018, 2018; Turtola et al., 2007; Turtola and Kemppainen, 1998; Warsta et al., 2014). Therefore, the simulations presented here apply only for sediment delivery via surface runoff.

The use of parameterisation P1-P3 in the IC/SDR approach revealed that IC_0 and K_{IC} parameterisation affected mainly the absolute magnitudes of the sediment delivery reduction rates but had only a very small effects on the relative differences in sediment delivery reduction rates between field parcels, which is in line with the findings of Hamel et al. (2015) and Tähtikarhu et al. (2022) who explored with broader range of parametrisation than in our study. However, the parameterisation of IC_0 and K_{IC} had a modest effect on the relative sediment delivery reduction rates by the erosion measures, and their appropriate values require further evaluation.

The parameterisation of W with RUSLE C factor values, similarly to Borselli et al. (2008), provided the right direction of sediment delivery changes by the erosion measures, although the accurate parameterisation remained unsolved. In the case of the 30 m wide buffer strips, the simulations resulted in average sediment delivery reduction of 39-55 % and 23-34 % (P1-P3) at Aura and Mustio River sub-catchments, respectively. The measurements at experimental fields in Finland, in turn, showed that 10-12 m wide buffer strips reduce sediment delivery via surface runoff by 53-72% (Puustinen et al., 2005; Uusi-Kämppä and Jauhiainen, 2010). The lower reduction rates in the simulations can be explained, at least partially, by the fact that simulations considered also the sediments exiting the fields from other sides than the buffer strip, which, this may not be considered in the measurements at experimental field plots. In the simulations, the sediment fluxes over the buffer strips were estimated to be on average 81-85 % and 64-66 % (P1-P3) of the total sediment flux from the field parcel at Aura and Mustio River sub-catchments, respectively. Also, reviews suggest that wider (>10 m) buffer strips do not necessarily bring significant additional sediment trapping effect (Liu et al., 2008; Yuan et al., 2009). The parameterisation of buffer strips in W, however, requires further evaluation and the appropriate values are likely to vary by local conditions.

In the case of parameterisation of no till in W, the sediment delivery was reduced on average by 71-83% (P1-P3) at Aura and Mustio river sub-catchments, whereas the observations at three Finnish experimental fields suggest 42-70 % reduction (Honkanen et al., 2021; Kukkonen et al., 2004; Puustinen et al., 2005). The difference between simulations and measurements can originate, at least partially, from the potentially larger sediment trapping effect at the simulated field due to their larger size and more complex topography compared to the experimental field plots. The parameterisation of no till in W requires also further evaluation.

5.2.4.2. Allocation and planning of erosion measures

The catchment scale allocation of erosion measures with RUSLE/IC/SDR brought only small to modest benefits compared to allocation with RUSLE, in terms of total sediment delivery reduction in the catchments. The benefits were larger when allocation was done using the unit of kg yr^{-1} for ranking the field parcels compared to the unit of kg ha^{-1} yr^{-1}, but the use of unit of kg ha yr^{-1} resulted generally in larger or similar total reductions in total sediment delivery. The use of the unit of kg ha yr-1 also did not discern with the size of the field parcels in allocation, but the use of the unit of kg yr-1 tended to allocate measures to larger and smaller number of field parcels.

The small benefits of RUSLE/IC/SDR imply that the magnitude of erosion at the field parcels of the case study areas is a strong predictor of the effectiveness of erosion measures and the sediment transport process, and that the pathways have a lesser role in these predictions. The sediment transport process and pathways had, however, a slightly more significance at Mustio River sub-catchment, where the high erosion areas are located further away from surface waters and the sediments travel longer distances. Altogether, it appears that at the case study areas the magnitude of erosion is a more important predictor of the effectiveness of erosion measures than the connectivity characteristics of the field parcels. This is likely related to relatively small size of field parcels and their isolation from each other with open ditches, and to relatively similar sediment flow pathways and connectivity characteristics of the riparian field parcels. The findings of RUSLE/IC/SDR benefits compared to RUSLE in allocation of erosion measures may not, however, apply to different agricultural settings, for example with more varying topography, and larger and more connected field parcels.

The RUSLE/IC/SDR approach revealed also new information on the effectiveness of the erosion measures with different implementation rates between the two case study catchments with differing topographical conditions. For example, the sediment fluxes over the buffer strip were on average 1.28 times higher and the buffer strips were on average 2.2 times more effective with the same implementation rates at Aura than at Mustio River catchment. Also, the implementation of erosion measures beyond the 60% rate did not result in considerable additional reduction in total sediment delivery.

At field parcel scale, the RUSLE/IC/SDR approach improves the understanding of the sediment transport within the field parcels, and consequently advances the opportunities for erosion management compared to RUSLE. The RUSLE/IC/SDR approach enabled the estimation of location and magnitude of sediment fluxes within the field parcels and, thus, the planning of local and more effective buffer strip configurations. The simulations at the two case study field parcels showed that configuration of the buffer strips according to the sediment transport pathways and magnitudes considerably reduced the sediment delivery from the field parcels.

4.3. WATEM/SEDEM

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4.3.1. Introduction

In Flanders, the WaTEM/SEDEM model is applied on the full territory (Deproost et al. 2018; Renders et al., 2021) and made available online (dov.vlaanderen.be). This is however a robust calculation based on official data sets and aims to give the expected mean annual net erosion/deposition, sediment transport and sediment delivery to the water system for the calculated year and its distribution in Flanders. Due to the static character of the broad scope data sets for official modelling, the use of the model in landscape planning is often not considered. In order to cater to the needs of local agencies active in landscape planning, it is, however, necessary to run the model on smaller scale (catchment scale) using more detailed information and incorporate future landscape management plans and erosion control measures to estimate the impact of certain management scenarios.

This small-scale modelling approach was executed in two catchments in the south of Flanders: Maarkebeek and Menebeek catchment. The Maarkebeek catchment is located in the southern part of the province East Flanders between 50°49'54.072" N, 3°35'19.465" E and 50°45'45.915" N, 3°43'4.483" E. This catchment is about 4 900 ha, of which 43% is agricultural land, and stretches over hilly terrain with altitudes between 10 and 160 m a.s.l.. The Maarkebeek catchment is one of the most erosion prone catchments in Flanders, due to its hilly topography and location on the Flemish Loess Belt, characterised by very erodible soil types, in combination with great agricultural pressure. The average erosion rate of the catchment is 9 t/ha/yr. The Menebeek catchment is located in the southern part of the province Flemish Brabant between 50°49'48.814" N, 4°47'46.831" E and 50°46'33.52" N, 4°55'49.386" E. In this catchment, measuring 3 000 ha, of which 57% is used for agriculture, the topography consists of steep hills with altitudes stretching from 40 to 110 m a.s.l.. Similar to the Maarkebeek catchment, the Menebeek catchment resides as well in the Flemish Loess Belt and combines as well a hilly topography with agricultural pressure, leading to average erosion rates of 7 t/ha/yr, making it one of the most erosion prone catchments of the eastern part of Flemish Brabant.

In both catchments an expert group was contacted with the purpose of gaining more insight on local erosion problems, soil management plans, modelling needs and model evaluation. The purpose of these case studies is mainly to investigate how modelling at local scale can be beneficial for local users and how different scenarios can be implemented into the WaTEM/SEDEM model. Incidentally, it is possible to see the impact of different reality-based scenarios and to compare and combine these different scenarios as guidelines for erosion management planning. Using Erosion Control Measures (ECMs) ranging from grass buffer strips and dams to land use conversion or even technical erosion mitigation such as Reduced Tillage, different scenarios are modelled to estimate the impact of certain ECMs on the catchment's erosion and sedimentation patterns. The aim of this case-study is to test the possibilities of the WaTEM/SEDEM model for the catchment scale modelling of erosion mitigation plans and receive feedback on the relevance and expectations of further development of the WaTEM/SEDEM model for the use in Flanders.

4.3.2. Data and methods

4.3.2.1. WaTEM/SEDEM

The spatially distributed model, WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002), allows to model erosion and sediment transport to deposition in the landscape. This by calculating a mean annual gross erosion rate (E) and a Transport Capacity (TC) for every pixel in the model domain. The amount of erosion/deposition in every pixel is defined by the relationship between these parameters, by using a routing algorithm to model the sediment transport throughout the model domain. For the relation between E and TC, two cases exist:

$$S_A \leq TC \text{ and } S_A > TC$$

where S_A is Available Sediment in a pixel existing of mean annual gross erosion in the pixel (E) + incoming sediment into the pixel (S_i). In the first case, erosion will occur in the pixel with the rate equal to E. The outgoing sediment (S_o) will in this case be equal to S_A. In the second case, the S_o will equal the TC of the pixel and the net erosion will be lower than E and will equal TC - S_i. If in this case the incoming sediment is higher than the transport capacity, net deposition will occur in the pixel at a rate equal to S_i – TC.

In WaTEM/SEDEM, the annual mean erosion rate is calculated using the RUSLE model (see section IV.1.) and the Transport Capacity is defined by following equation:

$$TC = kTC \cdot R \cdot K \cdot T$$

where kTC is the transport capacity coefficient (in m), R is the rainfall erosivity factor (in $MJ.mm.m^{-2}.h^{-1}.yr^{-1}$), K is the soil erodibility factor (in $kg.h.MJ^{-1}.mm^{-1}$) and T is the topographical factor (dimensionless).

4.3.2.2. Simulations

Data sets

In this case-study, the official data sets of the Flemish Government are used. These data sets are an assembly of public and private data sets that span the whole territory of the Flemish Region. The data sets consist of geographic data files (shapefiles or raster files) which are made available for their use in the sediment modelling for Flanders by the Department of Environment and Spatial Development of the Government of Flanders. These data sets are nevertheless property of external entities such as other departments of the Government of Flanders or other public and private companies.

Study Areas

The study areas for the case-studies were selected based on the severeness of the erosion problems and the willingness to contribute to the study. Both catchments are classified as severely prone to erosion based on the potential erosion risk mapping calculated for Flanders (Oorts et al., 2019), due to the undulating landscapes, high agricultural pressure and fertile yet easily erodible soil types which characterise these catchments.

In the Maarkebeek catchment (Figure 20), the stakeholders that were contacted for this study already had previous notion of the WaTEM/SEDEM model, as some local environmental planning projects have used the results from the model as applied by the Government of Flanders. The Maarkebeek catchment is located in the south of the province East Flanders. This catchment is the biggest of both study areas with a total area of 4 900 ha of which 2 100 ha (43 %) is used for agricultural cultivation.

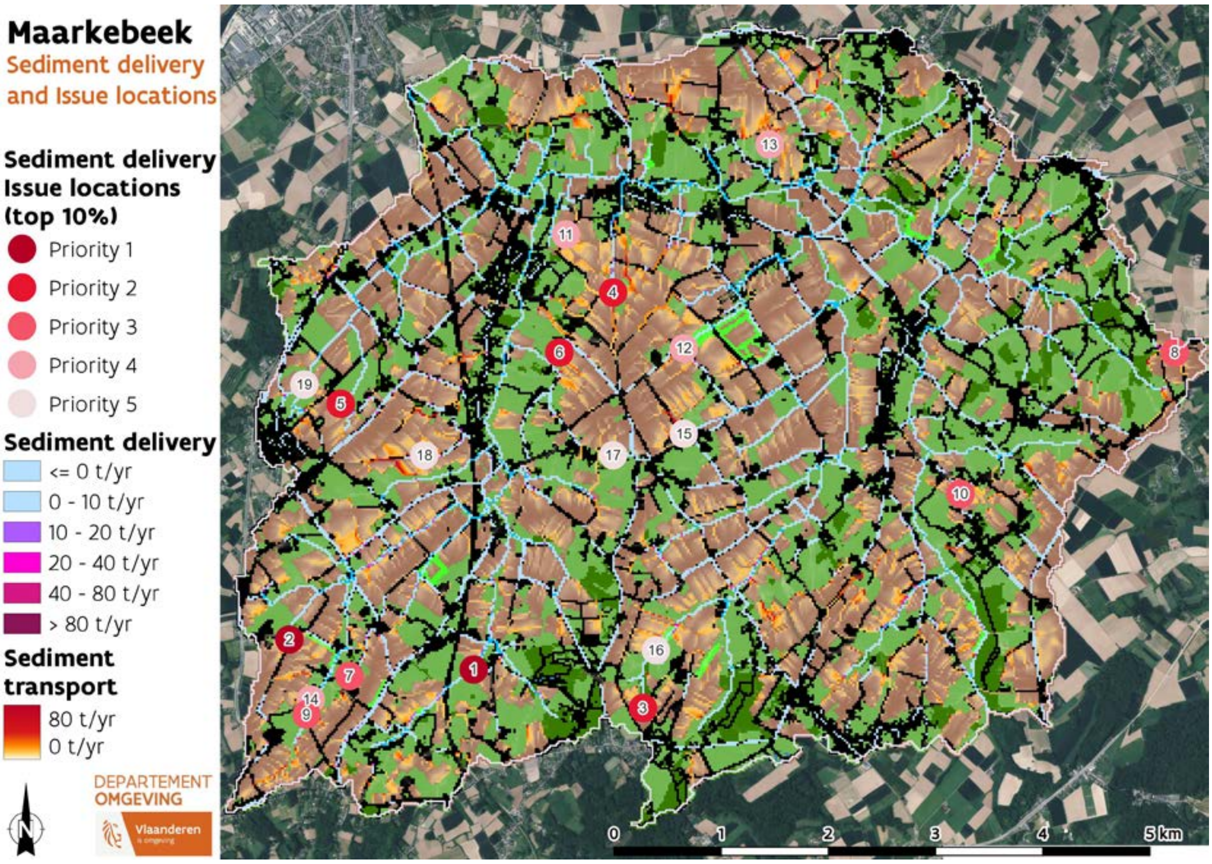

Figure 20. Catchment of the Maarkebeek with indication of sediment delivery and sediment transport on the land use map used for the WaTEM/SEDEM modelling.

The Menebeek catchment (Figure 21), the smaller of both catchments, is located in the southeastern part of Flemish Barbant. It encompasses a total area of 3 000 ha of which 1 700 ha (57 %) is used for agricultural cultivation. Here, the engaging stakeholders were relatively new to the WaTEM/SEDEM model and its application in Flanders.

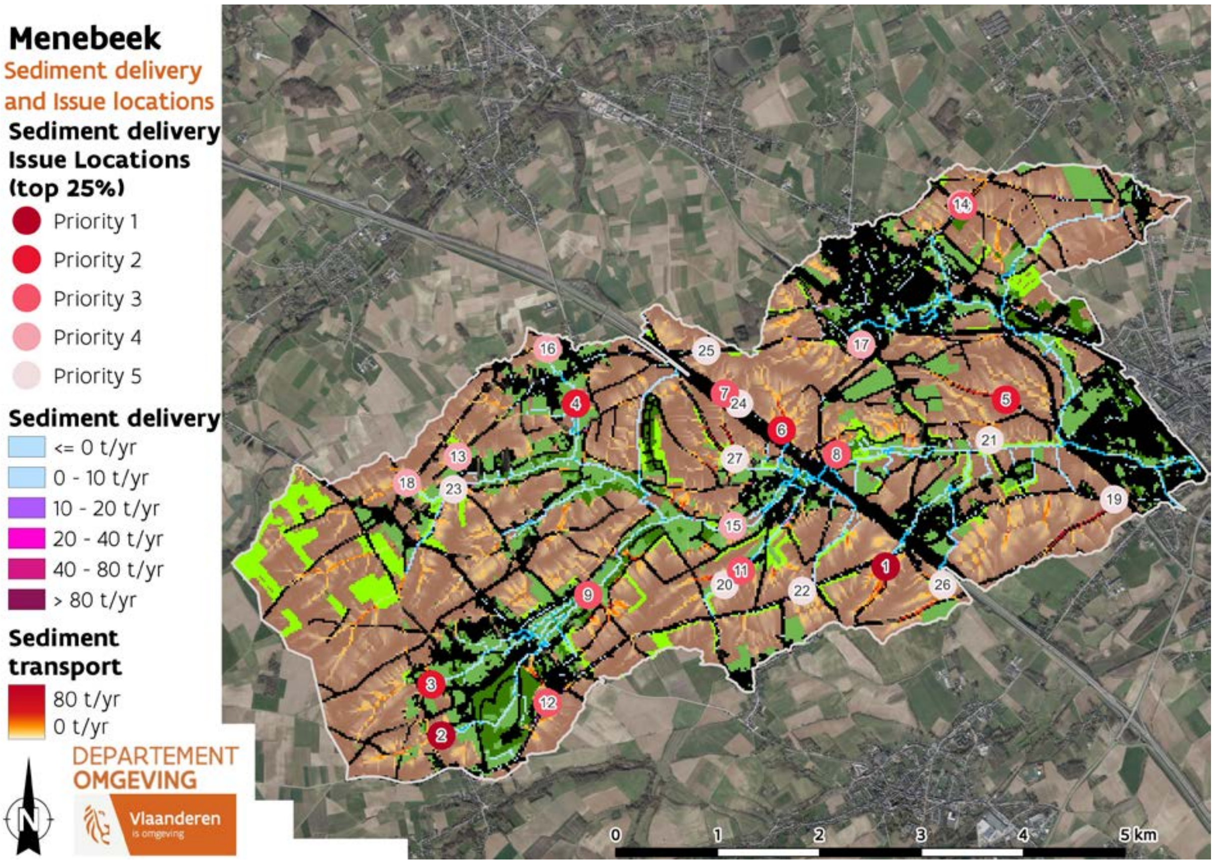

Figure 21. Catchment of the Menebeek with indication of sediment delivery and sediment transport on the land use map used for the WaTEM/SEDEM modelling.

Methods

The application of WaTEM/SEDEM in Flanders has a long history, where, in close collaboration with KU Leuven and consultancy agencies Antea and Fluves, the original WaTEM/SEDEM model (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002) has been adapted to fit the needs of the Government of Flanders for sediment transport modelling. This has led to a revision of the WaTEM/SEDEM model, which is in the process of being released as open-source model on GitHub. For this case-study, the WaTEM/SEDEM model used, and referred to, is this adapted version.

Using the WaTEM/SEDEM model, the impact of different erosion planning scenarios on catchment scale are being evaluated. By comparing different scenarios to a chosen baseline scenario, it is possible to relatively assess the impact of certain policies or planned features, and even gain insights on the particular aspects or spatial patterns that occur under certain scenarios.

In the study two types of scenarios are being considered. Firstly, some general scenarios where created based on insights and interests gathered by the division VPO of the Department of Environment and Spatial Development within the Government of Flanders. These scenarios, further called ‘standardised scenarios’, consist of possible pathways and measures that can be implemented in spatial planning policy and are useful in broad-scale applications. Most of these scenarios or the measures modelled by these scenarios are already being incorporated into the version of the WaTEM/SEDEM used by the Government of Flanders.

Secondly, after gathering insight and additional data from stakeholders, some specific scenarios were created for the studied catchments. These scenarios are tailored to the needs of local stakeholders but are dependent on the availability of geospatial data within the study area. In Table 13, the different standardized scenarios and their implications on the WaTEM/SEDEM model are described, while Table 14 and Table 15 describe the specific scenarios for the Maarkebeek and Menebeek catchments, respectively.

In the scenarios, different types of ECMs are modelled. For most of these ECMs, an interpretation script has been created by VPO in collaboration with FLUVES, to automate the implementation of the ECMs in the WaTEM/SEDEM model. These implementations make sure that the necessary parameters, i.e. C-Factor, Transport Capacity coefficient (kTC) values and the Parcel Trapping Efficiency (PTEF) are manipulated in the correct way to represent these changes. The third column in Table 14, Table 15 and Table 16 indicates which parameters need to change for the respective scenarios. For more technical information about the implementation of ECMs in WaTEM/SEDEM, see Darboux et al. (2023).

Table 13. Scenarios used in the case-study and the implementation/theoretical impact for the WaTEM/SEDEM model

Scenario Name	Description	Implementation/Impact
As-is Scenario	Scenario considering the current land use and all known and in-use erosion control measures (i.e. dams in organic materials, sediment retention ponds and permanent/temporary grass buffer strips). This scenario represents the as-is situation of the catchment.	This scenario is implemented by adding the temporary erosion control measures to the 'Base Scenario'. The temporary grass strips are included in the land-use map for WaTEM/SEDEM and corresponding C-factor and kTC values are calculated based on the width of the buffer strips (Darboux et al., 2023).
Base Scenario	Scenario also considering only fixed erosion control measures (i.e. dams in organic materials, sediment retention ponds and permanent grass buffer strips).	This scenario is implemented by selecting the fixed erosion control measures from the official registered erosion control measures dataset. Dams and sediment retention ponds shapefiles are converted to raster format for 'Buffers' used in WaTEM/SEDEM. The grass buffer strips shapefiles are included in the land use map for WaTEM/SEDEM and corresponding C-factor and kTC values are calculated based on the width of the buffer strips (Darboux et al., 2023).
Null Scenario	Scenario only considering the current land use without any erosion control measures.	This scenario is implemented by converting the current land use map of the catchment to the WaTEM/SEDEM land use format.
Reduced Tillage Scenarios	Scenario considering 'Reduced Tillage' practice on agricultural parcels based on determined 'Erosion Risk Class' of the parcel. The 'Erosion Risk Classes' in Flanders are colour coded going from Purple (Severe) to Red (High) to Orange (Medium) to Yellow (Low) to Light Green (Very low) to Dark Green (Negligible). In this scenario parcels up to an 'Erosion Risk Class' Yellow are considered in different sub-scenarios of which the name indicates the lowest 'Erosion Risk Class' considered.	This scenario is implemented by reducing the C-Factor of the agricultural parcels (arable land), that are affected by this measure, by 80% (Renders et al., 2021).
Riparian Buffer Strip Scenarios	Scenario considering the implementation of grass buffer strips alongside rivers directly bordering agricultural parcels. Different widths are being considered for the buffer strips in the sub-scenarios: 3, 6, 12 and 20m.	This scenario is implemented by creating grass strip polygons along the river shapefile of the catchment and only keeping those intersecting with agricultural parcel polygons (arable land). The width of the grass strips is added as attribute to the polygons shapefile, which can then be converted in the right manner for interpretation in the WaTEM/SEDEM model.
Extra Buffer Strip Scenarios	Scenario considering the implementation of grass buffer strips alongside rivers, ditches and sewers with above ground inlets directly bordering agricultural parcels. Different widths are being considered for the buffer strips in the sub-scenarios: 3, 6, 12, 20m.	This scenario is implemented by creating gras strip polygons along the rivers, ditches and sewer shapefiles of the catchment and only keeping those intersecting with agricultural parcel polygons. The width of the grass strips is added as attribute to the polygons shapefile, which can then be converted in the right manner for interpretation in the WaTEM/SEDEM model.
Grass-on-Slopes Scenarios	Scenario considering the implementation of the conversion of all agricultural land to permanent grassland on locations where the local slope is above a certain threshold. The sub-scenarios consist of three different threshold values: 8, 10, 15%.	This scenario is implemented by calculating the slope based on the DEM (5 x 5 m) of the catchment and vectorizing all cells inside agricultural parcels that have a value above the used threshold. This vector layer is then included into the parcel map while being given the attribute of grassland, which is then converted into the correct format for the land-use map as used by WaTEM/SEDEM.

Table 14. Specific scenarios for Maarkebeek catchment and the implementation/theoretical impact for the WaTEM/SEDEM model

Scenario Name	Description	Implementation/Impact
Municipal Erosion Mitigation Plan (MEMP) Scenario	Scenario considering all planned/desired erosion control measures (i.e. buffers and grass strips) as planned by the municipalities.	This scenario is implemented by converting the erosion control measures as planned by the municipalities into the correct format for use in WaTEM/SEDEM.
Local Environmental Protection Plans (LEPP) Scenario	Scenario considering the erosion control measures (i.e. buffers and grass strips) as designed by two local environmental protection plans (i.e. Landinrichtingsproject (LIP) and Ruimtelijk Uitvoerings- Plan (RUP)).	This scenario is implemented by converting the erosion control measures as planned in the Local Environmental Protection Plans into the correct format for use in WaTEM/SEDEM.
Strategic Grassland Scenario	Scenario considering the removal of all protected strategic grassland in the catchment and conversion into arable land. This scenario reflects the importance of keeping strategic grassland in place.	This scenario is implemented by adding the 'Strategic Grassland' shapefile, as provided by the stakeholders in the agricultural parcel map and adding the attribute of arable land to these polygons, while deleting any overlapping grassland parcels already in the parcel map. This parcel map is then converted into the format used by WaTEM/SEDEM.

Table 15. Specific scenarios for Menebeek catchment and the implementation/theoretical impact for the WaTEM/SEDEM model

Scenario Name	Description	Implementation/Impact
Municipal Erosion Mitigation Plan (MEMP) Scenario	Scenario considering all planned/desired erosion control measures (i.e. buffers and grass strips) as planned by the municipality.	This scenario is implemented by converting the erosion control measure as planned by the municipality into the correct format for use in WaTEM/SEDEM.
Land Consolidation Plan (LCP) Scenario	Scenario considering the land consolidation plans in the catchment. At the moment only the plan for the conversion from arable land to protected grassland is mapped, while the exchange of grassland to arable land is not yet finalised and is not considered in the scenario.	This scenario is implemented by adding the 'Land Consolidation' shapefile as provided by the stakeholders in the agricultural parcel map and adding the attribute for grassland to these polygons, while deleting any overlapping agricultural parcels already in the parcel map. This parcel map is then converted into the format used by WaTEM/SEDEM.
Erosion Control on Public Domain Scenario	Scenario considering the erosion control measures (i.e. grass buffer strips) planned in the public domain of the catchment.	This scenario is implemented by including the planned grass buffer strips shape file, as provided by the stakeholders. These are included in the land use map used in WaTEM/SEDEM and corresponding C-factors and kTC values are calculated based on the width of the buffer strips.

In each of the catchments the standardised scenarios have been modelled using WaTEM/SEDEM, and for each catchment the impact of the respective specific scenarios was calculated. The 'As-Is' scenario of each catchment is used as the baseline scenario for comparing the different scenarios. The different output parameters, that are generated by the model and used in the comparison, are listed in Table 16.

Calculated values have a merely indicative function and are only representative for the current case-study and its specific scenarios, since the values are highly dependent on model choices and settings as well as the used input data sets and model version. Therefore, only the values for the reference scenario are given to get a sense of magnitude, while the parameters of other scenarios are converted into a measure of change between both scenarios, given in percent.

For each scenario the impact on the agricultural area is given as well. For the parameter 'Impact on Agriculture', given in percent, different ways of interpretation should be noted, depending on the effect of the scenario on the agricultural area. On the one hand, if a minus- or plus sign is added to this parameter, the parameter should be interpreted as a reduction or increase, respectively, of agricultural area in the scenario as compared to the reference scenario. On the other hand, if no sign is specified with the parameter value, it should be interpreted as the proportion of agricultural land affected by the implemented measure(s) in the scenario.

Table 16. Used output parameters for the comparison of different scenarios.

Output Parameter	Description
Total Erosion	The total value of the modelled net erosion occurring in all the catchment. It is the total soil loss or the sum of all sediment that is transported over a distance of at least one model pixel (20 m) and does not take into account the transported distance nor the deposition of the sediment. One part of the soil loss is redeposited in the catchment, another part leaves the catchment by the water system or the borders.
Total Deposition*	The total value of the modelled deposition occurring in the catchment. It is the sum of all sediment that is deposited after being transported over a distance of at least one model pixel (20 m). This only takes into account the sedimentation process on land excluding eroded sediment reaching the modelled endpoints (i.e. rivers, ditches and sewers).
Total Sediment Loss	The total value of the sediment lost from the catchment. This value represents all sediment that leaves the catchment by the considered rivers or endpoints (ditches, sewers). These structures are expected to remove the sediment from the catchment landscape. This value is calculated by subtracting the Total Deposition value from the Total Erosion value. This value is not equal to the sum of the Sediment Delivery to River and Ditches/Sewers, due to loss of sediment over the catchment borders caused by conductive elements interfering with the expected routing.
Sediment Delivery to Rivers	The total value of sediment that is eroded and transported until reaching a river. This is perceived as the sediment supply to the catchment's river system and indicates a loss of sediment in the catchment, since it is taken out of the landscape interaction of the catchment modelled by WaTEM/SEDEM.
Sediment Delivery to Ditches/Sewers	The total value of sediment that is eroded and transported until reaching a ditch or sewer provided in the model. The sediment entering the ditch and sewer system is perceived as a loss of sediment in the catchment, since it is taken out of the landscape interaction of the catchment modelled by WaTEM/SEDEM.
Sediment trapped in Buffers	The total value of sediment remaining in buffer dams or erosion ponds. This value depends on the amount of sediment reaching the buffer pixels used by the model and the trapping efficiency of each buffer.
Mean Erosion Rate	The Mean Erosion Rate is the mean erosion over the whole catchment, calculated by dividing the Total Erosion by the total area of the catchment. The calculated value gives insight on the average sediment loss per hectare per year (in t/ha/year).
Sediment Delivery Ratio (SDR)	The Sediment Delivery Ratio is the ratio between the Sediment Delivery to Rivers and to Ditches/Sewers on the one hand and the Total Erosion on the other hand. The Sediment Delivery Ratio is an indicator of the sediment connectivity in the landscape.

**The Total Deposition parameter is deemed redundant in the comparison*

4.3.3. Results

4.3.3.1. Standardised Scenarios

The results for the baseline scenario of the Maarkebeek and Menebeek catchment, calculated by the model, are given in Table 17. These are the parameter values estimated by the WaTEM/SEDEM model for the model year of 2020 in the 'As-Is' scenario. The mean erosion rate of the Maarkebeek catchment is 8.7 tons/ha/year and the specific sediment delivery to the water system is 2.1 tons/ha/year. For the Menebeek catchement slightly lower values are calculated. The mean erosion rate of the Menebeek catchment is 7.1 tons/ha/year and the specific sediment delivery to the water system is 1.3 tons/ha/year. The Maarkebeek catchment is thereby distinguished by a higher Sediment Delivery Ratio compared to the Menebeek catchment.

Table 17. Modelled values for comparison parameters of the reference scenario in the Maarkebeek and Menebeek catchments. All values in tons/year, except the Mean Erosion Rate (in t/ha/year) and the Sediment Delivery Ratio (in %).

Catchment	Mean Erosion Rate	Total Erosion	Total Sediment Loss	Sediment Lost to River	Sediment Lost to Ditches/sewers	Sediment Trapped in Buffers	SDR
Maarkebeek	9	42 400	10 600	6 300	4 100	55	25%
Menebeek	7	21 000	4 500	2 000	1 900	280	19%

In Table 18 and Table 19 the resulting parameters for the different scenarios are listed, for the Maarkebeek and Menebeek respectively. The values are given in percentage of change to the baseline (‘As-is’) scenario, indicating the proportion of increase or decrease for a certain modelled parameter compared to the baseline model. In the tables, the value for ‘Impact on Agriculture’ is given as well and represents the increase (+) or decrease (-) in available arable land for the model implementation as proportion of the arable land available in the baseline scenario. If no sign is given for the ‘Impact on Agriculture’, it refers to the proportion of arable land that is impacted by a measure in the scenario, and no land use is converted to or from arable land.

First, the Base and Null scenarios are modelled. For both Maarkebeek and Menebeek, an increase in all modelled parameters can be seen, except for the ‘Sediment Trapped in Buffers’ in the Null Scenario for both catchments and for the Base scenario in the Maarkebeek catchment. It is apparent that between both catchments there is a great difference in magnitude of change, with for example changes in Erosion Rates of +7% in the Menebeek catchment and only +1% in the Maarkebeek catchment or the increase with 18% and 13% for the Total Sediment Loss in the Menebeek catchment as compared to only +4% and +4% increase in the Maarkebeek catchment for the Base and Null scenario, respectively.

Next, in the ‘Reduced Tillage’ scenarios similar trends are found in both catchments. For almost all parameters a decrease is evident, except for the Sediment Delivery Ratio. Considering the different subscenarios, the amount of change increases in all parameters with the addition of the Erosion Classes where reduced tillage is implemented. When looking at the ‘Impact on Agriculture’, an important difference can be observed between both catchments. In the Maarkebeek catchment the reduced tillage is applied on 12 – 94% of the arable land, while in the Menebeek catchment the measure only impacts 1 – 79% of the arable land.

In continuation, both ‘Buffer Strip’ scenarios (i.e. ‘Riparian -’ and ‘Extra Buffer Strips’) show similar results when comparing them to one another as well as comparing both catchments. All parameter values seem to decrease compared to the ‘baseline scenario’ and with increasing buffer width, with the exception of the scenarios with a buffer width of 1m. In these scenarios there is no significant change, or even a slight positive change in some parameters can be observed. These scenarios are amongst the scenarios with the lowest impact on agriculture ranging from -0.1 to -9%. Here there is once again a significant difference in impact on agriculture between both catchments, with the Maarkebeek catchment having impact values from -0.2 to 9% and the Menebeek catchment having impact values between -0.1 and -5%.

Lastly, for the ‘Grass-on-Slope’ scenarios, all modelled parameters decrease compared to the baseline scenario except for the Sediment Delivery Ratio, where slight increases are present in all sub-scenarios for the Maarkebeek catchment and for the ≥15% sub-scenario in the Menebeek catchment. Once more, the Impact on Agriculture is greater for the Maarkebeek catchment (-1 - -17%) than for the Menebeek catchment (-0.3 - -4%).

5.3.3.2. Specific Scenario

When looking at the specific scenarios for the Maarkebeek catchment (see Table 18, below bold blue line), the first two scenarios both have a negative impact on the calculated parameters. While the Municipal Erosion Mitigation plans have the highest reduction in Erosion Rate and Sediment Delivery Ratio, the Impact on Agriculture as well is greater than for the Local Environmental Protection Plans. In the latter scenario an increase of almost 5 times in the initial amount in 'Sediment trapped in Buffers' is evident. The last specific scenario for the Maarkebeek catchment then simulates a great positive impact on the modelled parameters. Almost all parameters increase for this scenario. While the Erosion Rate and Total Sediment Loss increase with 34 and 54% respectively, the Sediment Delivery Ratio increases only by 2%. Due to the conversion of grassland to arable land, a positive Impact on Agriculture value of +14% is calculated.

For the Menebeek catchment, all specific scenarios result in a decrease of the parameters calculated for the models as compared to the baseline scenario (see Table 19, below bold blue line). Here, the Municipal Erosion Mitigation plan scenario is expected to have a lower impact on the Erosion rate (-7%) as compared to the other specific scenarios (-9 and -11%), it, however, has a greater decrease in Sediment Delivery Ratio, -12% as compared to -2 and -8%. Looking at the Impact on Agriculture, a slightly negative impact can be observed for all the scenarios, namely -3, -4, -5% respectively.

*Table 18. Resulting parameters for the different scenarios in the Maarkebeek catchment. Values given as percentage of change compared to the baseline ('As-is') scenario. The Impact on Agriculture parameter values marked with: *, should be interpreted as agricultural land proportion affected by a measure without land use change, while values containing a '+'or '-' sign, should be considered as the proportion of agricultural land added or removed from agricultural land use. These proportions are based on the initial area of agricultural land under the baseline scenario.*

Scenario	Mean Erosion Rate	Total Sed. Loss	Sed. Lost to River	Sed. Lost to Ditches/ sewers	Sed. Trapped in Buffers	SDR	Impact on Agriculture
Base Scenario	+1	+4	+5	+2	-9	+3	+1
Null Scenario	+1	+4	+6	+5	-100	+5	+1
Reduced Tillage Purple	-18	-15	-21	-7	0	+3	12*
Reduced Tillage Red	-64	-58	-60	-54	-55	+16	59*
Reduced Tillage Orange	-74	-69	-71	-68	-73	+15	74*
Reduced Tillage Yellow	-83	-79	-79	-80	-73	+19	94*
Riparian Buffer Strips 3 m	-2	-19	-32	0	0	-17	-0.5
Riparian Buffer Strips 6 m	-3	-29	-48	0	0	-27	-1
Riparian Buffer Strips 9 m	-3	-31	-51	0	0	-29	-1
Riparian Buffer Strips 12 m	-3	-32	-52	0	0	-30	-2
Riparian Buffer Strips 20 m	-3	-32	-52	0	0	-30	-3
Extra Buffer Strips 3 m	-7	-36	-33	-39	0	-30	-1.4
Extra Buffer Strips 6 m	-9	-52	-51	-56	-18	-48	-2.9
Extra Buffer Strips 9 m	-10	-57	-54	-61	-18	-52	-4.3
Extra Buffer Strips 12 m	-10	-58	-56	-61	-27	-53	-7.2
Extra Buffer Strips 20 m	-10	-58	-56	-63	-27	-54	-9.1
Grass-on-Slopes ≥ 15 %	-5	-5	-3	-2	-27	+2	-1
Grass-on-Slopes ≥ 10 %	-20	-21	-25	-12	-27	0	-7
Grass-on-Slopes ≥ 8 %	-36	-35	-43	-22	-36	+2	-17
Municipal Erosion Mitigation Plan	-26	-50	-51	-59	-27	-38	-11
Local Environmental Protection Plans	-9	-27	-33	-27	+464	-24	-4
Strategic Grassland	+34	+54	+54	+10	0	+2	+14

This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement N° 862695

*Table 19. Resulting parameters for the different scenarios in the Menebeek catchment. Values given as percentage of change compared to the baseline ('As-is') scenario. The Impact on Agriculture parameter values marked with: *, should be interpreted as agricultural land proportion affected by a measure without land use change, while values containing a '+'or '-' sign, should be considered as the proportion of agricultural land added or removed from agricultural land use. These proportions are based on the initial area of agricultural land under the baseline scenario.*

Scenario	Mean Erosion Rate	Total Sed. Loss	Sed. Lost to River	Sed. Lost to Ditches/ sewers	Sed. Trapped in Buffers	SDR	Impact on Agriculture
Base Scenario	+5	+13	+30	+21	+25	+12	+5
Null Scenario	+7	+18	+20	+21	-100	+20	+5
Reduced Tillage Purple	-1	-2	0	0	0	+1	1*
Reduced Tillage Red	-30	-29	-35	-21	-25	+3	24*
Reduced Tillage Orange	-48	-47	-50	-37	-54	+8	43*
Reduced Tillage Yellow	-73	-73	-70	-74	-64	+6	79*
Riparian Buffer Strips 3 m	-3	-9	-15	0	-4	-5	-0.2
Riparian Buffer Strips 6 m	-4	-16	-30	0	-4	-12	-0.3
Riparian Buffer Strips 9 m	-4	-18	-35	0	-4	-15	-0.6
Riparian Buffer Strips 12 m	-4	-18	-35	0	-4	-15	-0.9
Riparian Buffer Strips 20 m	-4	-18	-35	0	-4	-15	-1.2
Extra Buffer Strips 3 m	-7	-24	-20	-32	+4	-20	-0.6
Extra Buffer Strips 6 m	-9	-40	-35	-47	-4	-35	-2
Extra Buffer Strips 9 m	-9	-40	-40	-53	-4	-41	-2
Extra Buffer Strips 12 m	-9	-44	-40	-53	-4	-41	-3
Extra Buffer Strips 20 m	-9	-44	-40	-53	-4	-41	-5
Grass-on-Slopes ≥ 15 %	-1	-4	0	0	-4	+1	-0.3
Grass-on-Slopes ≥ 10 %	-6	-11	-15	-5	-18	-4	-2
Grass-on-Slopes ≥ 8 %	-12	-20	-25	-11	-21	-7	-4
Municipal Erosion Mitigation Plan	-7	-20	-5	-32	-46	-12	-3
Land Consolidation Plan (LCP) Scenario	-9	-16	-20	0	-4	-2	-4
Erosion Control on Public Domain Scenario	-11	-22	-30	-5	-21	-8	-5

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research and innovation programme under grant agreement N° 862695

4.3.4. Discussion

This study shows that it is possible to calculate different erosion control scenarios, using the WaTEM/SEDEM model, by merely adapting some of the input data to fit the desired landscape settings. In this study, this was done using some programming tools used and created by the Flemish government in collaboration with FLUVES, however, most changes can be applied manually with the right expert knowledge.

Thanks to the model output of the WaTEM/SEDEM model, the impact of the different scenarios can be easily calculated and visualised. By calculating the Mean Erosion Rate (ER) and the Sediment Delivery Ratio (SDR) for the scenarios the impact of the choices made in the scenarios can be easily analysed in terms of on- or off-site erosion control and impact on the connectivity in the landscape.

When looking at the ER and SDR values for all scenarios, the scenarios can be grouped into roughly three types. First, there are the scenarios where the erosion problems of the catchments increase, namely, the 'Base', 'Null' and 'Strategic Grassland' scenario. In these scenarios, both the ER and SDR values increase compared to the baseline scenario as ECMs are deleted. When comparing the two study areas, it is evident that in the Menebeek the value of change is much greater than in the Maarkebeek. This can be attributed to the extent of erosion control measures already in place. In the Menebeek catchment an addition of 5% arable land can be observed by converting the ECMs back to arable land, while for the Maarkebeek catchment this is only 1%. The increase of ER and SDR in the Menebeek catchment can, therefore, be expected to be higher than in the Maarkebeek catchment.

Secondly, scenarios with a decrease in ER and an increase in SDR can be distinguished. These scenarios, namely the 'Reduced Tillage' and 'Grass-on-Slopes', can be characterised as on-site erosion control scenarios. This means that they will not impact the landscape connectivity as such, but rather be source-oriented and prevent soil loss and the amount of sediment that is transported in the whole catchment. By comparing both the Maarkebeek and Menebeek catchment, a distinction can be observed between both. In the Maarkebeek catchment the reduction of the ER value is greatly reduced by the scenarios, however the SDR increases drastically as well. This indicates that there is a disconnectivity between the agricultural parcels on the highly erodible and steep hillslopes and the river/sewer networks in the catchment. When looking at the Menebeek catchment, there can be observed that even though the reduction in ER value is comparable when considering the difference in affected agricultural area between both catchments, the SDR is less affected in this catchment. This suggests that the location of the parcels on the highly erodible and steep slopes are well connected to the river/sewer network. This is especially apparent when considering the Grass-on-Slope scenario, since the conversion of arable land to grassland can serve as an ambiguous erosion control measure. On the one hand, by covering the top soil layer, it will protect the soil against erosion, and, on the other hand, it will buffer incoming sediment streams and increase sediment deposition. This leads to both a decrease in ER and SDR values, only if these converted slopes are connected directly to the river/sewer systems in the catchment.

Lastly, the 'Buffer', 'Municipal Erosion Mitigation Plans', 'Local Environmental Protection Plans', 'Land Consolidation Plan' and the 'Erosion Control on Public Domain' scenario from the last category of scenario types, namely the off-site erosion mitigation scenarios. These scenarios are characterised by the importance of the decrease in SDR over the decrease in ER. In these scenarios all measures are taken in order to lower the landscape connectivity to the river/sewer system, while the source of the erosion is mostly neglected or is at most considered as a beneficial externality. In both catchments it is evident that the efficiency of buffer strips tops off at a certain width, i.e. around 6 to 9 m, and that it is more efficient to put more different smaller strips than fewer large ones in terms of ER and SDR reduction considering the impact on agricultural area. These scenarios however implement a lot of inefficient buffer strips, since the model creates buffer strips around all parcels-river/sewer borders and does not take into account expected sediment streams at these borders. In in-depth studies this can be done using expert knowledge of the catchment to identify locations where more buffers seem to be necessary or by using iterative modelling for critical sediment stream locations and selection of buffer strips location.

When considering the specific scenarios for both catchments, they might seem less effective than the generic scenarios. This can have two different causes: on the one hand, the formatting of the data is not generalised for model use. Municipalities often only have the marginal/preliminary plans of the planned erosion measurements available. These consist of simplified features, not representing the real extend or exact location of the ECMs that will be implemented in the landscape, while the official plans are often still not digitalised or not added and kept in a general database. This leads to inaccurate representation of certain ECMs in the model, giving the impression of inefficiency of the represented measures, for example by attributing a bigger area, and thus bigger impact on agriculture, of by attributing an incorrect location, and thus not capturing the expected sediment on that location. It is therefore important that the relations between modellers and stakeholders are being maintained and that stakeholders are involved and willing to contribute to the correct and complete inventory of (planned) ECMs in the landscapes in order to produce more reliable estimates of the modelled scenarios. On the other hand, the ‘tabletop’ generic scenarios do not have to consider any social or economic impact of the scenarios; this means that it is possible to test some extreme scenarios which are not viable in real life. At municipal level, however, there is often not the possibility to pursue these ‘what if’ scenarios, and only viable plans are kept and executed. This is often based on social and economic evaluation and prioritisation, and do not always consider the ecologic value of erosion control. The knowledge on which these municipal plans is based is sociably biased as well, since it often resides from civilian claims of erosion and/ or sediment problems by which they are affected, e.g. sediment on the streets, in houses, visible gullying on fields, … while hidden erosion problems, e.g. sediment streams entering river network or natural reserve areas, … are more easily neglected or unknown.

Therefore, it is still of utmost importance to exchange information between large scale modellers and local stakeholders, in order to better understand each other’s needs and make it possible to create accurate and relevant information for decision making and erosion control mitigation. As modeller, it is important to be transparent about used input data, model decisions and model output, in order to increase the confidence in and usability of the model. The WaTEM/SEDEM model gives already readily available output data which can be easily visualised in GIS programs, which increase the interest of stakeholders in the model, and help identify problematic hotspots for erosion and sedimentation. Stakeholders can, if well informed, help in the assessment of the model output and even support the creation of new scenarios, by providing correct and accurate input for the model or indicating interesting bases for other scenarios. In this way modellers and stakeholders alike can profit from using the WaTEM/SEDEM model in catchment scale modelling.

4.4. GAM+TI

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4.4.1. Introduction

Concentrated surface overland flow can cause severe linear erosion in the landscape and lead to ephemeral gully formation. Apart from anthropogenic influences, preferential flow paths are typically located where the landscape morphology allows for overland flow to concentrate in a thalweg, which allows the water to leave agricultural fields, potentially causing both on- and off-site damage. To prevent damage and soil loss, these preferential flow paths can be covered with permanent vegetation, for example as so-called grassed waterways (GWW). This measure is commonly used to allow surface runoff to flow from the field without causing erosion along thalwegs (Fiener & Auerswald, 2005). To mitigate the effect of erosion and sediment transport into waterways, it is essential to locate the areas where preferential flow paths and/or ephemeral gullies are likely to form, so that mitigation measures such as GWW can be implemented.

In Austria the implementation of GWWs is now subsidised under the Agri-Environmental Programme (ÖPUL). The areas where a GWW can be located and subsidised were designated through modelling of the location of preferential flow paths/ephemeral gullies. Thus, the original objective of the proposed modelling approach was to identify areas likely to have preferential flow/ephemeral gullying and thus be suitable locations for the installation of grassed waterways as mitigation measure. This led to selecting a trained model that performed best for Austrian conditions. For the study described here, we aimed to analyse whether the model trained in Austria could be applied to catchments in other countries for prediction of potential GWW locations.

Study area

For further investigation of the application of this model outside the initial areas for training and application in Austria, prediction of EG locations was tested in five catchments in Belgium, Finland, and Spain. In Belgium, two catchments (Molenbeek and Maarkebeek) were investigated. These catchments have areas of ca. 30 and 50 km^2, a rather large proportion of infrastructure and are located in a hilly part of Flanders with mean slopes of 4 and 7 %. In Finland, two coastal catchments (Aura and Mustio river catchments) were modelled. These catchments have areas of ca. 120 and 150 km^2 and are located in flat to mildly undulating areas. The catchments are described in more detail in the RUSLE/IC/SDR (4.2.1) and WaTEM/SEDEM (4.3.1) sections. In Spain, a small 6 ha catchment containing an established grassed waterway with a length of 200 m located near the city of Cordoba was modelled.

4.4.2. Data and methods

4.4.2.1. Generalized additive model (GAM)

A generalized additive model (GAM; (Hastie and Tibshirani, 1986)) is a statistical method for multiple regression and not thematically bound to a certain area of application. Such methods generally consist of a set of predictors and a target variable. According to the nature of the set of predictors, the target variable and the training dataset, all kinds of predictions can be made. The model is then fitted to perform well at predicting the training dataset. GAMs have been used to predict likely locations of natural hazards such as landslides (Park and Chi, 2010); Petschko et al., 2014; Steger et al., 2017), permanent (Garosi et al., 2018) or ephemeral gullies (Conoscenti and Rotigliano, 2020).

In our case, the target variable was the susceptibility of a certain grid cell to ephemeral gully (EG) erosion. A set of 8 first-order topographical indices (TI) was used as predictors, which are summarized in Table 20. Point features digitized from EG extent visible in optical satellite imagery (Google Earth) were used as training dataset. This means the GAMs were applied in a spatially distributed (grid-based) fashion. Figure 22 shows the modelling procedure in general.

Within the framework of this project, revolving around connectivity and the effects of best management practice implementation, this modelling approach can only be one of first steps. After likely EG locations have been identified, they can be protected by implementing GWW. The effects of the implementation of these GWW on runoff, soil loss, connectivity etc. can only be quantified by other modelling methods or measurements.

Table 20. Topographical indices used as predictors in GAM modelling of ephemeral gully (EG) locations, sources for their application in similar studies; indices marked with (X) were excluded for showing multi-collinearity.

Full name	Abbreviation	Source for application (EG-related)	Source for equation or tool
Flow accumulation (D-inf)	FAC	(Svoray et al., 2012), (Dumbrovský et al., 2020)	(Tarboton, 1997)
(X) Stream Power Index	SPI	(Dewitte et al., 2015), (Javidan et al., 2019), (Garosi et al., 2019), (Azedou et al., 2021), (Arabameri et al., 2021)	(Moore et al., 1991)
Convergence Index	CI	(Conoscenti and Rotigliano, 2020), (Arabameri et al., 2021)	(Köthe and Lehmeier, 1996)
Multiresolution Index of Valley-bottom flatness	MRVBF	-	(Gallant and Dowling, 2003)
Multiresolution Index of Ridge-top flatness	MRRTF	-	(Gallant and Dowling, 2003)
Compound topographic index	CTI	(Thorne and Zevenbergen, 1984), (Thorne et al., 1986), (Parker et al., 2007), (Sheshukov et al., 2018)	(Thorne and Zevenbergen, 1984), (Thorne et al., 1986), (Parker et al., 2007)
(X) mSlope*Area Index	SA	(Sheshukov et al., 2018)	(Moore et al., 1988; Vandaele et al., 1996a)
(X) Area*slope^2 Index	AS2	(Sheshukov et al., 2018)	(Montgomery and Dietrich, 1992)
Topographic Wetness Index	WTI	(Grabs et al., 2009) (Buchanan et al., 2014) (Pourali et al., 2016) (Daggupati et al., 2014), (Dewitte et al., 2015), (Garosi et al., 2019), (Conoscenti and Rotigliano, 2020), or (Arabameri et al., 2021)	
Channel initiation threshold index	CIT	(Montgomery and Dietrich, 1988) and (Montgomery and Foufoula-Georgiou, 1993)	(Montgomery and Dietrich, 1988; Montgomery and Foufoula-Georgiou, 1993)
(X) Slope*Area$^{0.4}$	SAP_04		(Desmet et al., 1999; Vandaele et al., 1996a, 1996b), by (Patton and Schumm, 1975), (Desmet et al., 1999)
Slope*Area$^{0.486}$	SAP_0486		
(X) Slope*Area$^{0.75}$	SAP_075		

4.4.2.2. Simulations

As outlined in the models section, a GAM was trained to predict features of linear erosion, which are in turn potential locations for GWW implementation. A cell size of 10 m was used both in the original study where the model was trained and for the predictions presented here. The training points were created by digitizing features of linear erosion visible in Google Earth imagery of three disjunct areas in Eastern Austria (extent of ca. 100, 200 and 300 km^2). The 8 TI used by the GAM for predicting susceptibility to EG erosion were calculated directly from the elevation data of the respective DEMs after pit-filling. The TI MRVBF, which exhibits high values for flat valley bottoms, was used as a cut-off-criterion with a value of 3. This value was determined for the original training area by visual inspection of the results and showed preferable for the training dataset. Originally, 5 additional TI were used, but they were showing multi-collinear behaviour and therefore excluded.

The creation of point training features from the mapped polygon features required multiple processing steps. They had to be aligned with the actual flow accumulation of the DEM (snapping to raster cells), and buffers were created to distinguish sharply between “inside” and “outside” of a digitized feature. These buffers were converted into point features and assigned values 0 or 1 according to their location being in- or outside.

After these preparatory steps, numerical values of the TI were sampled at each point. The resulting points with TI information were then used in fitting a GAM, with a 50:50 train-test split. The immediate GAM output is a continuous value of susceptibility to EG erosion between 0 and 1. An additional step was performed to find an “optimal” decision threshold (Beguería, 2006)
to convert this output into a binary raster containing only values 0 and 1, translating to “high” or “low” susceptibility to eg erosion.

The binary raster dataset was then transformed into a polygon dataset to allow for a more straightforward decision making. The "high” raster cells were vectorised into contiguous, conical polygons with a width of 18 m and 36 m at the upper slope and lower slope, respectively. These values were chosen by assuming a typical agricultural machinery working width of 6 m. At the same time, some dispersal of surface flow at the base of the slope is considered with a wider greening of the flow path at the lower slope. Only polygons with a minimum area of 300 m^2, i.e. 3 pixels were included to reduce artefacts.

In the original application, several additional GIS operations were performed on these features, as the prediction should be limited to agricultural areas. Intersections with other land use classes, like forests, settlements or water bodies were made in order to exclude these areas. In the predictions within this study, these steps were not performed but should be kept in mind.

Validation

The original model used for the predictions in this study was validated in several ways. Three methods for spatial (kmeans-clustering, factor-LOOCV) and non-spatial (random) cross-validation were employed. Additionally, each of the three trained models was tested alternately in the remaining training areas. A small number of predicted features (n=22) could be verified by field inspection together with landowners and agricultural extension services personnel. Any false classifications in these cases were clarified during the field observations and were found to be mostly due to limitations related to the coarse 10 m resolution.

Within this study, these steps could not be performed since no appropriate datasets were available for the 5 catchments investigated. Instead, the outputs of the predictions were visually compared with Google Earth imagery. An inventory of ca. 190 mapped gully features was provided for the Belgian Molenbeek catchment and could be compared to the model outputs.

Accuracy

The original model showed excellent performance, with AUROC values for the classification > 0.88. The small number of locations that were inspected in the field as described above showed a high accuracy of 0.85 (calculated from confusion matrix).

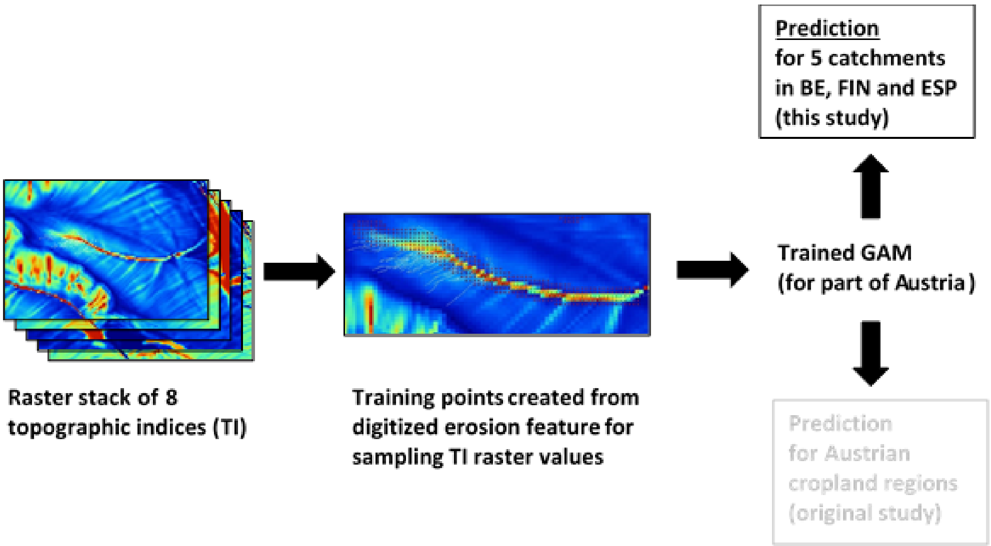

Figure 22. Schematic methodology of GAM modelling

Predictions for catchments in Belgium, Finland and Spain
To test the ability of the fitted GAM outside its initial training area, catchments in Belgium, Finland and Spain were selected for further simulations. Based on the data provided by the project partners from BE, FIN and ESP, the necessary input data for performing the prediction were generated. DEM data was provided for two catchments in BE and FIN, and one catchment in ESP. Details concerning these catchments can be found in the descriptions given in other sections. DEM elevation data was provided at different resolutions (1, 2, 5 and 20 m) and resampled to 10 m for better comparability. FIN and ESP DEMs were already filled beforehand. SAGA GIS was used to calculate the topographical indices, and the DEMs were masked where values of the TI MRVBF > 3, which is also a value obtained under Austrian conditions.

In the FIN catchment, the DEM provided was masked by the extent of agricultural fields. As each field is encompassed by a drainage ditch, the possibility of surface runoff entering neighbouring fields can be ruled out according to FIN project partners.

After calculation of the 8 topographical indices, the best-performing model for Austrian conditions was used to predict EG locations in these 5 catchments.

4.4.3. Results

Suitable data for validation of the predictions was provided for only one of these 5 catchments, so we were mostly limited to visual inspection and comparison with Google Earth imagery. Still, a qualitative rating of the predictions can be attempted.

In the Belgian catchments, poor agreement was found. Many EG were predicted by the GAM, but virtually none were visible in the images, i.e., very high false positive predictions. This may be due to the timing between image capture and any erosional events, land use, crop development, tillage practices etc. However, the model clearly finds the thalwegs (Figure 23 and Figure 24), and a number of coincidences with the gully inventory was found in the Molenbeek catchment. Large areas along streams, infrastructure or settlements were wrongly predicted. Following the workflow used in Austria until the end, these would be greatly reduced by intersecting the result with a mask containing only cropland.

Figure 23. Detail of Maarkebeek catchment in Belgium with visible likely (permanent) gully (left); detail prediction of location of ephemeral gullies and suitable locations for grassed waterways (right).

When comparing the gully inventory provided by Belgian project partners for the Molenbeek catchment, we found the model predictions showing very low Precision of 0.05, very low F1-score of 0.08 but acceptable Balanced Accuracy of 0.58. Figure 24 shows a detail of several predicted and measured gullies.

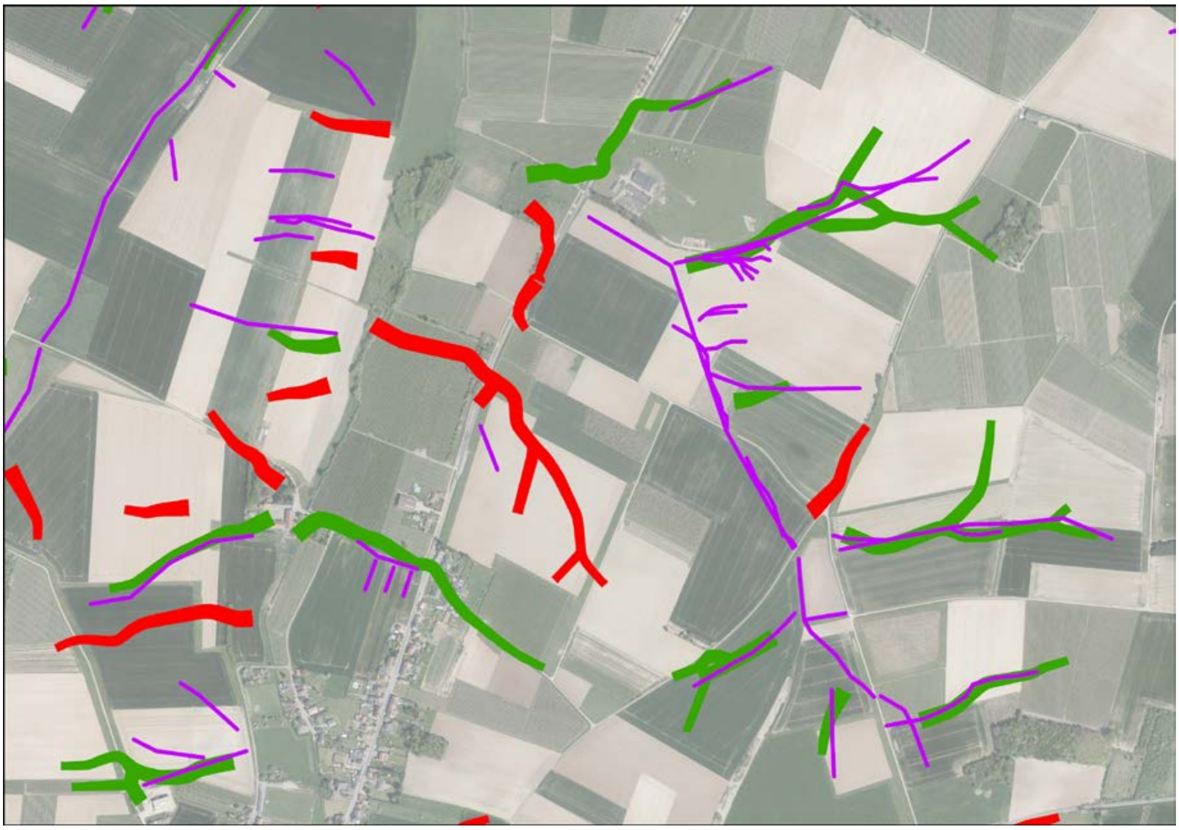

Figure 24. Detail of measured gullies from inventory (purple polylines) vs. GAM+TI model outputs in Molenbeek catchment. Green polygons are considered “coinciding” with the inventory (True Positive), Red polygons are not coinciding (False Positive)

In Finland, large parts of both catchments were discarded due to the condition of the topographical index MRVBF < 3. Higher values of the MRVBF signify wide flat valley bottoms, which are widely present in these rather flat sites. Thus, only 8 and 14 EG locations were predicted for Mustio and Aura catchments, respectively – despite both being quite large catchments at > 100 km^2. Practically none were visible in satellite imagery (Figure 25). This indicates poor performance of the model, but apparently better than with the Belgian catchments. Presumably, this means far less false positive predictions in comparison.

Figure 25. Examples of predicted locations for grassed waterways in Aura River catchment (left) and Mustio river catchment (right) in Finland.

In the small catchment in Spain there was a good agreement between the visible erosion features from the satellite image and the model-predicted locations of ephemeral gullies/grassed waterways (Figure 26). There seems to be a high rate of true positive predictions, while the false negative predictions are likely because the DEM was cropped with a rectangular mask, cutting off parts of the actual catchment area (especially in the east and north of the area).

Figure 26. Catchment in Spain with visible erosion features (left) and the model prediction of locations of ephemeral gullies and suitable locations for grassed waterways (right).

4.4.4. Discussion

In this study, we provide a straightforward and resilient method for identifying areas that are vulnerable to ephemeral gully erosion. In these areas, implementation of mitigation measures such as GWW, could be feasible to reduce erosion and sediment connectivity in the landscape. To apply the method, a DEM for topographical indices calculation, a GAM for prediction purposes, and an ephemeral gully inventory to train and validate the GAM model and predicted ephemeral gully locations are needed.

Landscape connectivity is only indirectly represented in the model, by using several TI that can be interpreted that way. It would be interesting to include dedicated connectivity TI into the model, though this might come at the cost of higher demand for input data.

The selected GAM model type is only one option, several other methods have been used in related studies. Feasible alternatives are GLM or machine-learning methods such as SVM, MARS, ANN or CART (Garosi et al., 2018). Performing model comparisons was not part of our study.

Concerning simulation scenarios, we assumed that the selected TI at the chosen DEM resolution of 10 m is practically static. Thus, we only considered one scenario for potential EG locations based on these static geomorphological conditions. Including dynamic components like rainfall events of certain return periods, soil moisture state or land use information seems desirable from a process point of view but introduces many new complications that we tried to avoid, as well as additional demand for input data.

We argue that in order to consider the TI static as we did, DEM resolution must not become too fine. During field validation in the original training area, it was found that false predictions are often the result of anthropogenic influences, i.e., comparatively small linear features that are not present in the DEM. Including these would probably necessitate spatial resolutions of < 0.5 m, greatly increasing computation demand and likely introducing a lot of noise into the TI signal. We see the 10 m resolution used as a compromise for the sake of availability and computational effort. No direct comparison of using different DEM resolutions was performed.

The choice of the TI used in prediction was based on literature research and somewhat arbitrary in nature. Including other TI and even completely different predictors would certainly be interesting. For calibration and validation purposes, a much higher number of initial training features would of course be desirable but is limited by resource constraints and availability of appropriate imagery. While spatial cross-validation was performed within the training area with satisfying results, a much larger number of field inspections would be necessary too. Still, even field inspection cannot give certainty with EG erosion potentially happening only at extreme events. Validation only by inspecting Google Earth imagery is clearly insufficient since their capture coincides with erosive rainfall event only by chance.

In terms of uncertainty management, any numerical uncertainties can only be reported adequately when a dataset for comparison is available in the predicted area that is not part of the training area. As for attaining such a dataset, the same constraints as for the calibration dataset apply.
The communication of results was included in the final steps of processing the model outputs. The output rasters were vectorized into continuous conical polygons along the predicted EG locations. These polygons indicate the proposed extent of an implemented GWW. Results were also communicated during the field inspections performed for validation purposes.

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