Towards climate-smart sustainable management of agricultural soils

SCALE

Managing Sediment Connectivity in Agricultural Landscapes for reducing water Erosion impacts

Deliverable WP2-D2

Guidelines for best-practice of selecting model-relevant parameters

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1 Introduction

Work package 2 (WP2) under the SCALE project deals with data sharing/pooling and harmonisation of datasets. Task 2 under this work package is entitled “Guidelines for best-practice of selecting model-relevant parameters”.

Soil erosion has a major impact on the delivery of ecosystems goods and services, causing severe on- and off-site effects. On-site impacts include loss of organic matter and reductions in soil depth, thus decreasing agricultural productivity. Off-site effects are caused by the water-mediated sediment export from the fields, resulting in environmental damages. Effective sediment management on the catchment scale, including the identification of sediment source areas and the way they connect to the channel network, is therefore essential for environmental management. However, the sediment source–mobilization–delivery process is a complex continuum, highly dynamic in space and time, depending on various factors that affect sediment connectivity in catchment systems.

In water soil erosion modelling, and in particular with special focus on connectivity aspects, the importance of selecting relevant, appropriate and accurate parameters is essential for gaining basic correlations between soil erosion, transport and sedimentation, and landscape features, as well as the understanding of processes in cause/effect perspectives.

A common and shared database has been created as part of Task 1 of WP2, to collect data to be used for erosion modeling on different scales across Europe. Data has been uploaded in a project repository and furnished with metadata.

Information provided by SCALE metadata and a bibliographic review of the importance of model-relevant parameters in modeling soil erosion and connectivity has served as base for discussion to address decisions of modelers in selecting and testing models and assessing model accuracy.

The aim of this deliverable is to provide brief guidelines for the selection of relevant parameters in erosion modeling from the analysis of data collected from SCALE partners.

2 Digital Elevation Models and Spatial Resolution

Topography plays an important role in hydrological modeling for water management and flood protecting. It can be derived from Digital Elevation Model (DEM) which is one of the most commonly used and widely available basic spatial information.

Topography has a large impact on the erosion of soil by water. For example, slope steepness and slope length are combined (the LS factor) in the universal soil-loss equation (USLE) and its revised version (RUSLE) for predicting soil erosion.

Topography is a soil-forming factor and, therefore, affects the soil characteristics that determine the use, management, conservation and degradation of this resource. In the case of erosion, topography is a factor that influences the transport and accumulation of soil by water, depending on the particular characteristics of the relief. The effect of relief on erosion has been related to variables such as slope length and steepness, shape and uniformity of the slope (Toy et al., 2002).

A DEM consists in digital representation of a topographic surface of the Earth, which is among the most invaluable quantitative models applied in geomorphic studies. DEMs serve as a basis for both modeling and measuring certain geomorphic processes, allowing their application to a wide range of soil erosion assessment applications. Its quantitative nature makes it highly valuable for various applications, particularly in the assessment of soil erosion (Mondal et al., 2016). In fact, in soil erosion modeling DEMs and geomorphometrics derived by Digital Terrain Analysis (DTA) represent the main source of data used. They have high potential to quantitatively characterize topography as an important input for different erosion models on different scales (Mitasova et al., 1996; Moore et al., 1991). The basic principle of geomorphometry analysis is the existence of a relationship between landforms and the numerical parameters used for its description and also with processes involved with the genesis and evolution of the landforms (Evans, 2012; Pike, 2000). The primary attributes are calculated directly from the elevation data and include slope, aspect, profile and plan curvature. The secondary attributes are derived from primary attributes, are important because they offer an opportunity to describe patterns as a function of process (Wilson and Gallant, 2000; Moore et al., 1991) and include the topographic wetness index, stream power index, radiation and temperature indices, and sediment transport capacity, among others.

The accuracy and reliability of soil erosion modeling heavily depend on the source and resolution of the DEM (Arabameri et al., 2021). Furthermore, understanding a DEM of proper spatial resolution and accuracy is essential for soil erosion assessment (Kariminejad et al., 2021). The accuracy of the DEM directly influences the soil erosion assessment precision, whereas spatial resolution determines the level of detail that can be extracted from such assessments.

The selection of optimal DEM resolution and source depends on the: i) size and characteristics of the study area, ii) research goals, and iii) reachable geospatial models and technologies. Although higher DEM accuracy and resolution are better, previous research has expressed that in some cases higher DEM spatial resolution and accuracy can introduce certain limitations. Recently, various geospatial technologies have made available faster and easier the creation of DEMs with better accuracy and higher spatial resolution (Sreenivasan and Jha, 2022). Regarding application for soil erosion assessment, the DEMs overall can be divided into the categories according to their resolution: low, medium, and high.

Low-resolution DEMs (≥ 30 m)

Low-resolution DEMs typically exhibit a spatial resolution of 30 m or greater, encompassing a diverse array of DEM sources acquired through satellite remote sensing techniques. Examples of such sources include the ASTER DEM, SRTM, and GTOPO30. Moreover, low-resolution DEMs are freely available and have global or almost-global coverage. Due to the coarser spatial resolution, however, such DEMs are much suitable for studying general environmental variables of soil erosion processes within very large and remote areas. Their applications in soil erosion research mainly revolve around large-scale estimations of annual soil loss using various equations to determine soil loss like the revised universal soil loss equation (RUSLE) or universal soil loss equation (USLE). Additionally, low-resolution DEMs are also commonly employed for large-scale soil erosion susceptibility mapping (Aslam et al., 2021).

Medium-resolution DEMs (2–30 m)

The category of medium-resolution DEMs encompasses a wide range of tools and models with spatial resolution ranging from 2 to 30 m, offering greater versatility for soil-erosion-related applications. Similar to low-resolution DEMs, medium-resolution DEMs are collected by different satellite-based remote sensing techniques (e.g., Spot-5 stereo DEM, EU-DEM, TanDEM-X, etc.). In addition, medium-resolution DEMs can be created by interpolation of contours and height points from topographic maps.

Medium-resolution DEMs offer a significantly higher level of detail compared to coarser resolution DEMs, making them valuable for soil erosion modeling. They are commonly used for soil erosion detection and mapping, estimating annual soil loss or soil erosion modeling within specific regions, river basins, or watersheds.

Medium-resolution DEMs can indeed be used for change detection studies because of their multitemporal coverage over time, allowing change detection analyses. Thus, due to the higher rate of errors and coarser spatial resolution, the applicability of medium-resolution DEMs is limited only to long-term studies, or very intensive soil erosion processes (Brosens et al., 2022). The coarser spatial resolution might not capture subtle or localized changes in terrain, making it more suitable for analyzing broader scale erosion patterns. Additionally, the higher rate of errors associated with medium-resolution DEMs could affect the accuracy and reliability of change detection results, necessitating caution in interpreting the findings.

High-resolution DEMs (0.5–2 m)

Low- and medium-resolution DEMs might not provide the required level of detail and accuracy for certain aspects of soil erosion studies. Thus, high spatial resolution DEMs ranging from 0.5 to 2 m are usually applied for various soil-erosion-related applications. The higher resolution of these DEMs enables the capture of finer topographic features, allowing for more precise analyses and assessments of erosion processes.

The applicability of high-resolution DEMs could be however limited by higher horizontal and vertical errors. Despite their high resolution, these DEMs are indeed subject to genetic errors arising from factors such as sensor characteristics, acquisition conditions, and data processing and post-processing. These errors can affect the accuracy and reliability of change detection analyses, especially when assessing subtle or localized changes in terrain over time.

A source of high-resolution DEMs is LiDAR surveys, i.e. aircraft-based aero-photogrammetric data, which permit coverage of large areas and acquisition of high resolution and accurate elevation data (Goodwin et al., 2017). This data collection method allows for detailed terrain modeling and analysis, offering a level of accuracy and resolution that is often superior to satellite-based DEMs. However, aircraft-based surveys tend to be costly due to the expenses involved in acquiring and maintaining specialized equipment, deploying aircraft, and conducting data processing. The high cost can limit the extent of coverage, making it challenging to carry out large-scale surveys or repeated monitoring over time.

LiDAR surveys or systematic aircraft-based aero-photogrammetric surveys are regularly conducted in different countries at periodic intervals, typically every few years, which serves as an excellent basis for multitemporal detection of soil-erosion-induced spatiotemporal changes (Stark et al., 2020). The systematic nature of these surveys ensures consistent data collection, allowing researchers to analyze long-term trends in soil erosion. This longitudinal perspective is crucial for understanding the dynamics of erosion processes, assessing the effectiveness of erosion control measures.

Figure 1 shows in terms of frequency which DEM spatial resolution has been used by SCALE project partners in modeling.

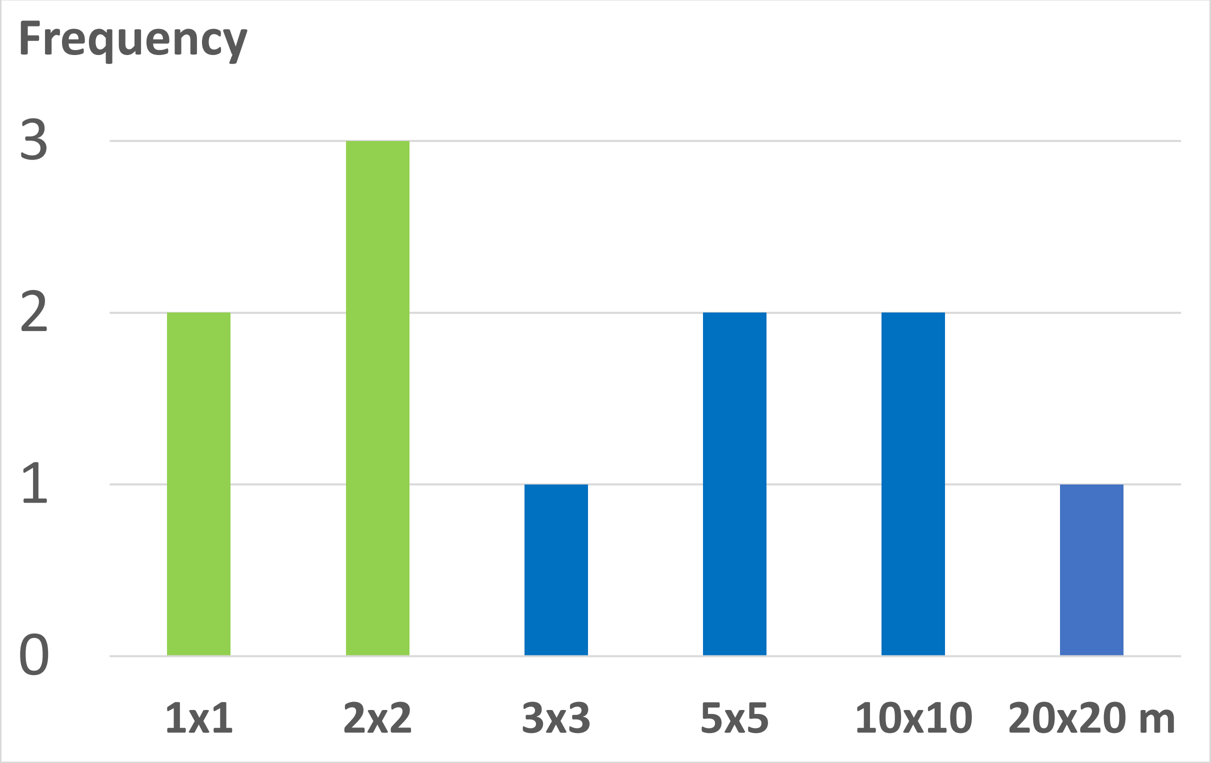

Figure 1. Frequency of DEM spatial resolution used in SCALE modeling. High-resolution DEMs in green, medium-resolution DEMs in blue.

Experience in modeling has brought project partners to selecting high-resolution DEM, generally a LIDAR product. If not available the choice was the most accurate (certified) and spatially resolute DEM available.

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3 DEM parameters and connectivity

Landscape connectivity is a key landscape characteristic, and plays a critical role in the soil erosion process. It shapes the occurrence and evolution of soil erosion from patch to watershed level. The connectivity indices and the spatially distributed soil erosion model are the two dominant approaches that can be used to link soil erosion with landscape pattern. Connectivity indices quantify the physical coupling among landscape units, and the functional connectivity, indicating the water or sediment delivery between landscape units. The spatially distributed soil erosion models explicitly incorporate landscape connectivity by taking landscape connectivity indices as parameters, implicitly modelling the in-situ sediment production and sediment routing between source areas and sink areas, or along the flow pathways. The connectivity concept framework links landscape pattern and soil erosion, and provides an effective solution for resolving the interaction between landscape and soil erosion dynamics.

Sediment connectivity is defined as the degree to which a system facilitates the transfer of water and sediment through the spatial arrangement of geomorphic features and processes (Heckmann et al., 2018). Two types of connectivity emerge from this definition: structural and functional. Structural connectivity is the spatial configuration of system components whereas functional connectivity represents the dynamic spatiotemporal processes of a system (Heckmann et al., 2018). Structural connectivity indices are more commonly applied (Cavalli et al., 2013; López-Vicente et al., 2013; Tiranti et al., 2018; Tarolli et al., 2019) as they require only topographic data. The Index of Connectivity (IC), developed by Borselli et al. (2008), is a commonly used method for numerically modeling sediment connectivity at the catchment scale and has been applied to examine the effect of land use change, rilled hillslope connectivity, and landslide susceptibility (Cavalli et al., 2013; Tiranti et al., 2018; Llena et al., 2019; Lu et al., 2019).

Structural connectivity indicates potential physical connection between patches of adjacent landscape related to spatial configuration (Papadimitriou, 2020) incorporating with transport path, distance and sediment transport resistance in a watershed system (Najafi et al., 2021). Functional connectivity denotes the actual mechanical process of sediment involved mainly in erosion, transport and deposition between hydrological and geomorphic systems (Lu et al., 2018; Pearson et al., 2020). In a catchment, natural factors such as climatic conditions (Chartin et al., 2017), complex geomorphic evolution, and anthropogenic factors such as soil and water conservation implementation, river regulation, land use-land cover change (Zanandrea et al., 2020) are triggering the sediment connectivity and related sediment transport processes (Liu et al., 2021).

Usually, soil erosion by water and connectivity parameter is highly controlled by terrain features. Therefore, increasing soil water retention capacity by improving infiltration and reducing peak discharge rate of surface runoff has been well recognized as the main direction to limit erosion and break-down connectivity. Modifications, interruptions and reshaping of the hill slope can obviously achieve this effect.

Accurate detection of real topographic features affecting erosion and connectivity is crucial for soil erosion modeling. DEMs are a powerful vehicle for conveying essential surface topographic information, which is very useful for terrain analysis of physical surface including various hydrological and biophysical properties. Therefore, the resolution of the DEM data plays an important role in controlling the soil erosion evaluation.

In particular, the sediment connectivity from agricultural land to surface waters is strongly affected by landscape patchiness and the linear structures that separate field parcels (e.g. roads, tracks, hedges, and grass buffer strips). Understanding the interactions between these structures and sediment transfer is therefore crucial when modeling erosion. Although soil erosion models can be used to understand lateral sediment transport patterns, model-based connectivity assessments are hindered by the uncertainty in model structures and input data.

Representing road connectivity is crucial for modelling sediment transfer from hillslope to water courses in agricultural catchment, especially in areas with a dense road drainage system.

Agricultural terraces form an important feature of sloping landscapes and have an important effect on the hydrological processes as they reduce the slope gradient and length. All these landscape features are then relevant parameters in modeling soil erosion and connectivity.

Definitely, DEM resolution has an influence on runoff and sediment yield by affecting derivative maps' accuracy. The higher the DEM resolution, the more precise the results of runoff and sediment simulations and the parameters related to connectivity.

Some experiments demonstrated that dynamic catchment-scale soil erosion and prediction modelling approaches that additionally consider aspects of connectivity relationships (i.e. the newly developed GeoWEPP-C model) yield more plausible results than traditional static representations of connectivity, but only in case a high-resolution DEM is used in the model, since landscape features related to connectivity can be digitally represented with a certain accuracy.

Irrigation ditches, small and spread settlements and non-asphalted trails are other hydrological features that commonly appear in the landscapes. Thus, these landscape features affect flow and sediment connectivity functions and they can be detected only by high-resolution DEM.

4 DEM quality

One of the most important data layers used in evaluating erosion risk is the digital elevation model, so it is important to know how accurate and precise your data are so you can better judge the validity of results.

Theoretically, higher resolution DEMs capture geomorphological changes with greater precision, resulting in more accurate estimation of erosion factors, especially when considering connectivity (both structural and functional).

Besides standard accuracy assessments using control points, the geometry can be evaluated using shaded 3D views, aspect, slope and curvature maps and flow tracing. However, this is a time-consuming procedure and requires additional resources.

Vertical precision in cm is needed. Meter precision is not sufficient as it creates a "step" effect that leads to zero slopes and a contour like slope pattern, which ultimately underestimates erosion. In a digital geographic environment that means that format of DEM must be in floating point.

Waves along contours, often not real and created by interpolation models in DEM generation by contours from topographic maps, create artificial erosion/deposition patterns. Artificial peaks and pits, generated in the same way, distort water flow simulation, compromising the accuracy of water/sediment flow/transport/accumulation patterns.

In certain cases, re-interpolation and smoothing (i.e. filtering) can improve the properties of a DEM, however this should be carefully evaluated and right Kernel (or moving windows dimension) and appropriate type of filter, need both to be tested.

Actions must be seriously taken into consideration as the unreal landscape features, discussed above, may cause big issues in the simulated water flow network. In this case stream enforcement, stream network burning must be considered to solve the problems. Hydrological correction of DEM has been recently developed in DTA introducing effective modeling techniques and minimizing the morphological impacts on the digital surface parameters. Since the DEM could be affected by errors, for example false sinks, imprecise roughness, etc., independently from the source and method of generation, it is strongly suggested to submit any DEM to hydrological correction.

The need for precision and accuracy is spatially variable, with flatter areas much more sensitive than mountains. Sometimes, in medium-resolution DEMs going to be used for simulations, it could happen that the artificial structures can be mistaken for the real topographic feature. Comparison with the higher resolution DEM from a different source can reveal more details about the difference between the DEM artifacts and true topographic features.

The LS factor is usually extracted from a digital elevation model (DEM). The grid size of the DEM will influence the LS factor and the subsequent calculation of soil loss.

Topographic slope information is one of the critical variables, which governs soil erosion. This topographic slope is derived from the Digital Elevation Model (DEM). Significant discrepancies are found in the estimation of soil erosion using different DEMs of different resolutions.

5 Other relevant data and parameters in soil erosion modelling

DEM is the most important and not unique input data in erosion models, many other parameters such as land cover-land use maps, soil maps, anthropogenic landscape features water and sediment determinations in field, climatic data and elaborations may be part of input data making the model prediction more logical and accurate, assuming the status of relevancy in modeling. In fact, the SCALE repository of modeling data has been populated not only by DEMs. Many other maps and data have been uploaded and stored by project partners especially those considered relevant to connectivity.

Resampling of raster data is frequently needed to bring spatial resolution of those data equal to the DEM resolution. The application of different interpolation algorithms may produce different results.

Since input data usually have different origin and manipulation, they might have different spatial and temporal accuracy, different datum and projection, a certain level of semantic accuracy. All these eventual issues if not considered, controlled and eventually corrected, may affect consistently the overall accuracy of the model.

6 Guidelines

Parameter	Action
DEM Resolution	- Choice of spatial resolution depends on scale of the region, morphology, landscape features. - Preference for high-resolution DEM. The higher the DEM resolution, the more precise the results of runoff and sediment simulations and the parameters related to connectivity.
DEM accuracy	- DEMs with higher accuracy will give more accurate results and will reduce the uncertainty. - Preference for floating point format. - Evaluate filtering and smoothing. - Running the hydrological correction using the most appropriate procedure. - Testing the most appropriate algorithms in generating DEM derivatives.
Input data	- Checking for any model input data spatial and temporal accuracy, datum and projection, level of semantic accuracy. - Preference to input data related to connectivity (i.e. connectivity indices).

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