

Pan-European Soil Erosion Risk Assessment for Europe: the PESERA Map

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Introduction: Purpose of the map; value and limitations

Erosion by running water has been identified as the most severe hazard threatening the protection of soil in Europe. By removing the most fertile topsoil, erosion reduces soil productivity and can, where soils are shallow, lead to an irreversible loss of natural farmland. Severe erosion is commonly associated with the development of temporary or permanently eroded channels or gullies that can fragment farmland. The soil removed by runoff from the land, during a large storm, accumulates below the eroded areas, in severe cases blocking roadways or drainage channels and inundating buildings.

Erosion rate is very sensitive to both climate and land use, as well as to detailed conservation practice at farm level. In a period of rapid changes in both climate and land use, due to global change, revised agricultural policies and international markets, it is very important to be able to assess the state of soil erosion at a European level, using an objective methodology that allows the assessment to be repeated as conditions change, or to explore the broad-scale implications of prospective global or Europe-wide changes. This provides a basis for estimating the overall costs attributable to erosion under present and changed conditions, and objectively identifies areas for more detailed study and possible remedial action.

The PESERA map of estimated loss of soil by water erosion is intended to provide an objective assessment of current rates of soil erosion, averaged over a series of years under current land use and climate. The map is based on the PESERA/RDI model, estimates of the rate of loss of material from hillsides having been made at a resolution of 1 kilometre. Sediment delivery through the river system is explicitly not taken into account, and most of the eroded material generally remains close to its source, with significant off-site effects generally confined to a local area.

There are several possible methodologies for creating an erosion map of Europe. Some of these are based on the collection of distributed field observations, others on an assessment of factors, and combinations of factors, which influence erosion rates, and others primarily on a modelling approach. All of these methods require calibration and validation, although the type of validation needed is different for each category. There are also differences in the extent to which the assessment methods identify past erosion and an already degraded soil resource, as opposed to risks of future erosion, under either present climate or land use, or under scenarios of global change

Distributed point data

One important form of erosion assessment is from direct field observations of erosion features and soil profile truncation. Erosion features consist of rills and gullies, some of these ephemeral, and associated deposition in creeks and small valleys. Soil profiles may show local loss from the upper horizons, or burial by deposition of material from upslope. Deposited material may be dateable which can indicate when the erosion occurred, but much of this evidence is cumulative over the period since cultivation began, or in some cases over the whole of the Holocene geological period. Data may be collected from regional soil scientists or experts on soil erosion. They may also be collated from field or remote (air photo) surveys of erosion features. High-resolution satellite imagery (e.g. from IKONOS) may, in the near future, also allow this method to be applied from space platforms. Some quantitative data are also available from erosion plot sites. Finally, measuring the sediment accumulating in reservoirs can quantify erosion at a catchment level.

These methods require validation to standardise differences in the intensity of study of different areas and in the clarity of suitable features on different soil types. There are also differences in methods and traditions between scientists in different areas of Europe. However, on their own these methods cannot provide a complete picture except for small sample areas, and require the use of other methods to interpolate between sampling points.

The main advantage of distributed observations of erosion is that where they exist the data are unambiguous, and give a good indication of the current state of degradation of soil resources. The main disadvantage of distributed observations is that they provide little or no information about when erosion occurred, unless supporting data are available from other sources. Many areas of the Mediterranean are thought to have suffered accelerated anthropogenic erosion since early classical times, with the result that many hills are now denuded of their former natural soil cover. Although of great historical interest, this stage of degradation has little bearing on current or prospective erosion hazards.

Factor or Indicator Mapping

Since many of the processes and factors which influence the rate of erosion are well known, as outlined above, it is possible to rank individual factors for susceptibility to erosion, providing a series of erosion indicators. For example, climatic indices may be based on the frequency of high intensity precipitation, and on the extent of aridity or rainfall seasonality. Soil indicators may reflect the tendency of the surface to form crusts and the experimental erodibility of soil particles or aggregates. Similar rank indicators may be developed for parent materials, topographic gradient and other factors. Clearly a high susceptibility for all factors indicates a high erosion risk, and a low susceptibility for all factors indicates a low erosion risk.

Individual indicators may be mapped separately, but it is more problematic to combine the factors into a single scale, by adding or multiplying suitably weighted indicators for each individual factor. There are difficulties both about the individual weightings and about the assumed linearity and statistical independence of the separate factors. The method should therefore be most effective for identifying the extremes of high and low erosion, but less satisfactory in identifying the gradation between the extremes.

Despite these theoretical limitations, factor or indicator mapping has the considerable advantage that it can be widely applied using data that is available Europe-wide in GIS format for topography and soils at 1 km resolution, and for climate at 50 km resolution. Kosmas *et al.* (1999) provides one example of this approach, applied at a regional scale to areas in Greece, Italy and Portugal.

Process modelling

There is a continuous spectrum between mapping based on ranked indicators and process models with a more explicit physical or empirical basis. Nevertheless it is fruitful to consider, as a third approach towards Europe-wide soil erosion assessment, the application of a process model. Although at first sight, this approach appears to be the most generally applicable, there are major problems of validation, and in particular in relating coarse-scale forecasts to available erosion rate data, much of which is for small erosion plots. Many of the most successful process models require more detailed distributed parameter and rainfall intensity data than are currently available at pan-European scales, so that they cannot be applied without radical simplification. One important aspect of this problem is the need to develop a model that can be used for validation at fine scales, and for Europe-wide forecasting at a coarse scale, so that cross-scale reconciliation must be as explicit as possible. Nevertheless this approach has the potential to provide a rational physical basis to combine factors which can be derived from coarse scale GIS, and overcome the difficulties about weighting and inter-correlation which are encountered in purely factor based assessments.

Process models have the potential to respond explicitly and rationally to changes in climate or land use, and so have great promise for developing scenarios of change, and ‘what-if’ analyses of policy or economic options. Set against this advantage, process models generally make no assessment of degradation up to the present time, and can only incorporate the impact of past erosion where this is recorded elsewhere, such as soil databases. Models also generally simplify the set of processes operating, so that they may not be appropriate under particular local circumstances. Although the Universal Soil Loss Equation (USLE) has been the most widely applied model in Europe (e.g. van der Knijff *et al.*, 2000, 2002), it is now widely considered to be conceptually flawed, and other models are now emerging, based on runoff thresholds (e.g. Kirkby *et al.*, 2000) or the MIR (Minimum Information Requirement) approach (Brazier *et al.*, 2001) applied to the more complex USDA WEPP model (Nearing *et al.*, 1989).

The application of a process model has been preferred here for three main reasons.

1. It applies the same objective criteria to all areas, and so can be applied throughout Europe, subject to the availability of suitable generic data.
2. It provides a quantitative estimate of erosion rate that can be compared with long term averages for tolerable erosion.
3. The methodology can be re-applied with equal consistency with improved current data, and for scenarios of changed climate and land use.

Scientific Rationale of the PESERA/RDI model

The PESERA (Pan-European Soil Erosion Risk Assessment) model is a physically based and spatial distributed model developed for quantifying soil erosion in environmentally sensitive areas relevant to a regional or European scale and defining soil conservation strategies. The current version of model was developed during the execution of the PESERA project (contract No QLK5-CT-1999-01323) funded by the European

Commission, Research Directorates General, DG VI (Quality of Life and Management of Living Resources), and was also based on previous funded and un-funded research (Kirkby and Neale, 1987; de Ploey et al, 1991; Kirkby and Cox, 1995; Kirkby et al, 2000).

The PESERA model combines the effect of topography, climate and soil into a single integrated forecast of runoff and soil erosion (Figure 1). Data for each of these three factors have been extracted from existing sources and combined in a physically based model to make rational forecasts of soil erosion.

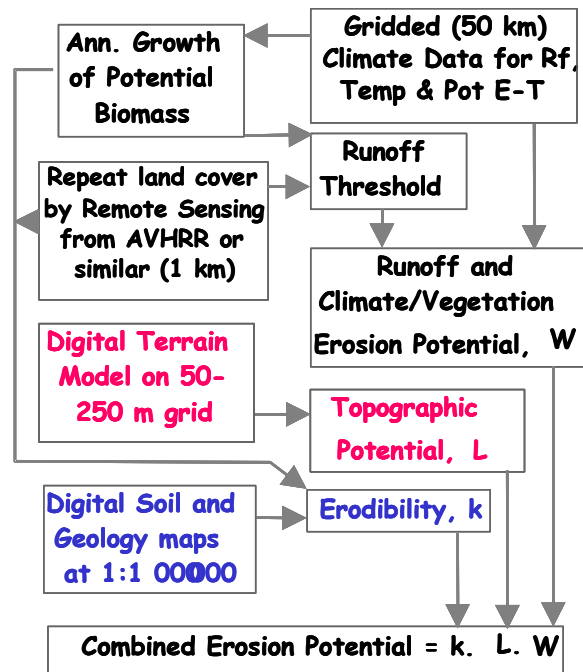


Figure 1. Factors used to estimate erosion rates in the PESERA/RDI model

The model is built in three conceptual stages, explained more fully below.

1. A storage threshold model to convert daily rainfall to daily total overland flow runoff;
2. A power law to estimate sediment transport from runoff discharge and gradient, and interpret sediment transport at the base of the hillside as average erosion loss;
3. Integration of daily rates over the frequency distribution of daily rainfalls to estimate long-term average erosion rates.

Storage Model

PESERA uses the simplest possible storage, or 'bucket' model to convert daily rainfall to daily overland flow runoff. Runoff is estimated as Rainfall minus a threshold storage. The threshold depends on a number of factors related to the soil, vegetation cover, tillage and soil moisture status. The most important soil factors are texture, depth (if shallow) and organic matter that determine the threshold storage beneath the vegetation-covered fraction of the surface. Where the surface is not protected by vegetation, the susceptibility of the soil to crusting and the duration of crusting conditions generally determine a lower threshold. The final threshold is a weighted average from vegetated and bare fractions of the surface. Corrections are made for the soil water deficit, which may reduce the threshold where the soil is close to saturation.

The model is normally linked to a simple biomass model to allow crops or natural vegetation to respond to seasonal variations in available moisture, and allows some subsurface drainage of soil moisture. Alternatively the model can make use of vegetation cover derived from remote sensing. This has the advantage of taking into account factors not included in the model, such as grazing intensity and fire, but does not provide scenario capability. All the factors are assessed on a monthly basis so that the threshold may vary markedly through the year. Calculations are modified appropriately where there is frozen ground or snow cover.

Power law sediment model

Daily total runoff is linearly scaled up to discharge for each point in an area, and daily sediment transport is estimated as:

$$Sediment\ Transport = Erodibility \times (Runoff \times Distance\ from\ divide)^2 \times Gradient$$

Erodibility is primarily associated with the soil texture, but is reduced to allow for a full or partial vegetation cover. Gradient is derived from topographic sources, but will not be required for estimating the whole-slope erosion loss.

If sediment transport is estimated at the slope base, then this expression can be re-written for sediment yield (*Total sediment transport ÷ Total slope length*) as:

$$Sediment\ Yield = Modified\ Erodibility \times Runoff^2 \times Relief$$

Where the modified erodibility includes a small correction factor for the ratio of slope-base local gradient to mean slope gradient (which is implicit in the term *Relief = Total slope Length × Mean gradient*). This allows the use of coarse resolution DEMs which can estimate Relief as the variability of local elevation, without the need to estimate local gradients directly, which is advantageous where DEM point spacing may be of the same order as total slope length.

Estimating long-term average erosion rates

Daily rainfall data is used because of its wide availability. The forecasting model can be used with a time series of daily rainfalls, but maps derived on this basis show a strong signal associated with the historic locations of the largest storms. Instead the map provides a weighted average of annual erosion, summed over the frequency

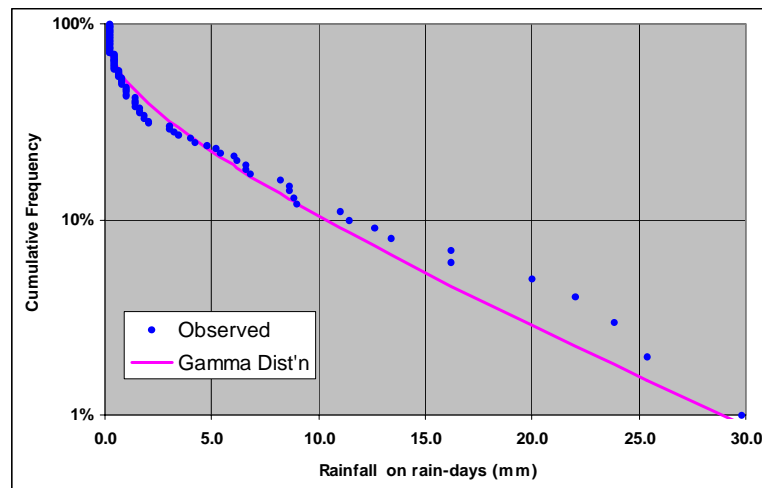


Figure 2: Fitting Gamma distribution to 6 years rainfall data for Nov/Dec: North 1, Nogalte, Murcia (SE Spain) 1997-2002

distribution of daily rainfalls for each month. This frequency distribution is derived from an analysis of historic time series for each month separately, using the number of rain days, mean rain per rain day and its standard deviation to fit a Gamma distribution which

provides an excellent fit (Figure 2) to long data series. The daily runoff and daily erosion for each possible rainfall event is weighted by its frequency in this distribution to estimate the long term averages for each month, and summed to give annual totals.

Integrated model

The calculations described above are performed independently for each cell within a 1 km grid across Europe. The 'one-cell model' is available as an Excel spreadsheet with Visual Basic macros through the PESERA web site (<http://pesera.jrc.it>) and can be used to estimate runoff and erosion rates for a single point, and to show the effect of changes in land use or climate on expected rates. The main or 'grid' model repeats these estimates for each 1km×1km cell within an area, combining data in ARC-Grid format with FORTRAN code, and creating output maps which can be examined or interrogated in ArcView or similar GIS software package. Advice on preparation of the databases and running the grid model can also be obtained through the web site, and a prototype system allows the model to be run remotely for small areas (up to 100 × 100 km) over the Internet.

Calibration and Validation

Because there are only a limited number (about 50-100) of acceptable measures of erosion rates across Europe, and these differ significantly in methodology and scale, a pan-European calibration of erosion rates is not practicable. The overall reliability of the model is based on an internal, intermediate and external calibration.

Internal validation is based on a qualitative and quantitative assessment of the physical representation of processes in the model. This includes our accumulated understanding of process mechanics and their incorporation in the model in a sufficiently simplified form and judgements on which processes should be included.

Intermediate validation is based on comparison with spatial distributions that are forecast within the model as intermediate products. The most important of these distributions is of vegetation cover and abundance, which are derived within the model by combining land use data with a growth model, and can be independently corroborated from remote sensing interpretations. Comparison can also be made with seasonal runoff patterns.

External calibration is based on comparison with erosion plot (40 m²), small catchment (0.01-1 km²) and reservoir (1-100 km²) data (Cerdan, 2003; Tsara *et al*, in press; van Rompaey *et al.*, 2003). These data have been used primarily to modify the pedo-transfer functions, particularly for soil erodibility. Comparative data are considered too sparse to allow a formal independent validation test.

Data: current sources and limitations

Four main datasets are required to run the model, to provide essential climate, soils, land cover and topographic data. These have been made available within the PESERA project from a mixture of public and restricted sources.

Climate data

The MARS database, assembled by the MARS (Monitoring Agriculture with Remote Sensing) Project JRC-Ispra, provides daily time series of rainfall, temperature and potential evapotranspiration, interpolated to a 30 second (approximately 50 km) grid for Europe. These data have been analysed to provide the following monthly data layers for the model:

1. *Rainfall: Number of rain days, mean rain per rain day and its standard deviation* to provide the distribution of daily rainfalls.
2. *Temperature: Mean, mean maximum and mean minimum* required only in areas where there is soil freezing or snowfall.
3. *Potential evapotranspiration* to estimate actual evapotranspiration, plant production and water balance.

These data are available under licence from the MARS Project, JRC-Ispra. The quality may be judged by comparing the inset map of mean annual rainfall based on these data with published national maps derived from individual station data. As one example, there are large difference between the distribution of annual average rainfall for Italy, computed from national archives, compared with the same parameter interpolated from the MARS climatic database (Figure 3). An improved climate database, particularly for rainfall, has the potential to significantly improve the erosion forecasts shown in the main PESERA map.

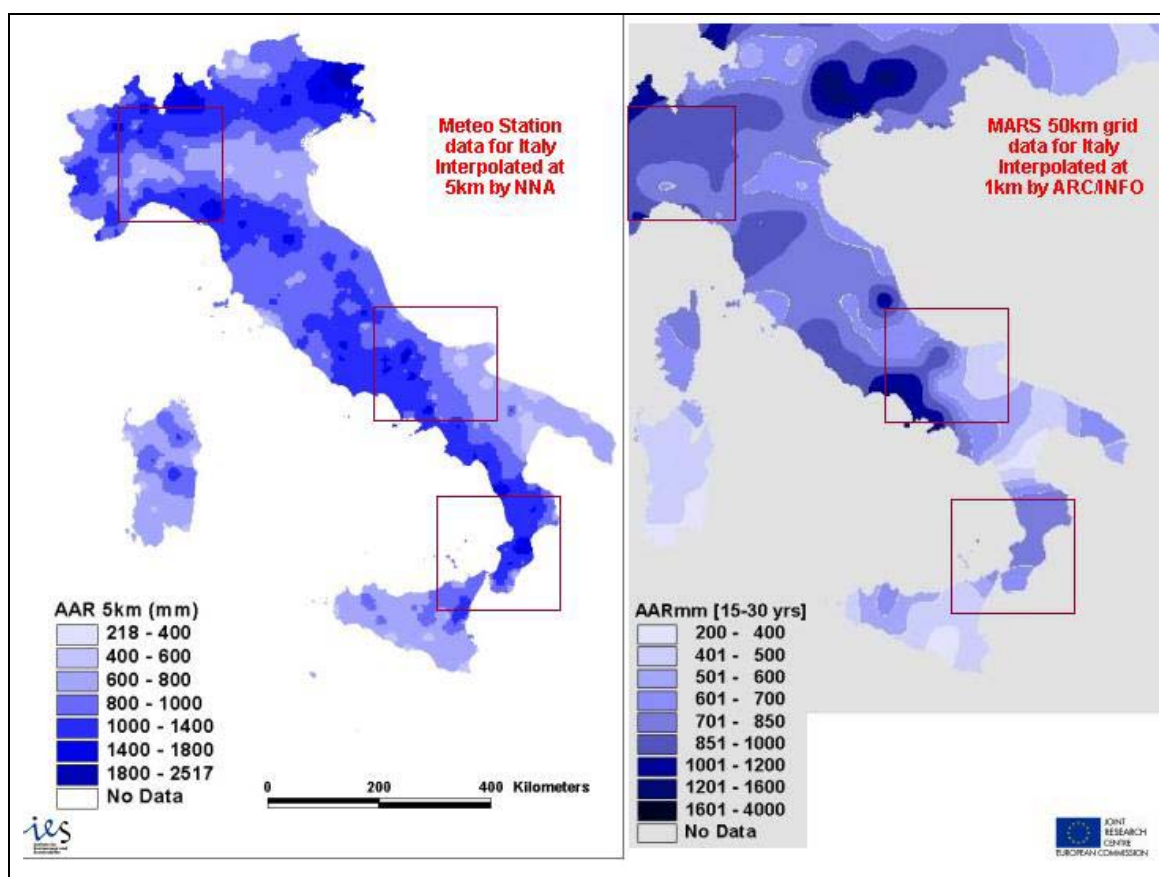


Figure 3. Average annual rainfall from national meteorological network (366 stations) compared to MARS 50km data interpolated to 1km, for Italy.

Soils data

The European Soil Database, compiled by the European Soil Bureau Network, coordinated by JRC-Ispra, has been used to provide a consistent level of soils data at 1 km resolution across Europe. In conjunction with a series of pedo-transfer functions based on work by INRA-Orleans and the JRC-Ispra, the database has been used to provide three data layers for the model:

1. *Soil erodibility*, which converts runoff to erosion rates using the power law for sediment transport.
2. *Readily available Soil Water Capacity*, which provides the maximum storage capacity of the soil before runoff, occurs under vegetation.
3. *Crustability*, which sets the lower limit of storage capacity for a crusted soil in unvegetated areas.

Soil water storage capacity is also used to define the drainage characteristics of the soil. Although there is scope to produce maps individually for these soil properties, and pedo-transfer functions over-simplify the complexities of soil dynamic properties, it is unrealistic to expect major improvements in these variables in the near future. However, some improvement can be made where more detailed soil maps are available for areas of particular interest.

Land cover

Land cover may be derived from remote sensing, or from land use maps in combination with a vegetation growth model. Remote sensing methods use data from AVHRR or LANDSAT imagery. AVHRR provides a 20-year monthly time series at 8 km resolution, and 15 years at 1 km resolution, but is limited by cloud cover in northern Europe. LANDSAT has the potential to provide 30m resolution, but has not been used. All remote sensing methods have the advantage of providing a measure of cover that includes the effects of all factors, but has no direct potential for scenario analysis, and, therefore, land use surveys have been the primary data source for the erosion map. Land use is based on CORINE land cover at 250 m resolution for 1989. CORINE 2000 will shortly become available to update the land use/cover estimates. Land use data are combined with cereal planting dates, generalised from EUROSTAT, to provide the parameters for a crop or natural vegetation growth model.

Topography

A 30 second (1 km) DEM has been available from EROS for some years, and has been provided the topographic basis for work on PESERA, and for the erosion map. The critical parameter for the model is local relief, which has been estimated from DEMs as the standard deviation of elevation within a circle of 3 km diameter around each cell. Comparisons with DEMs at improved resolution (down to 30 m) have shown that this measure is insensitive to DEM resolution, and can therefore be used reliably with the best DEMs available for each area. Recently the SRTM 3 second (90m) DEM has been released for Europe, and this is being used to refine the data layer for local relief.

The future: Land use and climate Scenarios; improvements in data quality

The greatest potential for improvement in these erosion estimates lies in better climate data, and this is potentially available from national archives, although not normally 'free of charge'. Soils data could also be improved in principle, although this is unlikely to occur in the near future. Land cover requires frequent updating, because changes in land use have a major impact on erosion rates. There is the potential to do this through the analysis of remotely sensed images. For scenarios of alternative erosion futures, improvements in GCMs and economic forecasts offer a potential that is still far from full realisation.

Conclusion on limitations

No erosion map at a European scale can be based on detailed knowledge at every point on the continent. Not every factor of local importance can be included in a comprehensive model, and there are some anomalies that are inherent limitations in the data. However, by applying a common methodology, based on physical understanding, throughout Europe, the PESERA map is able to highlight major differences between regions, to highlight areas particularly at risk. It also provides a uniform basis for comparison of erosion estimates across national boundaries and climate zones.

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