Interreg Sudoe climalert

EUROPEAN UNION

European Regional Development Fund

CHAPTER 3.5: Literature review of soil erosion

INDEX

1. Introduction

Erosion is a natural process evolving over geological time scales maintaining the balance between erosion and soil formation (Demangeot, 2002). The current imbalance, favouring erosion, is caused by anthropogenic land use changes and has implications for nutrient and carbon cycling, land productivity and as an economic consequence (Borrelli et al., 2017).

There is much controversy about the value and role of erosion. For some, erosion is the superficial removal of soil, while for others it is simply gullying. Indeed, erosion considers various processes that need to be defined. The purpose is to identify which of them is of interest to our work and would be likely to be monitored by satellite, and furthermore would be available on the Climalert platform. We will focus our research on the temperate and Mediterranean zone corresponding to the SUDOE area.

2. Mechanisms and products of erosion

The process of erosion takes place on surface in 3 stages: removal, transport, and deposition.

2.1. Removal

The dissociation of the material (also named weathering) is done by the action of atmospheric, cosmic, or biological agents. The final product of erosion will differ according to the nature and condition of the material.

Weathering has several origins:

- Mechanical desintregration occurs through alternating expansions and contractions. It encompasses many phenomena gradually emerging: gelifraction (freeze-thaw alternation caused by water filling the pores), solifluction (gradual descent of a water-saturated soil on a slope). In cultivated areas, certain events have become seasonal comprising splash effect (impact of large raindrops on non-coherent soil), sheet erosion (soil is removed by thin layers with the combination of splash erosion and surface runoff), rill erosion (disappearance of soil particles by concentration of flowing water), or even more violent such as gully erosion (flow concentration becomes larger and incision deeper than with rills) and landslides (mudslides) (Morgan 2005). The products are coarse fragments (gravel, sand) and visible to the naked eye. Borrelli et al., 2014 remind that wind erosion occurs when three environmental conditions coincide: i) the wind is strong enough to mobilize soil particles, ii) the characteristics of the soil make it susceptible to wind erosion (soil texture, organic matter and moisture content) and iii) the surface is mostly bare. Contrary to the popular belief, wind erosion is also present in Europe. The Mediterranean countries (Cyprus, Spain, Malta and Italy) have the lowest average erodible fraction values. The highest values appear in the areas surrounding the North Sea and the Baltic Sea, with Poland, Denmark, the Netherlands and northern Germany (Borrelli et al., 2014). Hence the SUDOE area is weakly impacted.

- Chemical weathering through the chemical alteration is more discrete. Water is the most effective agent, finding it in different forms (rain, fog, dew and air humidity). It can dissolve, oxidize, hydrolyze, and reduce the elements present in the soil. Water is also a vector of corrosive substances such as CO_2 which attacks limestone.

  The products are commonly found in solutions and are difficult to monitor.

- Biological erosion, which is not very visible, is not negligible. It can cause mechanical disintegration (e.g. swelling of rootlets) or chemical disintegration with acid roots.

At global scale soil erosion by water is the most important land degradation issue (Eswaran et al, 2001).

2.2. Transport

Transport consists in the movement of debris by an agent (water, wind, etc.). Weather debris is moved downstream by gravity. The size of the transported element varies according to the strength of the agent. Wind can only move fine dust and sand, unlike water. These transport agents and debris are acting as an abrasive when the velocity of the wind or the water is high.

2.3. Deposition

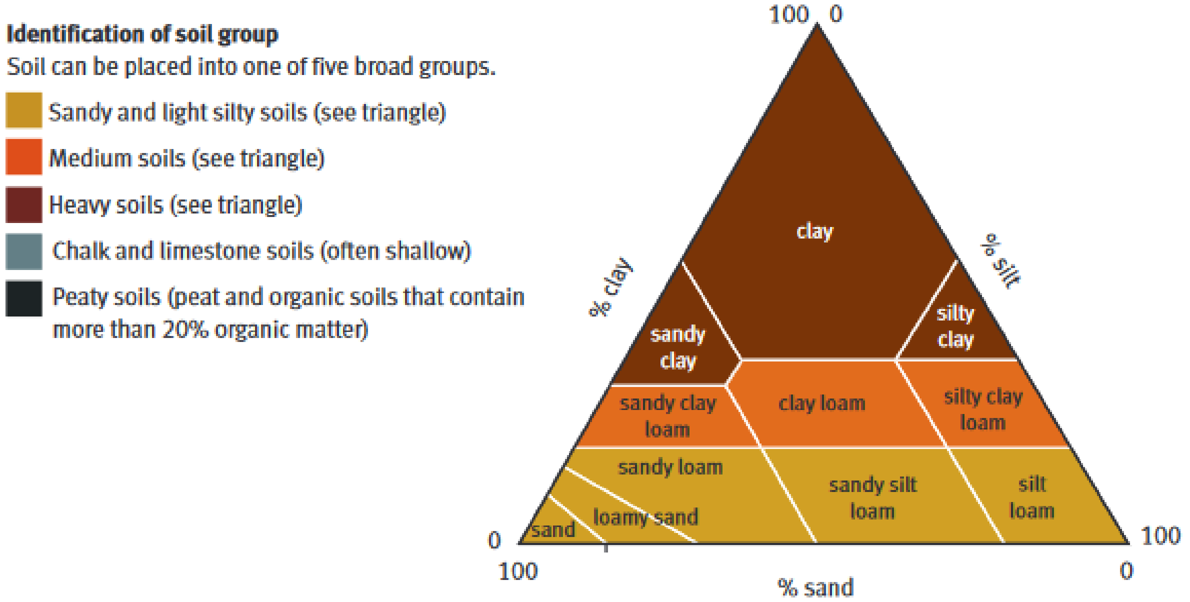
Meteor debris settles in another location as the kinetic energy of transport decreases or cancels out. The most common case is the deposition of elements when the watercourse slows down. This phenomenon can be caused by a flood or by the shape of the stream. The same occurs by the seas with dunes.

3. Erosion control factor

3.1. Soil properties

This part is mainly extracted from (Environment Agency, 2007).

3.1.1. Soil texture



Soil texture refers to the relative proportion of clay, silt, and sand. The risk of runoff and erosion is affected by small differences in texture. This is because texture influences the degree of percolation of water through the soil, and the stability of soil.

Soils containing large proportions of sand have relatively large pores through which water can drain freely. These soils are at less risk of producing runoff. As the proportion of clay increases, the size of the pore space decreases. This restricts movement of water through the soil and increases the risk of runoff. Soils with low clay content are less cohesive and are inherently more unstable.

3.1.2. Soil structure

Soil structure refers to the arrangement of soil particles in the soil. Clay content, organic matter and, in some soils, calcium and iron compounds, help to bind the soil together into structural units, aggregates. Well-structured soils allow the free movement of air and water through fissures (or cracks) between the structural units. Pores within the units also allow the movement of air and water. A soil with poor soil structure has a high risk of generating runoff. The risk of runoff is greatest when poor soil structure is near the soil surface. Soil structure deteriorates when structural units are deformed producing a dense single mass of soil (or large soil units). This occurs when pressure is applied to a wet and soft soil.

Pressure squeezes the soil units together and reduces pore space within the units. A dry soil can withstand pressure without deforming soil structure. Some soils are unstable when clay, calcium or organic matter content is low. Unstable aggregates disperse when wet, forming a solid mass as the soil dries. Where this occurs at the immediate soil surface, the soil may form a cap or crust. Soils can restructure due to natural fracturing processes when clay shrinks and swells, and by cultivation. Biological activity also restructures soil.

Soil containing high levels of organic materials are often more resistant to erosion by improving soil structure. Organic matter ‘cement’ particles of sand, silt and clay, giving water-resistant properties. This complex also improves drainage and moisture holding for use by plants whose growing roots contribute to soil cohesion (NSW government, n.d.).

3.1.3. Soil moisture

Wet soils have greater risk of runoff and erosion. After the summer and in well-structured soils, without deep fissures or cracks, rain wets the soil progressively from the surface. This creates a wetting front that moves down the soil profile. Compacted layers within the soil will affect this wetting front and it may cause areas water puddles across a field.

3.1.4. Soil surface roughness

Rough surfaces (e.g. in ploughed land, coarse seedbeds) help to slow down runoff. Roughness provides storage of rainwater, allowing water to collect before it soaks into the soil. For some fields, extra storage can be created if the ploughed land is worked across a slope and not up and down a slope i.e. the ridge and furrows now act as little dams and storage areas. Rough surfaces also help to reduce wind speed at the immediate soil surface, preventing wind erosion.

3.1.5. Soil cover with plants (see 3.3.2 and 3.4)

A bare soil without vegetation is more vulnerable to erosion than soils covered by plants with roots maintaining the aggregates. No tilling allows maintaining, on the surface and first cm of soil, old biomass from the previous crop, hence fixing the soil and reducing the direct impact of the rain droplets (splashing effect).

3.2. Rainfall

Raindrops can detach and disperse soil particles, washing them into pores, causing sealing of the soil surface, even if there would be no relationship between annual rainfall, erosion, and runoff values (Hudson dans 1969). The real driver of erosion would be the intensity of the rain. The cumulative impact of millions of raindrops hitting the ground loosens fine particles from the surface of the aggregates and carries them in suspension by bouncing off them and creating a "splashing" effect. The kinetic energy of a drop of water, characterized by its mass and velocity, is fundamental for the erosion effect. In the Mediterranean area, the short-term repetition of rainy episodes influences the erosive character. Runoff occurs when rainfall intensity exceeds infiltration rate and the soil becomes saturated at the surface. During winter, soils are often described as being at field capacity. This is the maximum water content held in the soil under free drainage within the micropores. At field capacity, air is held in macropores and the soil can absorb rainfall until it becomes saturated (water takes the room of air into macropores). Naturally well drained soils rarely become saturated and readily absorb most rainfall. Where the surface loses its porosity, runoff can occur on well drained soils when rainfall is as low as 1mm/hr. The more macropores the soil has, the more it can store rainwater during intense storms, but it is generally limited to 10 to 20 mm.

Maps of erosivity using the rainfall erosion index have been produced for the USA (Wischmeier and Smith, 1978) and other parts of the world (Panagos et al., 2014).

3.3. Landscape

3.3.1. Slope effect

Secondary after water, slope and vegetation are the elements that most influence erosion. Slope accelerates the speed of the transport agents and increases the abrasive role. Conversely, it slows down the phenomenon of chemical erosion by circulating water. This slope also has a role in the installation of the plant cover. Large fields with long slopes can accumulate large volumes of water, particularly where water percolation into the soil is slow (on naturally slowly draining soil or where there is poor soil structure or both). Highest risk fields are those greater than 7°. Fields with gentle slopes less than 3° are at lower risk to rapid runoff and erosion. But water can still run and gather momentum on gentle slopes, particularly where the slope is long and infiltration rate is slow. Valley floors can concentrate water flow causing channel erosion (Environment Agency, 2007).

3.3.2. Vegetation cover

“Natural” ground cover and forest are the best form of protection against erosion by protecting the impact of rain, which preserves the soil from mechanical erosion and reduces the effects of the slope. Litter and roots, however, encourage chemical erosion.

3.4. Land-use and agricultural practices

3.4.1. Soil management

Alternative soil management practices to conventional tillage, have been developed, partially encouraged by the concern raised by water erosion. Positive effects of soil conserving farming methods have been demonstrated compare to plough-till and reduced tillage. Prasuhn, 2012 studied the effects over 10 years in Switzerland at a catchment scale considering a large variety of annual crops (e.g. wheat, potato, maize, sugar beet, fallow, rape seed, …). About half of erosion takes place in summer and the highest mean soil loss is dedicated to potato. Indeed, it is difficult to employ soil conserving tillage practises with sufficient soil cover in the production of potatoes. Fallow and winter wheat are quite sensitive, and in contrast soil loss below mean is observed for maize, sugar beet and rape seed.

Soil erosion is extreme in Mediterranean orchards due to management impact (and high rainfall intensities, steep slopes, and erodible parent material). Under olive tree plantations and apricot orchards in Spain, Gomez et al., 2009 and (Keesstra et al., 2016) concluded that chemical weed control that maintains the soil bare without tillage, leads to severe sediment losses and will lead to severe sediment losses and the worsening of the water balance by increasing runoff. On the other side, cover crop soil management improved soil properties during 7 years in an intensive olive plantation on a heavy clay soil.

3.4.2. Crop type

Agricultural areas (especially annual crops) are sensitive to erosion due to alternating vegetation cover and bare soil.
Winter cereals sown during late October and November and summer crops (maize, sunflower, …) seeded during Spring can put the land at risk of runoff and erosion on sandy and light silty soils due to lack of crop cover over the winter and because of the high risk of the soil surface becoming capped.
Land with a fine and smooth seedbed provides little surface storage capacity, and a sandy and light silty soil is at risk of becoming capped causing runoff and erosion. Fine, dry sandy tilths are vulnerable to wind erosion.
Land under winter cereals is at risk to generating runoff where the soil is compacted (e.g. when sowing is carried out on wet soil, or where soil has become compacted during previous land work in the rotation). Crops established by shallow cultivation are at risk of runoff if there is poor soil structure and not much organic matter near the soil surface.
In the same way as rain, with sprinkling irrigation, if the soil infiltration capacity is less than the application rate, runoff starts and flow increases down the land slope, even with sprinkler irrigation which normally uses moderate water application (Boulal et al., 2011).

3.4.3. Agricultural machinery

When cereals are harvested in wet conditions, there is a risk of causing soil compaction and runoff. Compacted tramlines and wheelings are at most risk of runoff, especially when aligned up and down a slope. Wheelings and cultivation marks can also influence the direction of water movement. Field tracks and roads provide a route-way for runoff, soil sediment and associated pollutants to enter watercourses. Roads and field tracks can link fields with watercourses that are kilometres apart. Runoff from roads and adjacent land can also wash onto fields causing field runoff and erosion. Furthermore, soil compaction affects the permeability of the soil to water. More compacted soils will have a larger amount of surface runoff than less ones.
Growing root crops and vegetables often involves deep cultivation, stone removal and clod separation, bed forming, and use of plastic. In steep fields, rows and beds are formed up and

down the slope because harvesting equipment cannot operate across the slope. Rows and beds channel water downhill increasing the risk of rapid water runoff (Environment Agency, 2007).

4. Spatial erosion assessment

4.1. Remote sensing observation

Remote sensing is characterized by the acquisition of information of an object at a distance, generally from satellite and airborne images (including UAV). The UAV technique demonstrates a high level of flexibility and can be used, for instance, after a major erosive event. It delivers a very high resolution DEM (pixel size: 6 cm) which allows us to compute high resolution runoff pathways and to quantify gully erosion (Pineux et al., 2017). According to Neugirg et al., 2016 and their study on Calanchi Badlands, UAV photographs are ideal methods to analyse and quantify denudation and erosion processes.
Even though the UAV has the advantage of covering a relatively large area (few km²), our study area extends over the entire Sudoe zone. In operational context, the use of products that operate routinely with a minimum of intervention is to be favoured. Then satellite appears as the optimal solution, moreover many types of satellite images and image-derived products obtained from earth-observing space missions are presently available free of charge (e.g. Sentinel or Landsat constellations). UAV or airborne images have to be privileged to areas presenting more specific risks (e.g. after a significant event according to Pineux et al., 2017).

4.2. Mechanisms identified by satellite

In past years, multispectral satellite images were adopted to detect erosion features and eroded areas (e.g. large and medium-sized gullies and badlands) or erosion consequences (e.g. water quality assessment in terms of suspended sediments in reservoirs and lakes) (Vrieling, 2007). The scale or resolution of these data should correspond with the desired output scale of the mapping exercise (Woodcock and Strahler, 1987). Eroded areas larger than 1 ha may in some cases be distinguished from surrounding because vegetation cover is reduced (Pickup and Nelson, 1984), soil properties have changed (Hill et al., 1995) or random changes appeared (Lee and Liu, 2001). However, these applications are generally limited to (semi) arid natural and rangeland environments. In more humid region, vegetation covers the visibility of soil and agricultural activities greatly influence vegetation cover, soil properties and surface roughness with a very high degree of heterogeneity within a watershed.

The complexity of the mechanisms characterising erosion makes its monitoring by remote sensing complex. An indirect observation, through the factors, is then easier.

4.3.Controlling factors from satellite

The other, indirect, way to assess erosion is to monitor the erosion factors including climate, soil, terrain, and vegetation characteristics.

Mechanisms and products of erosion	
Removal	✗: slow evolution, lack of spatial resolution
Transport	
Deposition	
Soil properties	
Soil texture and structure	✗: information only on the surface, often hidden by the vegetation cover
Soil moisture	✓
Soil surface roughness	✓
Weather and rainfall	
	✗: suited for ungauged areas (Marra et al., 2017)
Landscape	
Slope	✓
Vegetation cover	✓
Land-use and practices	
Crop type	✓
Agricultural machinery	✗: lack of spatial resolution, not visible on the surface

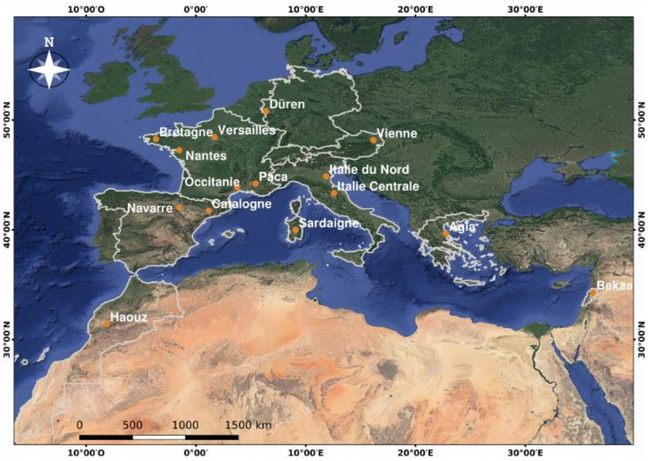
4.3.1. Factors derivation: from method to operational

The rainfall amount and intensity are precious climate parameters for erosion studies. It must be coupled to the attributes of the slope using digital elevation models at a fine resolution scale.

Soil moisture monitoring

Literature: Soil moisture monitoring requires frequent and well distributed information which is available at low spatial resolution thanks to SMOS (resolution of ~30 km × 30 km), SMAP (resolution ~36 km × 36 km), or ASCAT (resolution ~25 km × 25 km). Spatial disaggregation helps to improve this resolution until the arrival of the new constellation Sentinel-1 operating in C-band. From C- or X-bands SAR data the soil moisture is inverting using statistical models or physical. The first requirement is the easiest to set up but site-specific calibration is necessary. The most widely used physical models are the Integral Equation Model (IEM) in bare soil situation and the Water Cloud Model (WCM) for soils under vegetation cover. These models are quite accurate with errors under 10 vol % and are even improved using neural network techniques to invert backscattering models and to estimate soil moisture (El Hajj et al., 2017).

Operational: Irstea (UMR Tetis) and Cnes developed an algorithmic to produce humidity maps by combining the IEM and WCM models with a neural network. The data used were taken from the Copernicus Sentinel 1 radar and Sentinel 2 optical image series. The radar signal inversion algorithm uses neural networks. It is applied on agricultural plots (with or without vegetation). Sentinel 2 images were used to calculate the Normalized Vegetation Index (NDVI). This index is required as input to the inversion algorithm, on the one hand, to segment the agricultural areas from the land use map, and, on the other hand, to simulate the contribution of vegetation to the total radar signal received by the satellite. Segmentation makes it possible to extract homogeneous polygons within agricultural plots and thus to propose objects finer than the plot contour. Superficial (few centimetres) soils moisture estimation on the campaign near the city of Montpellier (nearly 500 in situ measurements) reaches an accuracy of about 6 vol.%.



Data can be downloaded: https://thisme.cines.teledetection.fr/#!/home

Soil surface roughness

Literature: The commonly used techniques for measuring soil roughness are laser scanner, photogrammetry, and mechanic profilometer. The roughness is often presented as the standard deviation of the surface height (root mean square surface height, Hrms), defining the vertical scale of the roughness. For 95% of in situ measurements in agricultural areas, Hrms ranges from 0.25 cm for extremely smooth soils to 4 cm for ploughed fields, and the correlation length ranges between 2 and 20 cm (Baghdadi et al., 2016). It is generally very difficult to retrieve the roughness by inverting the backscattered radar signals of current SAR sensors. Despite the new perspectives offered by the new C-band radar satellites Sentinel-1 (in 2014), the possibility of retrieving surface roughness is insufficiently investigated, but it is still in investigation. (Baghdadi et al., 2018) even concluding as results “that the use of C-band in VV polarization for estimating the soil roughness does not allow a reliable estimate of the soil roughness”.

Operational: up to date, no known service or product available

Slope and topography derivation

Literature: Digital Elevation Models (DEM) data are available for parts and the whole of the Earth’s surface at different spatial resolution from a range of sources. Airborne and spaceborne are more efficient than ground methods with a vast sampling. Publically and freely available DEMs with global coverage originate from spaceborne topographic mapping missions, notably from the SRTM and ASTER missions at about 30 m of spatial resolution. For ASTER or SRTM, information cannot be ambiguously attributed to either the ground or the top of canopy. Overall, both represent terrain heights at the 10 m accuracy level. Other products are commercially available with a higher spatial resolution (e.g, InSAR and TanDEM-X: about 12 m, ALOS: 5 m). For specific areas, extremely detailed DTMs have been produced from airborne laser scanning with often 1-meter resolution and sub-m-precision (Hirt, 2014).

For specific area and time, DEM can be derived from UAV images with a very fine resolution (few centimetres). Pineux et al., 2017 reminds that the georeferencing can be difficult, hence ground point controls are adjusted manually by respecting the minimal absolute error MAE of 4 cm which time consuming.

Operational: EU-DEM is a precisely a digital surface model (DSM) of EEA member and cooperating countries representing the first surface as illuminated by the sensors. It is a hybrid product based on SRTM and ASTER GDEM data fused by a weighted averaging approach to obtain the 25 m spatial resolution (DEM can be download at https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem). At national scale:

- France: a product named Litto3D is freely available at 1m resolution for some coastal areas (https://data.shom.fr/donnees).
- Portugal: no better model is known at finer resolution.
- Spain: an open DEM is available at 5m resolution even 2m for some part of the country (http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=LIDA2).

Vegetation cover & crop type

Literature: The main advantage of using satellite Remote Sensing data within soil erosion studies is the ability to account for seasonal variability of vegetation. In temperate regions, vegetation cover often obscures the visibility of the soil, whereas agricultural activities may furthermore greatly influence vegetation cover, soil properties, and surface roughness. In cases where optical data suffer from a lack of information (cloud cover and shadows), radar images offer new opportunities. For this section, please refers to the detailed part "CHAPTER 3.2: Crop biomass and yield estimation based on satellite images."

Operational: Theia Land Cover SEC produces automatically land cover maps for Metropolitan France using Sentinel-2A and Sentinel-2B data. These maps have a 10-meters resolution and are available for the 2018 and 2019 years using 23-categories nomenclature (https://www.theia-land.fr/product/carte-doccupation-des-sols-de-la-france-metropolitaine/).

As far as we know no map is available in real time during the season.

Spain is covered by the SIOSE product on a scale of 1:25,000 for the years 2005, 2011 and 2014.

For all the SUDOE countries, the CORINE Land Cover (CLC) inventory has been produced in 2000, 2006, 2012, and 2018. Updates have been produced in 2000, 2006, 2012, and 2018. It consists of an inventory of land cover in 44 classes. CLC uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena (scale of 1:100.000). Products can be downloaded at https://land.copernicus.eu/pan-european/corine-land-cover.

A new open source system, named Sen2-Agri, automatically ingests and processes Sentinel-2 and Landsat 8 time series in a seamless way to derive: cloud-free composites, dynamic cropland masks, crop type maps and vegetation status indicators. This system is based on machine learning algorithms and quality controlled with *in situ* data. The independent validation of the monthly cropland masks provided overall accuracy values higher than 90%, and already higher than 80% as early as the mid-season. The crop type maps depicting the 5 main crops for the considered study sites were also successfully validated (Defourny et al., 2019).

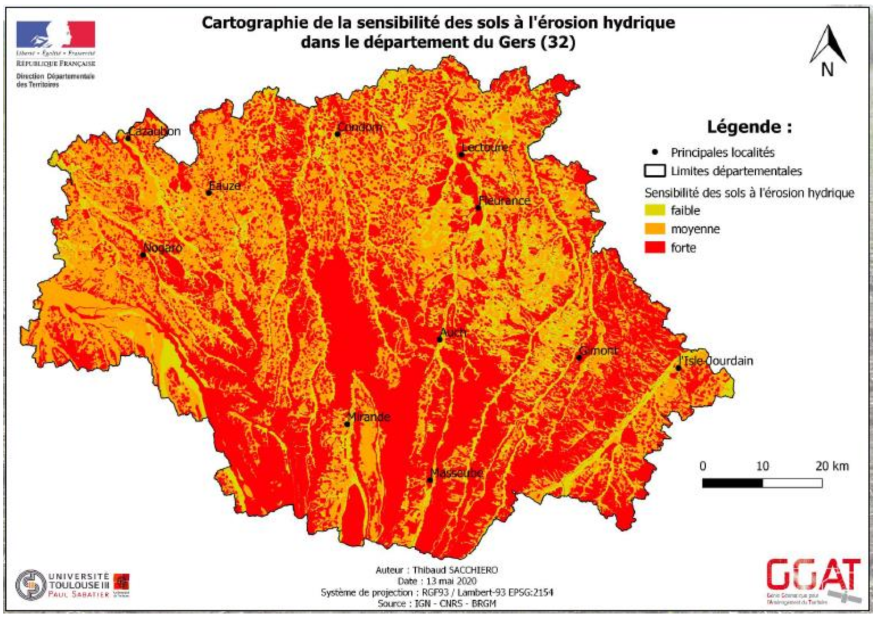
4.3.2. Examples of work using satellite imagery

The “Direction Départementale des Territoires du Gers” created a map of sensitivity to water erosion. The method consists of 2 main steps:

- Determination of the structural sensitivity of soils to water erosion by cross-referencing 4 classified factors: slope (IGN DTM, accuracy 5 metres), pedology (INRAE, scale 1: 250,000), lithology (BRGM, scale 1: 50,000), land use (IGN GE CSO, scale 1: 5,000).
- Consideration of cyclical elements that can aggravate structural sensitivity: detection of bare soil in "real time", particularly during periods when rainy episodes are the most erosive. ESA's Sentinel 2A/B images for the year 2018-2019 were used in this phase of identifying the actual land use in an automated process:
- Calculation of the vegetation index (NDVI)
- NDVI crossover / areas of high structural sensitivity
- Export of plots with bare soil surface > 30 %.

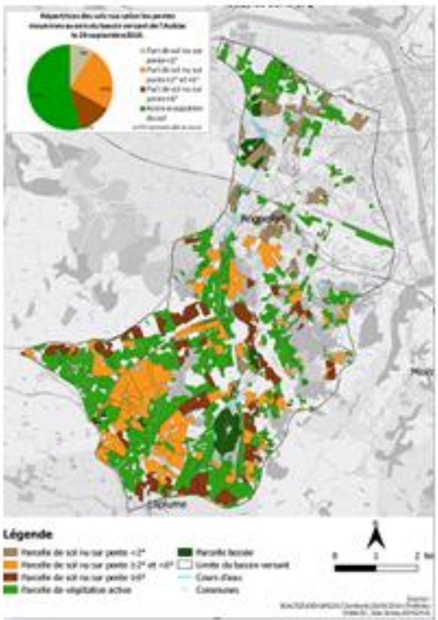
The method is reproducible at larger scale throughout SUDOE and at different scales. The updating of the bare soil indicator from the NDVI is automated, making it possible to monitor the evolution of "at-risk" plots almost in real time.

The main limit is the update frequency of satellite images (Sentinel 2A, 2B) specially in cloud conditions. It is also necessary to take into account the diversity of the scales of the input data.

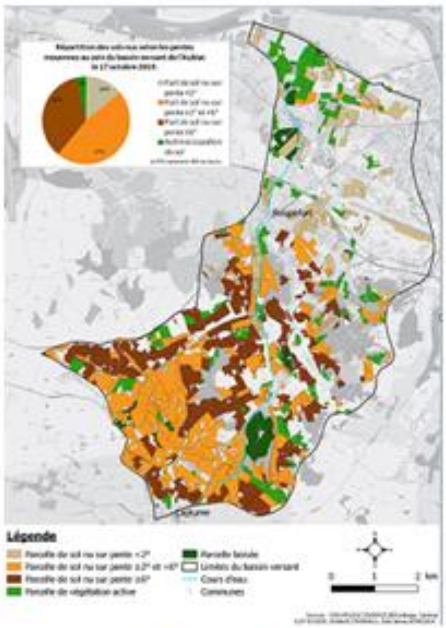


To overcome the presence of cloud, the ACMG developed in 2018 a method to determine the majority occupation of agricultural plots in order to quantify and qualify the erosion risk using Sentinel 1 radar satellite imagery. The land occupations are divided into four categories: active vegetation (vegetation able to retain runoff flows), wood, vineyard and bare soil. Bare soil on a significant slope (greater than or equal to 6°) is a potential source of erosion during climatic hazards.

These maps allow to link the sludge flow phenomena observed in municipalities with land use. Local authorities thereby are able to assess the risk and have the documents to take action. As we recall, actions must above all be based on an exchange between the actors.



29 Septembre



17 octobre

4.3.3. Multi-temporal or punctual

The most dynamic factors of erosion are rainfall and vegetation that evolve over several months. Hence the solution is to assess the factors continuously using multi-temporal satellite imagery thanks to satellite constellations. Low spatial resolution (e.g. MODIS at 1 km of pixel size and a swath of 2330 km) offers one day of revisiting while for high spatial resolution few days are necessary to acquire information (e.g. 16 days for Landsat with 30 m resolution). Since 2016 and the arrival of the Sentinel constellation the pixel size and repetitivity have been respectively reduced to 10m and 10 days (5 with Sentinel-2b). As a result of these improvements, high spatial resolution is now affordable for multi-temporal monitoring.
Other phenomenon such as soil properties may be altered on short time-scales due to e.g. tillage or crusting. Mono-temporal acquisition should be used to evaluate these new conditions under the highest erosion risk.

4.3.4. Mapping accuracy

Any erosion map will result in a nice-looking map, but without validation of the results it is unknown whether the obtained results are accurate. A proper validation of presented results is required, which currently is not or poorly done in many studies. Validation is essential for identifying methods that allow accurate mapping and monitoring of erosion. Long-term erosion field measurements and detailed field surveys are indispensable for this purpose, although costly and time-consuming. Close collaboration between the remote sensing community and field-based erosion scientists is therefore required, and accordingly forms the key towards achieving regional operational erosion monitoring systems (Vrieling, 2007). Devices can be installed to gather ground data information. For instance, erosion pins can be deployed to estimate rates of change in land surfaces, specifically for bare and undisturbed environments. They may be used for short- and long-term surveys and are quick and easy to install and measure (Boardman and Favis-Mortlock, 2016).

5. Erosion modelling

The spatial assessment of soil erosion cannot be deduced directly from satellite observation. The previous factors, derived from the satellite, must be implemented in models. These models are simple schematic representations of reality by integrating the main erosion processes.

5.1. Local measures or observation of specific forms

Spatial assessment of soil erosion can be done by monitoring soil erosion rates at different locations using some measuring device or erosion plots (Hudson, 1993; Mirás-Avalos et al., 2020). However, accurate measurements are generally expensive and time-consuming, standard equipment is hardly available (Stroosnijder, 2005), and measurement results may be highly variable under similar circumstances (Nearing et al., 1999). The evaluation of the specific degradation of an entire watershed can be calculated by taking the weight or volume of solid transport and dissolved substances exported by the annual drainage, all in relation to the unit of surface area. The transport of funds (coarse sands, gravel) and dissolved matter is rarely counted. Finally, field measurements are mostly used for assessing the role of a specific erosion factor, model development, or validation purposes but cannot be extended on a larger scale (Demangeot, 2002).

Another approach is the observation identified features due to erosion processes, such as pedestals or rills. This method is based on qualitative criteria by classifying the degree of erosion. This requires a significant amount of fieldwork as these forms can appear punctually, particularly according to the agricultural calendar. Only small catchments of about 2-km^2 are concerned (Vrieling, 2007).

5.2.Erosion model

Erosion models are all developed for a certain region and scale, and transferring a model to other scales or regions is not straightforward and may give poor or erroneous results (Vrieling, 2007). An ideal model would describe all the individual processes on the basis of hydraulics, hydrology and sediment transport theory equations, providing the basin response in terms of volume of sediments passing through the closing section for a given input rainfall. However, nowadays there are many simplified models in the literature.

(Gianinetto et al., 2019a) classify models based on their constitutive framework, as follow: empirical models; conceptual models; and physics-based erosion and sediment transport models.

5.2.1. Empirical models

Empirical models do not depend on a rigorous description of the physical process and require few computational costs and a priori information. They are useful for estimating soil loss at a catchment scale when limited data and input parameters are available (Merritt et al., 2003). The most widely used empirical models are Universal Soil Loss Equation (USLE) and its derivatives, Revised USLE (RUSLE), Modified USLE (MUSLE) (Wischmeier and Smith, 1978), and AGricultural Non-Point Source pollution model (AGNPS) (Young et al., 1989) or SEdiment Delivery Distributed (SEDD) (Ferro and Porto, 2000). Many other erosion models exist that allow spatial mapping of erosion.

We will focus on the RUSLE model (Renard and Ferreira, 1993) which is widely used in the scientific community. RUSLE estimates the annual potential soil erosion rate E [t ha-1 yr-1] through five parameters, as follows: $E = R \times K \times LS \times C \times P$

where: R is the rainfall erosivity [MJ mm ha-1 h-1 yr-1], also called R-factor, which is the driving force of erosion and is a function of precipitation rate, air temperature and snow cover dynamics; K is the soil erodibility [t ha h ha-1 MJ-1 mm-1], also called K-factor, which

describes the soil properties (i.e. soil structure and organic matter content) that influence the predisposition of soil to erosion; LS [-] is a dimensionless combined parameter, also called LS-factor, that describes the impact of slope length and slope steepness on soil erosion; C [-] is a dimensionless parameter, also called C-factor, that describes how land-use and land-cover protect the soil from erosion (lower C-factor values correspond to higher protection, thus to lower erosion); P [-] is a dimensionless parameter, also called P-factor, that describes the impact of soil conservation practices to reduce the potential erosion.
Gianinetto et al. (2019b) proposed a revised version: D-RUSLE for Dynamic RUSLE. It allows the intra- and -inter-annual variability of land use and land cover using satellite imagery through the NDVI index.

5.2.2. Conceptual models

Conceptual models describe the watersheds with a series of storage units and incorporate the general description of the catchment dynamics in terms of the underlying processes of sediment and runoff generation (Merritt et al., 2003). Some examples are field scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980) and LArge Scale Catchment Model (LASCAM) (Viney and Sivapalan, 1999).

5.2.3. Physics-based erosion and sediment transport models

Physically based erosion and sediment transport models use the mass conservation equation for flow and sedimentation processes simulation. They can describe the different phenomena contributing to erosion and their interactions, simultaneously. The rigorous description of the physical processes makes possible to extend their use to areas with very different characteristics. Although providing a more realistic representation of the processes, these models can suffer from high uncertainty due to a large number of input parameters required, that often need to be calibrated against observed data (Merritt et al., 2003). Some examples are EUROpean Soil Erosion Model (EUROSEM) (Morgan et al., 1998), Water Erosion Prediction Project (WEPP) (Laflen et al., 1991) and Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1980).
In a context of availability of input data, it would be preferable to favour the use of simple methods allowing global scale applications with reasonably accurate results. Outcomes of these methods are generally a qualitative measure of erosion risk, which is the relative risk that erosion will occur at a certain location as compared to other locations in the region mapped. Spatial data are needed for the application of these erosion models.

5.3. Conclusions

Erosion is characterized by 3 mechanisms: abrasion, transport, and deposition. It is the result of complex processes induced by a multitude of factors (soil properties, relief, anthropic impact...). The impact of erosion is real on the quality of soils and their sustainability. Even if exceptional events may occur, these processes must be considered over the long term, which makes it all the more difficult to measure. Several local measurement methods can be put in place, but they remain expensive. Remote sensing allows observation of the main factors on a larger scale. Since the arrival of the Sentinel mission (in addition to the Landsat program), the high temporal and spatial resolution of the radar and optical images allow filling gaps, particularly in temperate zones with cloudy conditions. Several factors such as soil moisture, surface roughness, topography and vegetation cover can be monitored with this type of image at a regional scale. However, gaps such as the automatic detection of individual erosion features like gullies or medium-sized rills requires a finer spatial resolution only available using UAV. These data must be preferred for specific area and event.

Satellite information can be coupled to modelling in order to understand all the processes characterizing erosion. Satellite-derived vegetation information has been the most important input for erosion mapping approaches. For simple empirical models generally one well-timed image is sufficient, but for process-based models multi-temporal imagery is often needed to account for seasonal variability of vegetation cover.

Due to the complexity of erosion processes, regional differences, and scale dependency, it cannot be expected that a standardized operational erosion assessment system using satellite data will be developed soon.

6. References

Baghdadi, N., Choker, M., Zribi, M., Hajj, M., Paloscia, S., Verhoest, N., Lievens, H., Baup, F., Mattia, F., 2016. A New Empirical Model for Radar Scattering from Bare Soil Surfaces. Remote Sensing 8, 920. https://doi.org/10.3390/rs8110920

Baghdadi, N., El Hajj, M., Choker, M., Zribi, M., Bazzi, H., Vaudour, E., Gilliot, J.-M., Ebengo, D., 2018. Potential of Sentinel-1 Images for Estimating the Soil Roughness over Bare Agricultural Soils. Water 10, 131. https://doi.org/10.3390/w10020131

Beasley, D.B., Huggins, L.F., Monke, E.J., 1980. ANSWERS: A model for watershed planning. American Society of Agricultural and Biological Engineers. https://doi.org/doi: 10.13031/2013.34692

Boardman, J., Favis-Mortlock, D., 2016. BRITISH SOCIETY FOR GEOMORPHOLOGY. Geomorphological Techniques 10.

Borrelli, P., Ballabio, C., Panagos, P., Montanarella, L., 2014. Wind erosion susceptibility of European soils. Geoderma 232–234, 471–478. https://doi.org/10.1016/j.geoderma.2014.06.008

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K.V., Montanarella, L., Panagos, P., 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications 8. https://doi.org/10.1038/s41467-017-02142-7

Boulal, H., Gómez-Macpherson, H., Gómez, J.A., Mateos, L., 2011. Effect of soil management and traffic on soil erosion in irrigated annual crops. Soil and Tillage Research 115–116, 62–70. https://doi.org/10.1016/j.still.2011.07.003

Defourny, P., Bontemps, S., Bellemans, N., Cara, C., Dedieu, G., Guzzonato, E., Hagolle, O., Inglada, J., Nicola, L., Rabaute, T., Savinaud, M., Udroiu, C., Valero, S., Bégué, A., Dejoux, J.-F., El Harti, A., Ezzahar, J., Kussul, N., Labbassi, K., Lebourgeois, V., Miao, Z., Newby, T., Nyamugama, A., Salh, N., Shelestov, A., Simonneaux, V., Traore, P.S., Traore, S.S., Koetz, B., 2019. Near real-time agriculture monitoring at national scale at parcel resolution: Performance assessment of the Sen2-Agri automated system in various cropping systems around the world. Remote Sensing of Environment 221, 551–568. https://doi.org/10.1016/j.rse.2018.11.007

Demangeot, J., 2002. Les milieux “naturels” du globe, Armand Colin. ed.

El Hajj, M., Baghdadi, N., Zribi, M., Bazzi, H., 2017. Synergic Use of Sentinel-1 and Sentinel-2 Images for Operational Soil Moisture Mapping at High Spatial Resolution over Agricultural Areas. Remote Sensing 9, 1292. https://doi.org/10.3390/rs9121292

Environment Agency, 2007. Think Soils Manual (No. GEHO1007BSCV-E-E). Environment Agency (UK).

Ferro, V., Porto, P., 2000. Sediment Delivery Distributed (SEDD) Model. Journal of Hydrologic Engineering 5. https://doi.org/10.1061/(ASCE)1084-0699(2000)5:4(411)

Gianinetto, M., Aiello, M., Polinelli, F., Frassy, F., Rulli, M.C., Ravazzani, G., Bocchiola, D., Chiarelli, D.D., Soncini, A., Vezzoli, R., 2019a. D-RUSLE: a dynamic model to estimate potential soil erosion with satellite time series in the Italian Alps. European Journal of Remote Sensing 52, 34–53. https://doi.org/10.1080/22797254.2019.1669491

Gianinetto, M., Aiello, M., Polinelli, F., Frassy, F., Rulli, M.C., Ravazzani, G., Bocchiola, D., Chiarelli, D.D., Soncini, A., Vezzoli, R., 2019b. D-RUSLE: a dynamic model to estimate potential soil erosion with satellite time series in the Italian Alps. European Journal of Remote Sensing 52, 34–53. https://doi.org/10.1080/22797254.2019.1669491

Gomez, J., Sobrinho, T., Giraldez, J., Fereres, E., 2009. Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. Soil and Tillage Research 102, 5–13. https://doi.org/10.1016/j.still.2008.05.005

Hill, J., Mégier, J., Mehl, W., 1995. Land degradation, soil erosion and desertification monitoring in Mediterranean ecosystems. Remote Sensing Reviews, 107–130.

Hirt, C., 2014. Digital Terrain Models, in: Grafarend, E. (Ed.), Encyclopedia of Geodesy. Springer International Publishing, Cham, pp. 1–6. https://doi.org/10.1007/978-3-319-02370-0_31-1

Hudson, N., 1993. Field measurement of soil erosion and runoff. Food and Agriculture Organization, Rome, Italy FAO Soils Bulletin.

Keesstra, S., Pereira, P., Novara, A., Brevik, E.C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., Cerdà, A., 2016. Effects of soil management techniques on soil water erosion in apricot orchards. Science of The Total Environment 551–552, 357–366. https://doi.org/10.1016/j.scitotenv.2016.01.182

Knisel, W., 1980. CREAMS: A field scale model for chemicals, runoff, and erosion from agricultural management systems, Science and Education Administration.

Laflen, J.M., Lane, L.J., Foster, G.R., 1991. WEPP: A new generation of erosion prediction technology. Journal of Soil and Water Conservation 34–38.

Lee, H., Liu, J., 2001. Analysis of topographic decorrelation in SAR interferometry using ratio coherence imagery. IEEE Transactions on Geoscience and Remote Sensing 39, 223–232.

Marra, F., Morin, E., Peleg, N., Mei, Y., Anagnostou, E.N., 2017. Intensity–duration–frequency curves from remote sensing rainfall estimates: comparing satellite and weather radar over the eastern Mediterranean. Hydrology and Earth System Sciences 21, 2389–2404. https://doi.org/10.5194/hess-21-2389-2017

Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environmental Modelling & Software 18, 761–799. https://doi.org/10.1016/S1364-8152(03)00078-1

Mirás-Avalos, J.M., Ramírez-Cuesta, J.M., Fandiño, M., Cancela, J.J., Intrigliolo, D.S., 2020. Agronomic Practices for Reducing Soil Erosion in Hillside Vineyards under Atlantic Climatic Conditions (Galicia, Spain). Soil Systems 4, 19. https://doi.org/10.3390/soilsystems4020019

Morgan, R.P.C., Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., Styczen, M.E., 1998. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms 23, 527–544. https://doi.org/10.1002/(SICI)1096-9837(199806)23:6<527::AID-ESP868>3.0.CO;2-5

Nearing, M., Govers, G., Norton, LD., 1999. Variability in soil erosion data from replicated plots. Soil Science Society of America Journal, 1829–1835.

Neugirg, F., Stark, M., Kaiser, A., Vlacilova, M., Della Seta, M., Vergari, F., Schmidt, J., Becht, M., Haas, F., 2016. Erosion processes in calanchi in the Upper Orcia Valley, Southern Tuscany, Italy based on multitemporal high-resolution terrestrial LiDAR and UAV surveys. Geomorphology 269, 8–22. https://doi.org/10.1016/j.geomorph.2016.06.027

NSW government, n.d. Soil organic matter [WWW Document]. URL https://www.dpi.nsw.gov.au/agriculture/soils/structure/organic-matter

Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., Alewell, C., 2014. Soil erodibility in Europe: A high-resolution dataset based on LUCAS. Science of The Total Environment 479–480, 189–200. https://doi.org/10.1016/j.scitotenv.2014.02.010

Pickup, G., Nelson, J., 1984. Use of Landsat radiance parameters to distinguish soil erosion, stability, and deposition in arid Central Australia. Remote Sensing of Environment 16, 195–209.

Pineux, N., Lisein, J., Swerts, G., Bielders, C.L., Lejeune, P., Colinet, G., Degré, A., 2017. Can DEM time series produced by UAV be used to quantify diffuse erosion in an agricultural watershed? Geomorphology 280, 122–136. https://doi.org/10.1016/j.geomorph.2016.12.003

Prasuhn, V., 2012. On-farm effects of tillage and crops on soil erosion measured over 10 years in Switzerland. Soil and Tillage Research 120, 137–146. https://doi.org/10.1016/j.still.2012.01.002

Renard, K.G., Ferreira, V.A., 1993. RUSLE Model Description and Database Sensitivity. Journal of Environmental Quality 22. https://doi.org/10.2134/jeq1993.00472425002200030009x

Stroosnijder, L., 2005. Measurement of erosion: is it possible? Catena, 162–173.

Viney, N.R., Sivapalan, M., 1999. A conceptual model of sediment transport: application to the Avon River Basin in Western Australia. Hydrological Processes 13. https://doi.org/10.1002/(SICI)1099-1085(19990415)13:5<727::AID-HYP776>3.0.CO;2-D

Vrieling, A., 2007. Mapping erosion from space. Wageningen.

Wischmeier, W., Smith, D., 1978. Predicting rainfall-erosion losses: A guide to conservation planning. Agricultural Handbook US Department of Agriculture.
Woodcock, C., Strahler, A.H., 1987. The factor of scale in remote sensing. Remote Sensing of Environment 311–332.
Young, R.A., Onstad, C.A., Bosch, D.D., Anderson, W.P., 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. Journal of Soil and Water Conservation March 168–173.