Evaluating, Monitoring and Forecasting Erosion

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Abstract: This century, numerous methods of erosion evaluation have been developped by researchers of various disciplines in relation to their objectives, processes, ecological conditions and time, people and funds available. This note report an approach and some methods efficient to evaluate quickly the present erosion status, to measure at various scales processes and factors explaining their intensity, and finally to forecast erosion risks in relation to specific scenarios. Evaluating erosion status can be made by fast observation of the intensity of erosion processes, soil surface features, and inquiries to compare this diagnostic to the farmers one. Measuring erosion rate requires statistical design at various scales in relation to objectives : microplots ($1m^2$) for infiltration dynamic, plots ($100\ m^2$) for sheet and rill erosion, fields ($N \times 1{,}000m^2$) for sheet and linear erosion and deposition of farming systems, gullies or microwatersheds for channel erosion and deposition behind antierosive systems. Forecasting must be validated by observations, local measurements and spatial extension of efficient indicators with GIS. Till now, empirical models adapted to local conditions are more efficient that numerous process based models.
Keywords : methodology, erosion evaluation, monitoring, erosion risks forecasting

1 Introduction

Methods to evaluate erosion risks are recent and numerous, depending on processes, spatio-temporal scales, objectives and disciplines concerned.

Geomorphologist are studying processes and denudation rates in order to explain the landscapes evolution at the regional scale. They begon with naturalistic approach : observations on terraces systems, natural differences of elevation of the soil surface (erosion pins, pegs, paint collars, pedestal, tree mounds, cross sections of rills, gullies & mass movements, sediment trapped in reservoirs, etc)(Rapp *et al*., 1972). They are now modelling the proccesses and studying their extension with GIS and indicators.

Soil scientists and agronomists developped networks of runoff plots (1930 in USA, 1956 in Africa) to measure water, soil, nutrients and pollutant losses in relation to cultivation and antierosive practices, slopes, soil erodibility, rainfall erosivity: these data were included in empirical models like USLE, RUSLE, MUSLE allowing to define conservation approaches to reduce erosive risks under the tolerable level. Presently the tendency is to use rainfall simulators to define efficient indicators like waterstable macroaggregates (Barthès, Roose, 2001), soil surface features (surface covered, crusted or compacted, roughness), prepounding rainfall, stable infiltration rate, or Césium 137 used efficiently with GIS to evaluate local erosion or deposition variability (Ritchie *et al*., 1974; Bernard, 1991).

Hydrologists showed that sediment delivery in the rivers is generally weaker than soil losses at the field scale (colluvium deposition) except in young mountainous landscapes where river erosion is more efficient than sheet erosion. Sediment ratio is depending on soft clay rock surface, vegetation cover and max flow rate not only related to the rainfall intensity (HORTON flow) but also to the saturation of partial contributive areas of the watershed (Cosandey, Robinson, 2000). They developped models for water & suspended sediment fluxes at various watershed scales (erosion efficiency ratio) on flumes. Combining rainfall simulators studies, soil surface features , indicators, GIS and satellital imagery, models were developped on small watersheds for flood prediction in semi-arid areas. (Lamachère, Guillet, 1996). But in the humid tropics where the infiltration volume is important, watertables flux are dominating and surface features are less efficient indicators.

In this note , will be proposed a general approach and some methods in order to evaluate fastly the present erosion status, to measure processes and factors of erosion for validation of models of erosion risks.

2 Quick evaluation of erosion problems

2.1 Observation of erosion processes and intensity

Before measuring erosion processes, it is usefull to observe in the field after a serie of aggressive rainstorms typology, intensity and explanatory factors of erosion on the whole concerned territory. After it will become possible to measure them acurately at the right place in the most problematic areas.

The landscape must be divided in " functional segments " where the behavior seems to be homogenous as far as land use, slopes and soils : on each segment, erosion processes intensities will be observed systematically. In Table 1, is summarised one system.

Table 1 Preliminar diagnostic of erosion risk and intensity

Sheet erosion (Interrill erosion =1 t/(ha · year) — 15 t/(ha · year))		
S1:	1t/ha	:local traces of sealing crust and loam/ SOM deposit,
S2 :	4t/ha	:sealing crust localised, with loamy sediments,
S3:	8t/ha	:topsoil frequently crusted with coarse sandy sheet deposits,
S4:	12 t/ha	:pedestal, micro-cliffs and crusts, or gravel deposits,
S5 :	15 t/ha	:very large rills scouring only the humiferous tilled topsoil.
Linear erosion (10 t/(ha · year) — 150 t/(ha · year))		
L1	10t/ha	:little rills of <10 cm depth,
L2	30t/ha	:rills of 10 cm — 30 cm depth,
L3	60t/ha	:deep rills and ephemeral gullies (depth>30 cm),
L4	100t/ha	:gullies frequent or wide or deep,
L5	150t/ha	:badland where gullies have scoured completely the soil surface.
Mass movement erosion (20 t/(ha · year) — 500 t/(ha · year))		
M1	20t/ha	:slow creeping of the topsoil,
M2	40t/ha	:tillage erosion from the hilltop to the embankment of the field limit,
M3	100t/ha	:landslide on a superficial soil,
M4	200t/ha	:landslide with rotation,
M5	500t/ha	:undermining of river banks and of hillslopes by the river.

Each erosion type corresponds to a soil loss intensity: from 1 t/(ha · year) to 15 t/(ha · year) for inter-rill erosion, 10 t/(ha · year) to 150 t/(ha · year) for linear erosion, 20 t/(ha · year) to 500 t/(ha · year) for mass movements. The erosion index for each segment of the hillslope will be the sum of the product of the maximum level by their frequency wich varies from 0 (absence) to 1(presence over the whole surface) :

$$\text{Erosion index of segments} = S(S_{\max} \times f_s) + S(L_{\max} \times f_l) + S(M_{\max} \times f_m)$$

Another erosion estimation have been made by comparison of the difference of elevation between the topsoil surface and some stable material like pedestal, tree roots, stones, herbaceous mounds, fences, etc. Nevertheless it was demonstrated that these estimates are much bigger than the others because the apparent topsoil surface could be raised by sediments or roots and termites activities, while between vegetation, topsoil has been compacted by rainfall, men and animals traffic (Hudson, 1993).

All these precious observations must be situated in the space (with GPS) : maps are efficient presentation system to do a synthesis of the data.

2.2 Inquiry on explanatory factors

When erosion observations are made on the hillslopes segments, explanatory factors of erosion intensity are measured along 3 transects of 10 meters (Roose, 1996b):

- the slope: %, length or distance to the hill summit, length limit before the beginning of rills,the straigth , concave or convexe profil, the topographic position and the orientation in relation to humid winds ;
- the soil surface covered by the canopy (shadow surface on the soil surface), by litter and creeping vegetation and by stones (quadratic points method);
- the crusted soil surface: sealing crust, sedimentation crust, compacted spots, rocks included in the soil crusts;
- the soil surface roughness (5 classes);
- the surface covered by rills, or their empy volume (length × averaged sections);
- With a cylindric sampler of the ten first cm, it will be possible to measure the soil moisture deficit, the bulk density, the ratio of stable macro-aggregate sieved in water, texture , soil organic matter, all parameters which inform on the porosity and soil erodibility (Le Bissonnais, Arrouays, 1997; Barthès, Roose, 2001).
- If a rainfall simulator is available, it is interesting to evaluate the pounding rainfall amount before runoff begins and the stable infiltration rate after a long rainstorm.

A regressions matrix allows the selection of the most efficient parameters able to foresee various erosion processes. Multiple regressions are a second level of modelling erosion features.

2.3 Rapid environment inquiry with the rurals

Within a few hours of discussion with a dozen of representative farmers, it is possible to evaluate on the village territory erosion typology, intensity and frequency in relation to soils, land use, farming systems, form and slope %, topographic position, traditional soil and water ressources management systems, implication of farmers to save their water and soil ressources. Once accepted by the rurals, it is possible to get a good description of traditional strategies for water and soil fertility management, an estimation of their efficiency and validity limits, the implication of farmers to soil conservation and their openings to new methods of natural ressources management (Sabir *et al*., 1999).

In two weeks, it is possible to a multidisciplinatory research team and half a dozen of rurals to propose an acceptable expertise defining the erosion risks at the village territory scale, the major explanatory factors and some managements scenarios to be tested by the rurals managed by a valuable/expert SWC officer.

3 Measuring erosion processes and factors

To improve knowledges about erosion processes and factors in order to propose new farming systems more productive and sustainable, or test the efficiency and acceptability of new antierosive systems, it is necessary to dispose during a long period (5 years — 10 years) of an experimental design taking into account the variabilities of vegetation cover in relation to rainfall agressivity and repartition, soil surface features, etc.The statistical design can be similar to the agronomic trials (variance analysis), or to the hydrologic approach on watersheds which cannot be replicated (regression analysis). The first year must be devoted to building the devices and educating the technical team, with only one treatment to evaluate the spatial variability of the experimental field. Next years, one plot will be maintained while others can be managed to get accurate knowledges on the regional cultural systems, the soil resistance of a bare fallow, and a few improved systems (or various factors intensities). But generally it is difficult to find funds and researchers for more than 3 years — 5 years ; as the soil degradation is not linear, it is possible to get discontinues observations series .

3.1 Measuring change of surface level or gully volume

This method consist in setting a network of reference marks (like erosion pins : Haigh, 1977) allowing to observe along many years the evolution of the topsoil surface, rills, gullies, cattle tracks, mass movement. To avoid artificial accumulation or erosion at the foot of the pegs, it is recommended to dispose a network of iron or bamboo pegs or cemented pod fixed deedply in the soil, on which one can set an horizontal bar with rods which can be lowered down to the soil surface (Hudson, 1993).

The advantages of these methods are the flexibility to manage the periodicity of observations in relation to the main events, the low cost for installation and maintenance. But these materials interest generally the poor rural population: to avoid their degradation, an explanatory campain is needed to get the rural confidence and the devices protection. Their precision is not famous because one mm of erosion corresponds to 15t /ha if bulk density attain 1.5: this method is well adapted to fast scouring effect but not to evaluate losses by runoff nor the quality of runoff and erosion. They are not adapted to tilled cultivated fields where the decompaction modify the soil elevation on a few centimeters. The presence of pegs or pods can modify the runnof fluxes, landslides and sedimentation. To avoid these inconveniences, pods are deeply fixed in the subsoil and the profile is measured between two pods distant of 1 m — 2 m (profile meter of Hudson, 1993).

3.2 Plots to measure runoff and erosion under natural rainfalls

They are rectangular fields insulated by sheet metal driven in the topsoil. At the lower part, runoff and erosion are capted in a channel, a captor for coarse sediments, then a serie of storage tanks with divisors or a H-flume with a water-level recorder. A rainfall recorder must be situated just near the field center. It is interesting to separate suspensions and coarse sediments (sand and aggregates) wich would be deposited before reaching the river. These runoff plots allow also to evaluate the water balance, nutrients losses and pollution. Poesen distinguished four scales in relation to research objectives :

- **microplots (1m²)** to measure acurately the infiltration rate dynamic (pounding rainfall amount, stable infiltration rate) and the aggregate stability (suspension rate) but not erosion because the slope is not long enough to develop concentrate runoff energy, border and roughness effects. The slope gradient effect is reduced by the absence of runoff energy. In order to evaluate soil erodibility, the topsoil surface must be prepared smoothly with the rake to get little clods (< 2 cm) and regular slope, without any root nor crop residue.
- **runoff plots (50 m² — 500 m²)**. It is the conventional scale used to measure runoff, sheet and rill erosion for various soils, vegetation covers, cultural practices, slopes and some permeable antierosive techniques (grass strips, hedges, stone bunds) to the exclusion of runoff diversion or storage practices. Because slope length effect is questionable, it is reasonable to limit the length to 20 m—25 m. The width must be adapted to the surface roughness and selected between 1/5 — 1/10 of the length to avoid excessive channel effect : the more the channel side is wide, the easier the sediments attain the measuring device. In this channel a first tank (1/2 m^3) may separate coarse sediments which could be easily deposited along the hillslopes. Then runoff and suspension are conducted in large storage tanks (very good precision) or in little tanks (0.2 m^3 — 1 m^3) connected with divisors (1/5 — 1/20). A screen must be placed before the divisor to intercept floating organic material. These divisors must be checked and cleaned acurately. Most of the models have been validated at this scale, but many authors have demonstrated that total erosion measured at this little plot scale is bigger (2 times — 7 times) than sediment delivery at little watershed scale (Rapp, 1994 ; Diallo *et al*., 2000).
- **fields (0.1 ha — 1 ha)** can include ephemeral gullies, tillage erosion but sedimentation also and must be used to evaluate the impact of antierosive practices like ridging on the contour, graded channels, terraces. Generally runoff is measured in a special flume with level recorder and an automatic sampler (Coshocton wheel)(Hudson, 1993). It is interesting to have coarse sediment captor in front of the flume.

- **gullies or micro watersheds** (>1 ha). They integrate all the erosion types on the hillslopes and the channel processes in the bed of the river and colluvial-alluvial sedimentation. The runoff is evaluated on special flumes passing sediments (ex.Parshall flume) or weirs built in the channel. If the sediment load is too important (like in torrential rivers), special water level recorders must be adapted (ultrasonic or resistance) after a bedload trap (Richard, 1997). Observations on gullies are particularly interesting because they integrate the functioning of the whole hillslope . Poesen *et al*., (1996) have shown that in the intensively cultivated loess areas of Europe, 44% of sediments of little watersheds are originated from gullies, and more than 88% in the gravelly soils of the mediterranean zone.

3.3 Sedimentation in small hill reservoir

Sediment delivery in reservoirs is still questionnable when based on sediment transport in rivers because the suspension and the bedload are varying a lot during the floods into the riverbed : generally, the sediment delivery estimated on rivers is lower than the sedimentation observed in the reservoirs, mainly for torrential rivers (Hudson, 1993).

The studies of sedimentation in small reservoirs (drying each year) give precious indications on erosion rate of small watersheds (Albergel *et al*., 2000). The majority of sediments, particularly coarse sediments, are capted by the reservoir. In semi-arid Central Tunisia, 26 small hill dams were equipped with classic hydraulic recorders : annual bathymetric measurements of sediments and the evaluation of overflowing suspensions at the spillway allowed an estimation of silting hazard between 1.6 t/(ha · year) (for stable basins) — 28 t/(ha · year) (for gypsitic marl) in relation to lithology, soils and land uses. The life time of these small reservoirs in Mediterranean zone is very short (<10 years — 50 years) because of dangerous floods during exceptional intensive rainstorms.

3.4 Rainfall simulation

To pass round the problems of long duration of field experimentations and spatio-temporal variations, the importance of exceptionnal rainstorms and previous soil moisture, many rainfall simulators were developped with different qualities : mobility, spatial homogeneïty of rain drops, energy similar to natural conditions for various rain intensities.

We distinct three simulator types :

- **infiltrometers (1m²)** allowing to test the evolution of infiltration, runoff, aggregate stability and suspensions (MES) in relation to surface features, bulk density, soil moisture. To obtain enough energy for each intensity of rain, veejets are selected giving a beam of drops (1 mm to 4 mm) under pressure (1 bare): the flow intensity must be reduced by rotating disc (Morin *et al*., 1967), solenoid valve (Meyer, 1988), or by rotation (Asseline, 1997) (Hudson , 1993).
- **rainfall simulators** (N×10 m^2) are much more expensive, use plenty technicians and clear water (30 m^3 for 60 mm · hour on 200 m^2), but they allow to evaluate correctly runoff and sheet and rill erosion in relation to cultural practices, vegetative covers, soils, % slopes, etc. (Swanson, 1965 ; Meyer,1988 ; Roose et Asseline, 1978).
- **Simple irrigators** who bring intensities of representative rainfalls, without respect to their energy. Some simplified irrigators work manually on 1 m² (Roose et Smolikowski, 1997), others irrigate many dozen m² (Hudson, 1993) and allow to evaluate hydraulic characterstics, soil erodibility, in particular on steep montainous areas where erosion is more depending on runoff energy than on drops energy.

4 Models and erosion risks forecasting

Modeling erosion risk in relation to observations, measures and simulation of scenarios, is one main objective of the erosion research, to be able to answer the initial questions : silting time of a reservoir, risk of buildings destruction or soil degradation, scenarios to restrict these risks.

4.1 Naturalistic models

Spatial repartition of erosion processes and intensity gives a first level of meaning for the erosive functioning in relation to factors like topographic situation, land uses, traditional strategies of water and fertility management. This inquiry analysis may suggest very fast a proposal for a management draft for the village territory and improvements of the farming system in relation to populations socio-economical limits.

4.2 Empirical (statistical) models

The second level analysis is based on the statistic regression between best explanatory factors and erosion measures. If the experimental design is good, it become possible to forecast erosion risks in relation to efficient parameters of models USLE, RUSLE or MUSLE on steep slopes and semi-arid areas :

- rainfall and runoff energy with frequential repartition in the seasons ;
- land uses, vegetation cover, cultural practices, organic matter management (biomasse) ;
- topographic position, slope % and length thresholds for the beginning of linear or mass erosion ;
- soil erodibility, their degradation status and their ability to be restored ;
- antierosive techniques and their efficiency in relation to soils and slopes.

These empirical models, if locally adapted, are able to precise erosion hazards in relation to scenarios proposed after fast inquiries and help to improve them (Roose, 1996a).

4.3 Process based models

They are numerous (WEPP, EUROSEM, LIMOSEM, GUEST, MEDALUS, HYDROMED, etc). but very few are satisfactorily validated in various countries. They want improve the knowledges of erosion and sedimentation processes and hope to be applicable in the world: but till now they are less efficient than empirical models with local parameters.

5 Conclusions

The quantification of various erosion processes can be made at various levels to answer to selected objectives :

- the rapid inquiry at the village territory scale allows in two weeks to estimate erosion risks, explanatory factors, frequency and intensity of major processes.
- On experimental plots/fields, erosion risks are measured on a few dangerous locations.
- To answer the questions of the rural development, one can obtain quick estimations with multi-regression or empirical models like USLE-RUSLE-MUSLE.
- To answer to scientifical questions, it may be better in the future to use processes based physical models.

Modeling is an elegant way to valorise observations and datas accumulated in order to forecast spatial variations for different scenarios of landscapes management.

Nevertheless, “ all models are approximations, but some are worse than others” concluded a specialist orator of Silsoe conference in 1980...I would say that they are no universal method but various approaches adapted to objectives and tools available.

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