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RELATIVE CONTRIBUTION OF RILL/INTERRILL AND GULLY/CHANNEL EROSION TO SMALL RESERVOIR SILTATION IN MEDITERRANEAN ENVIRONMENTS

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ABSTRACT

Reservoir siltation due to water erosion is an important environmental issue in Mediterranean countries where storage of clear surface water is crucial for their economic and agricultural development. The high density of gully systems observed in Mediterranean regions raises the question of their contribution to reservoir siltation. In this context, this study quantified the absolute and relative contributions of rill/interrill and gully/channel erosion in sediment accumulation at the outlet of small Tunisian catchments (0.1-10 km^2) during the last 15 years (1995-2010). To this end, a fingerprinting method based on measurements of cesium-137 and Total Organic Carbon combined with long-term field monitoring of catchment sediment yield was applied to five catchments in order to cover the diversity of environmental conditions found along the Tunisian Ridge and in the Cape Bon region. Results showed the very large variability of erosion processes among the selected catchments, with rill/interrill erosion contributions to sediment accumulated in outlet reservoirs ranging from 20 to 80%.

Overall, rill/interrill erosion was the dominant process controlling reservoir siltation in three catchments whereas gully/channel erosion dominated in the other two catchments. We identified the presence of marly gypsum substrates and the proportion of catchment surface covered by soil management/conservation measures as the main drivers of erosion process variability at the catchment scale. These results provided a sound basis to propose guidelines for erosion mitigation in these Mediterranean environments and suggested to apply models simulating both rill/interrill and gully/channel erosion in catchments of the region.

Keywords: Erosion. Gully. Rill and interrill. Sediment fingerprinting. Small Mediterranean reservoirs.

INTRODUCTION

Water erosion is considered to be one of the main causes of land degradation and is a major threat to the soils worldwide (Cerdan et al., 2010; Lal, 2001; Mendal & Sharda, 2013; Zhao et al., 2013). The Mediterranean region is particularly prone to erosion and higher sediment yields were reported in this environment than in many other regions across the world (Woodward, 1995; Vanmaercke at al, 2011, 2012). This situation is due to the specific Mediterranean context (Cerdà et al., 2010; Cantón et al., 2011; García-Ruiz et al., 2013) characterised by an erosive climate affecting steep catchments composed of poor soils and a very long history of intense cultivation including some inappropriate farming practices (Cerdà et al., 2009; Laudicina et al., 2014; Raclot et al, 2009). The severe soil losses observed in this region have direct on-site effects by affecting both soil sustainability and agricultural productivity (De Vente & Poesen, 2005) and off-site effects by increasing flood risk, and affecting water quality and quantity. The rapid siltation of numerous artificial reservoirs built during the last decades to mitigate water scarcity represents an important societal issue in

North African countries, as the decline of surface water storage capacity may greatly impact their agricultural, economic and social development (Ayadi et al., 2010; Ben Mammou & Louati, 2007; Hentati et al., 2010; Habi & Morsli, 2011; Lahlou, 2000). The prediction of the main erosion processes occurring in catchments is therefore essential for guiding the implementation of erosion control measures adapted to the catchment context.

The dominance of gully erosion as the main source of sediment in Mediterranean environments has been underlined by many authors. Studies conducted at the local scale, i.e. plot or gully scale, in Algeria (Collinet & Zante, 2005; Roose et al., 2000) showed that gully erosion could produce ten to one hundred times more sediment than sheet erosion. Similarly, when moving up to the catchment scale, several studies highlighted the important role of gullies controlling the reservoir siltation in Spain (De Vente et al., 2008) and in Italy (De Vente et al., 2006). In a review on gully contribution to total catchment erosion (Poesen et al., 2003), this feature appeared to provide the dominant source of sediment in all catchments located in Mediterranean regions. For example, in Spanish reservoirs, gully erosion supplied 83% (Poesen et al., 1996) of sediment and largely dominated compared to rill and inter-rill erosion. However, similar measurements detailing the respective contribution of individual erosion processes at the catchment scale are rarely available (Porto et al., 2014). Existing estimations are often given for a limited number of erosive events as the collection of required data through detailed topographic surveys is very difficult and time consuming to cover the entire catchment area. As a result, there is a lack of information regarding the contribution of gully erosion to sediment fluxes at the catchment scale over the-mid to long-term. In addition, the factors explaining the differences of erosive behaviour (i.e., absolute and relative contribution of the rill/interrill and gully/channel erosion processes) between catchments are poorly understood.

In this context, sediment fingerprinting may provide an alternative technique to quantify the relative contribution of individual erosion processes at the catchment scale. This approach aims to provide useful quantitative information on sources delivering sediment to rivers that is very difficult, time-consuming and expensive to assess using classic monitoring surveys in the field. This technique has been successfully applied to floodplain deposit samples (Collins et al., 2010; Wasson et al., 2010; Wilkinson et al., 2009); to suspended sediment (Collins et al., 1998; Devereux et al., 2010; Mukundan et al., 2010; Nagle et al., 2007; Walling, 2005), or to core reservoir samples (Ben Slimane et al., 2013; Juracek & Ziegler, 2009; Mourrier, 2008) to apportion the respective contributions of surface and subsurface soils as sediment sources. In these studies, the use of fallout radionuclides (in particular, caesium-137) alone, or in combination with other tracers has proven to be powerful in discriminating between subsoil and topsoil sources. Several recent papers (Guzmán et al., 2013; Haddadchi et al., 2013; Walling, 2013) have reviewed the current approaches, advantages and challenges of this technique.

The objectives of this paper are to: 1/ quantify the mean inter-annual absolute (in Mg ha^{-1} yr^{-1}) and relative (in %) contribution of rill/interrill and gully/channel erosion processes to the outlet sediment yield of several Mediterranean catchments; 2/ investigate the main driving factors that may explain reservoir siltation, and check whether these driving factors change when considering total sediment yield (i.e., sediment providing from rill/interrill plus gully/channel erosion processes) or individual soil erosion processes (either rill/interrill or gully/channel) contribution to catchment sediment yield. To this end, we combined catchment sediment yield measurements derived from field monitoring with a fingerprinting approach applied to reservoir deposits accumulated at the outlet of five catchments covering a large range of environmental conditions found in Maghreb countries.

MATERIAL AND METHODS

Study sites

Five rural catchments were selected among a pilot network of more than 30 small hillside catchments with reservoirs (0.1-10 km^2) distributed across the Tunisian Ridge and the Cape Bon (Figure 1). These five catchments (El Hnach, El Melah, Fidh Ali, Kamech, and Sbaihia) were chosen because of their contrasted landscape characteristics as described in Table 1 and their continuous monitoring by the Tunisian Direction of Soil and Water Conservation (DGACTA-CES) and the French Research Institute for Development (IRD).

The surface area of these catchments ranges from 0.61 to 3.67 km^2. They drain into small reservoirs built between 1991 and 1994 with an initial storage capacity ranging from 20,000 to 150,000 m^3 where sediment has accumulated for more than 15 years. In 2009-2010, El Melah, El Hnach and Fidh Ali reservoirs were completely filled with sediment, but Kamech and Sbahia lakes were still operational. They are all associated with very low nutrient levels as generally found in North African rural environments. The drainage density including both wadis (i.e., dry creeks) and gullies ranges from 48.2 to 158.3 m ha^{-1} (Rebai et al., 2012). The catchments are distributed along an annual rainfall gradient comprised between 285 and 650 mm. The lithology mainly consists of marls (soft substrate), sandstones and limestones (hard substrates), but their relative surface cover varies from one basin to another. Marly gypsum was the most widely found in Fidh Ali catchment. Cropland occupied 10 to 70% of the total surface depending on the catchment. The rest of the surface was covered by scrubland devoted to grazing, by forests, by gullies/badlands and by a few houses. The main active erosion processes in these catchments are related to either rill/interrill or gully/channel (including bank) processes. Contribution of other processes such as mass movements is negligible. Two catchments were equipped with a large panel of erosion control measures covering between 30 and 40% of the surface area. They consist in contour bench terraces, tree planting, small contour stone bunds and a few small stone check-dams installed across gullies in upstream positions. The main climate, lithology, topography and land cover characteristics of the studied catchments and their erosion control measures are synthesized in Table 1. An aerial view derived from Google Earth and ground-based photographs showing gullies, land cover, reservoirs and erosion mitigation measures are also provided for each catchment as supplementary material.

Hydrological and total sediment yield measurements

Monitoring in the reservoir of the five studied catchments was undertaken since the construction of the small reservoirs. This continuous monitoring consisted of instantaneous measurements of rainfall using a tipping bucket rain gauge (0.5 mm) and water levels with a 1 cm precision water level gauge recorder. Between 3 and 10 precise bathymetric surveys were also conducted in each reservoir to establish up-to-date depth/volume and depth/surface curves. Reservoir siltation volumes were quantified between successive bathymetric surveys. Sediment concentrations during overflow through the spillway or emptying through bottom drain valve were also measured through manual sampling. All these measurements enable the calculation of i) mean annual rainfall depth and mean rainfall erosivity by calculating the EI30 index (Wischmeier & Smith, 1958); ii) continuous variation of water level within the reservoir; iii) variation of sediment deposits between successive bathymetric surveys and iv) continuous outputs of water and sediment from the reservoir.

Continuous runoff input into the reservoir was then quantified by drawing a hydrologic budget of the reservoir. In addition, sediment input into the reservoir was computed by drawing sediment budgets for successive bathymetric surveys following the method described in Albergel et al. (1998, 2005). Mean annual runoff (in mm yr^{-1}) and sediment yield (in Mg yr^{-1}) were finally quantified for each catchment and for the longest period of records available.

In this study, catchment sediment yield is expressed as an area-specific yield (SSY in Mg ha^{-1} yr^{-1}) by dividing the reservoir sediment input by the contributing surface area of the catchment. The precision on the SSY evaluation then mainly depends on: (i) the precision of the DEM as derived from bathymetric surveys (estimated to about 10 %); (ii) the precision on volumes discharged over the spillway (5%) and on measured sediment concentrations (30%); (iii) the precision on average silt density (10%). As a result, global error on SSY was estimated to reach about 20% for these small Tunisian reservoirs (Raclot & Albergel, 2006).

Field sampling

Sampling of representative source material was conducted in 2009-2010 within each of the five catchments. In total, between 10 and 17 samples representative of rill/interrill and gully/channel source types were collected within each study site. Each sample was composed by at least five subsamples collected within an approximate 5-m radius around the sampling point to increase the representativeness of the sample. During sampling, attention was paid to document the entire range of geomorphological and pedological conditions observed within the catchments (see supplementary material for sampling source location). Gully and channel source sampling was restricted to freshly cut sections in the bottom or the banks (when those features were deeper than 40 cm). The sampling depth of topsoil material for rill/interrill source was 0-10 cm in tilled cropland (as soil is homogenized in the entire ploughed layer), and only 0-2 cm in untilled scrubland environments.

Two to four sediment cores were also collected in 2009-2010 in each reservoir simultaneously to the source material sampling (see supplementary material for sampling core location). Each core covered the entire layer of sediment at the sampling locations in the reservoirs and ranged from 0.60 to 2.50 m. This was confirmed by the presence of a more compact soil layer at the base of the core. In addition, the core depths were consistent with data provided by topographical surveys conducted immediately after the reservoir construction. The number and location of cores in reservoir deposits were chosen in order to collect one core in the vicinity of the dam and additional cores at the outlet of each main tributary delivering material to the reservoir. Ben Slimane et al. (2013) showed that this type of sampling scheme where a limited number of sediment cores are collected at strategic locations within the reservoir offered a good compromise to reduce the cost of laboratory analyses while providing relevant and representative sediment fingerprinting results. Cores were then described at the laboratory before and after drying. A single composite sample of each core was then prepared.

Laboratory analysis

Chemical and radionuclide analyses were conducted on all samples. Total Organic Carbon (TOC) contents and caesium-137 (^{137}Cs) activities were measured as they were shown to provide relevant information to apportion the sources that delivered sediment material accumulated in North African reservoirs built after 1986 (Ben Slimane et al., 2013). Arguments supporting the selection of these two tracers in the context of this study are presented in the discussion section. Samples were described, air-dried, hand-disaggregated and sieved to 2 mm at the *Environmental and Soil Science Laboratory (INAT, Tunisia)*.

Activities in ^{137}Cs were quantified by gamma-spectrometry using the very low-background coaxial N- and P-types GeHP detectors (Canberra / Ortec) available at the *Laboratoire des Sciences du Climat et de l'Environnement* (Gif-sur-Yvette, France). The detectors were periodically controlled with internal and IAEA soil and sediment standards and decay-corrected to the date of sampling (Evrard et al., 2010). Uncertainties on results were estimated by combining counting statistics and calibration uncertainties. Summing and self-absorption effects were taken into account by analysing standards with similar densities and characteristics as the collected samples.

Total Organic Carbon (TOC) was measured by high temperature combustion (NF ISO 10694) at the *Bioemco Laboratory* (Paris, France) for samples collected in Kamech catchment, and at *the Soil Analysis Laboratory* (Arras, France) for samples collected at the other study sites.

After the preliminary destruction of organic matter and dispersion of soil and sediment particles, the grain-size distribution was determined based on the principle of laser diffraction using a Beckman Coulter LS 13320 particle size analyser at the *Laboratoire Géosciences Montpellier* (Montpellier, France). This device is equipped with an agitator and an adjustable ultrasonicator to maintain uniform suspension, which enables the analysis of particles with diameters comprised between 0.375 and 2,000 µm. Specific Surface Areas (SSA, square metres per cubic metre) were derived from these laser diffraction data.

Fingerprinting main steps

The fingerprinting properties were first corrected in order to take into account the grain size effects on their adsorption onto particles, as ^{137}Cs and TOC are known to be enriched in the finest (clay to loam-sized) particle fractions (Motha et al., 2003). He and Walling (1996) tested the particle size effects on the adsorption of ^{137}Cs on soils and sediments and showed that ^{137}Cs content can be closely represented by a power function of SSA values calculated for the samples, with exponent values varying between 0.6 and 0.8. In this study, the correction was performed using this power function with an exponent value of 0.7 and applied to both ^{137}Cs activities and TOC content values. Each soil source (i.e. surface topsoil and gully/channel bank) was subsequently characterised by its mean concentration/activity and the standard deviation of each of its fingerprint properties.

The ability of individual fingerprinting properties to discriminate between the potential soil sources was then confirmed by conducting a non-parametric Kruskal-Wallis *H*-test as suggested by Collins & Walling (2002). A detailed description of this procedure is provided by Evrard et al. (2011). To characterise the properties of both groups of sources, we assumed that their concentrations ($c_{i,j}$) could be represented by a normal distribution (Eq. 1).

$$c_{i,j} \approx N(\mu, \sigma^2) \qquad (1)$$

Where j is a specific group of sources; i is a specific fingerprinting property; μ is the average concentration in fingerprint property i measured in source j; and σ^2 (Eq. 2) is the variance of the probability distribution of the mean of property i in source j.

$$\hat{\sigma}^2 = \left(\frac{S.D.}{\sqrt{d}}\right)^2 \quad (2)$$

Where d is the number of independent samples and $S.D.$ is the standard deviation associated with the values of the fingerprinting properties measured in the samples.

A multivariate mixing model was then used to estimate the relative contribution (in %) of the potential sediment sources in each core sediment sample (Eq. 3).

$$\begin{bmatrix} \bar{c}_{1,1} & \bar{c}_{1,2} & \dots & \dots & \bar{c}_{1,S} \\ \bar{c}_{2,1} & \bar{c}_{2,2} & \dots & \dots & \bar{c}_{2,S} \\ \dots & \dots & \bar{c}_{i,j} & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \bar{c}_{V,1} & \dots & \dots & \dots & \bar{c}_{V,S} \end{bmatrix} \begin{bmatrix} \hat{\beta}_1 \\ \dots \\ \hat{\beta}_j \\ \dots \\ \hat{\beta}_S \end{bmatrix} = \begin{bmatrix} y_1 \\ \dots \\ y_j \\ \dots \\ y_V \end{bmatrix} \quad (3)$$

where $\overline{c_{i,j}}$ is the mean value of fingerprinting property i measured in source j ; $\hat{\beta}_j$ is the coefficient representing the contribution of source j to river sediment; S corresponds to the number of potential sediment sources and V represents the fingerprinting properties selected by the Wilk's lambda procedure.

The following physical constraints were applied to $\hat{\beta}_j$ (Eq. 4):

$$\sum_{j=1}^{S} \hat{\beta}_j = 1; \quad 0 \le \hat{\beta}_j \le 1 \quad (4)$$

These additional constraints ensured that the sum of all source contributions in the sediment was equal to one and that each fraction of these contributions lied between zero and one, inclusive.

Based on the Monte Carlo method, a series of p=10,000 random positive numbers was then generated for each fingerprinting property and for each source. The robustness of the source ascription solutions β_j was then assessed using a mean 'goodness of fit' (*GOF*) index (Eq. 5; Motha et al., 2003).

$$GOF = 1 - \left\{ \frac{1}{p} \times \left(\sum_{i=1}^{V} \frac{\left| y_i - \sum_{j=1}^{S} \hat{\beta}_j \bar{c}_{i,j} \right|}{y_i} \right) \right\} \qquad (5)$$

We only used the sets of simulated random numbers that obtained a *GOF* index value higher than 0.80 in the subsequent steps. The use of the Monte Carlo method allowed the calculation of 95% confidence intervals.

RESULTS

Analysis of catchment sediment yield

Sediment yield was evaluated for each catchment from field measurements by adding sediment stored in the reservoir to sediment exported from the reservoirs during overflow through the spillway or emptying through bottom drain valve. Sediment exported from the reservoirs during overflow or emptying represented less than 10% of the total sediment inputs to the reservoir in all five catchments. This indicates their very high sediment trapping efficiency -more than 90%- confirming previous results found for several similar reservoirs across the Maghreb region (Albergel et al., 1998).

Sediment yield corresponds to reservoir sediment inputs due to the combination of all active erosion processes in the catchments. The corresponding monitoring periods are provided in Table 2 together with additional hydrological characteristics.

Three of the five catchments were characterised by very similar catchment sediment yields (between 15 and 17 Mg ha^{-1} yr^{-1}), whereas Fidh Ali catchment showed a significantly larger sediment yield (38 Mg ha^{-1} yr^{-1}) and Sbaihia catchment a significantly lower sediment yields (10 Mg ha^{-1} yr^{-1}). The lifetime of the reservoir (number of years to be completely silted) is about 11 years for Fidh Ali and El Hnach; 15 years for El Melah, and about 30 years for Kamech and Sbahia.

Quantification of the relative contribution of rill/interrill and gully/channel erosion to catchment sediment yield for the five catchments

Both ^{137}Cs and TOC passed the Kruskal-Wallis test and were used in combination for discriminating sediments sources in the five studied catchments. Their values and the related specific surface areas (SSA) in both source material and composite sediment core samples collected in the different study sites are presented in Table 3.

A significant difference in ^{137}Cs and TOC values between both potential sediment sources was observed in all study catchments, with systematically higher values in the topsoil source than in the gully/channel material. Mean ^{137}Cs activities in the topsoil samples varied from 3.5 Bq kg^{-1} to 10.1 Bq kg^{-1} whereas they were systematically lower than 0.7 Bq kg^{-1} in gully/channel samples. Values of ^{137}Cs exceeding 1 Bq kg^{-1}in the topsoil samples indicate that there has been significant caesium atmospheric fallout during the last decades across the entire Tunisian Ridge and Cape Bon. This confirmed previous ^{137}Cs measurements conducted across the Maghreb region (Damnati et al., 2012; Faleh et al., 2005). The mean TOC value varied from 0.3% and 0.9% in gully/channel material and from 0.5% to 2.5% in topsoil. A recent study conducted in 25 soil samples collected under cropland and 10 additional samples collected under forests in Tunisia showed that the organic carbon content of the topsoil ranged from 0.8 to 3.2% for all soils, with a median TOC value of 2.4% for forest soils and 1.4% for cultivated soils (Annabi et al., 2009). The topsoil samples analysed in the 5 study sites were characterised by TOC values that are usually found in Tunisian cultivated soils located in similar bioclimatic zones. Compared to TOC contents found in soils of many other parts of the world, the low values measured in Mediterranean environments can be explained by the low precipitation amounts and the high temperatures prevailing in this region, which are favourable to C mineralization. Among the five studied catchments, samples collected in both El Melah and Fidh Ali sites had TOC values < 1% which indicates a poor soil quality, even for Mediterranean areas (Jones et al., 2004). The very low TOC values measured in topsoil samples of these 2 catchments may also be explained by their coarser texture (i.e., lower SSA values in Table 3) that is known to be less effective to store soil organic carbon than fine-textured soils (Meersmans et al., 2012).

The SSA values measured in core and source material samples of a given catchment remained very similar for 4 of the 5 study sites, which means that enrichment and depletion effects caused by selective mobilisation and transport of sediment were of limited magnitude. A significant enrichment of fine-grained sediment during erosion and transportation between soils and the reservoir was only observed in El Melah catchment.

Fingerprinting results obtained for the different cores collected in each reservoir were extrapolated to the entire catchment scale by attributing to each core a weighting factor corresponding to its representativeness in terms of sediment volume accumulated in the reservoir as proposed by Ben Slimane et al. (2013). Figure 2 illustrates the results of the source apportionment for each catchment.

Results showed the contrasted contribution of erosion processes within the five selected catchments, as the soil surface relative contribution to reservoir sediment ranged between 20% and 80% depending on the site. The surface topsoil was the dominant source of sediment in Fidh Ali, El Melah and Kamech sites, whereas gully/channel material dominated in El Hnach and Sbaihia catchments.

Rill/interrill and gully/channel erosion contributions to catchment sediment yield

Rill/interrill and gully/channel erosion contributions to catchment sediment yield were calculated by applying the relative source contribution to the catchment sediment yields measured in each catchment (Figure 2). Rill/interrill erosion contribution varied from 2.2 Mg ha^{-1} yr^{-1} in Sbaihia catchment to 26.5 Mg ha^{-1} yr^{-1} in Fidh Ali catchment, whereas gully/channel erosion contribution varied between 3 Mg ha^{-1} yr^{-1} for Kamech and 11.5 Mg ha^{-1} yr^{-1} in Fidh Ali. The lowest rill/interrill erosion contribution of 2.2 Mg ha^{-1} yr^{-1} obtained in Sbaihia catchment remained significantly higher than the tolerable soil loss estimated to 1.4 Mg ha^{-1} yr^{-1} (Verheijen et al., 2009), indicating the severe levels reached by soil erosion along the Tunisian Ridge and in the Cape Bon region.

The range of variation of rill/interrill erosion contribution was larger (from 1 to 12) than catchment sediment yields and gully/channel erosion contribution (from 1 to 4) considering the five investigated catchments. Quantification of individual erosion process contributions therefore provided important information that was not well reflected by catchment sediment yields.

Overall, Fidh Ali catchment was clearly characterized by the highest catchment sediment yields and the highest rill/interrill and gully/channel erosion contributions. When considering the other four catchments, the ranking was modified depending of the erosion type considered. This is illustrated for instance by the fact that Kamech catchment had the second most important rill/interrill erosion contributions but the lowest gully/channel erosion contributions.

DISCUSSION

Selection of ^{137}Cs and TOC as sediment tracers in this study

One of the main challenges associated with the choice of tracers in fingerprinting technique still lies in the need for better accounting for the selectivity/conservative behaviour of sediment and fingerprint properties between the sources of sediments and the collected material (Koiter et al., 2013). A recent extensive review on sediment tracers in water erosion studies (Guzmán et al., 2013) showed that fallout radionuclides are the most extensively used soil redistribution tracers reported in the scientific literature and that ^{137}Cs is by far the dominant one, especially for medium time scales (tens of years) across a broad range of spatial scales from hillslope and small catchments to large basins. Its use in fingerprinting techniques -alone or in combination with other tracers- has proven to be effective in discriminating between subsoil and topsoil sources in several studies (Owens et al. 1999; Zhang & Walling, 2005, Juracek & Ziegler 2009; Smith et al. 2012). The conservative behaviour of ^{137}Cs in soil environments has been demonstrated in many studies and detailed arguments may be found in Guzmán et al. (2013) for instance. If biochemical properties have the potential to provide better spatial constraints for sediment sources compared to other fingerprint properties (Koiter et al., 2013), the use of organic constituents as soil redistribution tracers is less usual. One reason is that the behaviour of organic constituents may often be suspected as poorly conservative. Many arguments have been formulated by Ben Slimane et al (2013) regarding the ability of TOC to be used as an additional tracer to ^{137}Cs in the specific context of recent North African reservoirs (less than 20 years old) : i) autochthonous source of organic constituents in oligotrophic North African reservoir is negligible as proved in a series of more than 20 modern Tunisian reservoirs (Rahaingomanana 1998); ii) TOC degradation in the deposits is also negligible for recent reservoir as the kinetics of TOC degradation were proved to be very slow in oligotrophic lake deposits as demonstrated by Patience et al. (1995) for the Lac du Bouchet (France); iii) terrestrial organic residues probably did not experience major changes via bacterial alteration during their transport, settling and incorporation into the sediment because terrestrial higher plant debris had already been submitted to strong biotic as well as abiotic degradation under oxic conditions in soils (Vandenbroucke & Largeau 2007); iv) degradation during mobilisation and transport is also likely to be limited due to the very short sediment transport distances within the small studied catchment. The conservative behaviour of TOC was also corroborated by previous studies conducted in recent North African reservoirs. Albergel et al. (2006) demonstrated for instance that the majority of the organic matter found at two Tunisian reservoirs (El Gouazine and Fidh Ali) originated from upstream soil sources, and that this organic matter was not transformed in the recently accumulated sediment (approximately 10 years old in their studies). Ben Slimane et al. (2013) confirmed the terrestrial origin of TOC in the Kamech reservoir deposits using Rock-Eval analysis and δ13C measurements to demonstrate the very low kinetics of TOC degradation through analysis of the entire sediment deposit sequence.

Previous research and the very different TOC contents found in topsoil and subsoil sources (Table 3) support the relevance of using TOC in combination with ^{137}Cs as potential sediment tracers in the context of this study. It was verified by comparing results from fingerprinting approach using either the combination of ^{137}Cs and TOC or ^{137}Cs alone. Figure 3 shows that very similar results are obtained by both methods. As the use of multiple tracers in a mixing model allows for more reliable source apportionment than the use of only one tracer (Walling et al. 1993; Small et al. 2002; Martinez-Carreras et al. 2008) we finally focused our discussion on the fingerprinting results derived from the combined use of ^{137}Cs and TOC as tracers.

On the driving factors of reservoir siltation

Although Fidh Ali catchment is characterized by the lowest mean rainfall amount and the lowest rainfall erosivity index values, it clearly showed the highest erosion contributions whatever the erosion processes considered (Figure 2). The extreme intensity of erosion in Fidh Ali catchment can be explained by its soil composition that contains a very high percentage of marly gypsum showing intense swelling/shrinkage processes (clayey soils). They are known to increase soil sensitivity to erosion (Cantón et al., 2001; Sfar Felfoul et al., 1996, 1999) as they facilitate both aggregate dispersion and gully initiation. In this catchment, this specific lithological feature directly appears as the first-order factor driving the very high erosion rates. Areas covered with a large marly gypsum surface should therefore be considered as priority zones for implementing erosion protection measures in the Tunisian Ridge.

A simple statistical analysis by means of linear regressions was performed in order to investigate the relationships between dominant erosion processes contributing to reservoir siltation and the following characteristics: total catchment area, mean annual rainfall, mean annual erosivity index, mean annual runoff, mean annual runoff coefficient, global slope index, drainage density, percentage of catchment surface covered by (i) soft lithological substrate types, (ii) badlands, (iii) cropland, (iv) equipped with soil conservation measures. Table 4 summarizes the correlation coefficient values obtained for each linear relationship tested when considering the 5 studied catchments. The significant correlations at the 0.05 level are mentioned when considering the 5 catchments but also when excluding Fidh Ali as its extreme erosion values may greatly affect some correlations. As this analysis is restricted to a set of 4 or 5 catchments, its statistical significance is relatively low. Consequently only correlation values significant at the 0.05 level are discussed in the remainder of the text and further investigations will be required to confirm these preliminary findings regarding the identification of first-order factors controlling reservoir siltation.

First, correlation coefficient values between potential driving factors and the contribution of a single individual erosion process (related to either rill/interrill or gully/channel sediment sources) were generally higher than the ones obtained between driving factors and SSY. This may indicate that the tested factors explain individual erosion process contributions rather than the combined effect of all erosion phenomena. Second, several correlations values were significant at the 0.05 level when considering the five studied catchments but non-significant when excluding Fidh Ali. This means that the significance of the correlations is mainly due to the extreme erosion values recorded in Fidh Ali catchment and not to the tested factor. On the contrary, a significant negative correlation was obtained between the percentage of catchment area under cropland and the gully/channel erosion contribution (at the 0.05 level) by both including and excluding the Fidh Ali site. This result can be interpreted as the fact that gully/channel erosion took place in a highly degraded environment unsuitable for cultivation. Finally, the percentage of total catchment area equipped with erosion control measures (% of total managed area) appeared to be the most relevant driving factor of reservoir siltation in the five studied catchments. It was significantly correlated with the relative contribution of individual erosion processes (with or without Fidh Ali) and with rill/interrill erosion rate (when excluding the Fidh Ali catchment), both in a negative way. This confirms that soil protection measures have a significant impact on surface erosion by limiting either soil detachment or sediment transportation from hillslopes to catchment outlet. This is a major finding of this study as this factor is anthropogenic and can therefore be controlled.

Main erosion processes contributing to reservoir siltation

Jebari et al. (2010) have proposed to use a rough direct relationship between rainfall characteristics (maximum 15-min duration rainfall intensity) and the respective contribution of rill, interrill and gully erosion processes to sediment siltation in 28 Tunisian small reservoirs. Their results indicated that rill/interrill erosion was largely dominant in the major part of the Tunisian Ridge as gully erosion contribution exceeded 20% in only 5 of the 28 studied catchments, and 50% in one single catchment. Considering the same sites of investigation used in this study, they found a dominant contribution of rill/interrill erosion with values between 82% and 90% for the five catchments. There is therefore a contradiction between the findings provided by Jebari et al. (2010) and our results as we found that two of the five investigated catchments were in fact dominated by gully/channel erosion processes. This inconsistency may arise from the fact that rainfall characteristics are important but not sufficient to explain the dominant erosion processes in a catchment and that we need to take into account human activities such as soil conservation measures as major driving factors to understand and characterize properly the erosive processes in a catchment.

To a wider extent, the predominance of gully/channel erosion contribution in two of the five studied catchments confirms the significant contribution of subsuperficial erosion processes (other than sheet and rill erosion) to catchment sediment yield in the Mediterranean zone as recently underlined by Vanmaercke et al. (2012) who compared sheet/rill erosion rates and sediment yield in a large number (n = 1794) of European catchments. This result is likely valid in other regions of the world as for the Alpine zone (Vanmaercke et al., 2012) or in Northern Ethiopa (Haregeweyn et al., 2013).

Implications for catchment management

A simple sediment source apportionment method conducted at the catchment scale showed that the variability observed for individual (i.e., rill/interrill or gully/channel) erosion process magnitude was two or three times higher than the variability observed for total erosion. The explicit consideration of different erosion processes provided a more efficient way to outline the high variability of erosion processes between catchments than the simple calculation of specific sediment yields (SSY). Moreover, the ranking of catchments following an order of increasing/decreasing erosion contributions proved to be significantly modified depending on the type of erosion processes considered. Identification and quantification of the dominant sediment sources is crucial for our understanding of human impacts on catchment SY and for the design of efficient management strategies to reduce SY at the catchment scale

(Vanmaercke et al., 2012). In Tunisia, implementation of conservation farming practices should be encouraged in catchments characterised by similar features as Kamech, Fidh Ali and El Melah sites. In these environments, maintaining a minimal vegetation cover of the soil during autumn may provide a good solution to protect it from sheet and rill erosion (Crosaz, 1995; Maetens et al., 2012; Menashe, 1998; Rey & Berger, 2002). In contrast, measures dealing with gully and channel erosion should be targeted on sites similar to El Hnach and Sbaihia catchments. To a wider extent, installation of any erosion protection measure must be carefully designed as it is well-known that complex interactions exist between these different types of erosion processes at the catchment scale (Bryan, 2000; de Figueiredo & Fonseca, 1997; Romkens et al., 2001; Roose et al., 2010). In our study, we showed that the use of conservation measure was efficient in decreasing both relative (in %) and absolute (in Mg ha^{-1} yr^{-1}) rill/interrill erosion contributions to reservoir siltation. These measures that were targeted to reduce rill/interrill erosion therefore fulfilled their objective. However, the significant correlation between the percentage of total managed area and the relative contributions of individual erosion processes (including or excluding Fidh Ali) also means that the implementation of soil conservation measures has a negative effect on the contribution of gully/channel erosion processes. This result suggests that measures aimed to control topsoil erosion must be implemented in association with complementary measures aimed to gully stabilization. Such a combination is especially required when topsoil conservation measures aim to reduce sediment detachment or to enhance sediment trapping without decreasing runoff as it is the case for contour stone bunds for instance. This confirms the need for combining several types of measures (vegetative and structural) to increase sediment trapping and protect reservoir from siltation (Mekonnen et al., 2014).

Identification and quantification of the dominant sediment sources are also crucial to identify the most appropriate models to simulate erosion at the catchment scale (De Vente et al., 2013; Morgan, 2011; Vanmaercke at al, 2012) and avoid their misapplication (Govers, 2011). Poor modelling results are frequently obtained when a single model is applied to a wide series of catchments, as most models are generally designed for describing a limited number of processes (either sheet and rill erosion or gully and bank erosion) but they are rarely designed to simulate the complete range of phenomena (De Vente & Poesen, 2005; De Vente et al., 2013, Haregeweyn et al., 2013). In Mediterranean environments, the occurrence of severe catchment sediment yield was explained by a complex combination of rill/interrill and gully/channel erosion processes. In the light of these results, we suggest that interactions between both processes need to be further investigated and integrated into soil erosion models.

CONCLUSIONS

This work confirmed the relevance of using a fingerprinting method based on the measurement of ^{137}Cs and TOC to estimate the relative contribution of rill/interrill vs. gully/channel erosion processes to reservoir siltation in Northern Africa catchments. Among the five investigated catchments, three of them were characterized by dominant rill/interrill erosion contribution, whereas gully/channel erosion contribution prevailed in the two other sites. The results also showed that a very large variability of erosion processes contributed to reservoir siltation in catchments located along the Tunisian Ridge even when similar catchment specific sediment yields were recorded. The presence of a large surface cover of marly gypsum material was confirmed to enhance both rill/interrill and gully/channel erosion processes. Furthermore, the implementation of soil protection measures was also identified as a main factor driving erosion in this region. This work also corroborated the existence of complex interactions between rill/interrill and gully processes. Consequently, implementation of soil conservation measures must be carefully designed at the catchment scale. Indeed soil conservation measures aimed to prevent particle detachment on cultivated hillslopes and their downstream transportation seemed to have negative feedback by amplifying downstream gully/channel erosion. In catchments where rill/interrill erosion contribution dominates, we therefore suggest to implement topsoil protection measures that significantly reduce sediment concentration and runoff at the same time. To a wider extent, this work also corroborated the interest to combine different types of conservation measures (vegetative and structural, in both the fields and gullies/channels) to limit reservoir siltation.

Overall, our results also suggest the need to develop erosion models simulating interactions between rill/interrill and gully/channel processes in order to guide the implementation of erosion control measures in Mediterranean catchments.

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801 **Figure legends**

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803 Figure 1. Location of the selected catchments within a pilot network of monitored catchment reservoirs along the Tunisian Ridge and the Cape Bon region (modified from Temple-Boyer et al., 2007). Rainfall information (isohyet) has been superimposed.

806 Figure 2. Catchment sediment yield, rill/interrill and gully/channel erosion contribution to reservoir siltation for the five study catchments.

808 Figure 3. Sediment source apportionments for the five studied catchments using the mixing model either with the combination of 137Cs and TOC or with 137Cs only.

Table 1. Characteristics of the five studied catchments as of 2010. The bioclimatic zones were extracted from the bioclimatic map of Tunisia (CNEA, 2007). The global slope index (m km^{-1}) is defined by the ratio between altitude difference (m) of approximately 5% and 95% of the catchment surface and the length of the equivalent rectangle (km).

Catchments	Description				Characteristics / Factors							
			Reservoir		*Regional climate*			*Topography*			*Catchment management*	
Name	*Area (km^2)*	*Drainage density (m ha^{-1})*	*Building year*	*Initial volume (m^3)*	*Bioclimatic zones*	*Mean annual rainfall (mm)*	*Lithology*	*Altitude range (m)*	*Global slope index (m km^{-1})*	*Land cover*	*Type of management*	*Total managed area (%)*
El Hnach	*3.67*	*97.3*	1992	77 400	Higher Semi arid	*436*	25% limestone, 75% Marls	Max:745 Min:500	*104*	*47% cropland, 7% l*imestone outcrops, 7% badlands, 39% scrubland.	contour bench terraces + small stone check-dams+ small contour stone bunds + tree planting	***32***
El Melah	***0.61***	***48.2***	1991	20 000	Higher Semi arid	*450*	50% Marls 50% sandstone	Max:190 Min:90	*36*	*60% cropland, 40% scrubland.*	Without management	*0*
Fid Ali	***2.38***	***158.3***	1991	134 700	Lower semi-arid	*285*	85% gypsum marl, 15% limestone	Max:460 Min:360	38	*35% cropland, 53%* scrubland, 12% badlands.	*Small weir dry stone*	*6*
Kamech	***2.63***	***79***	1994	142 500	Sub-humid	*650*	80% Marls, 20% sandstone	Max:203 Min:95	*40*	*70% cropland, 30% scrubland.*	Without management	***0***
Sbaihia	***3.57***	***53.3***	1993	135 500	Higher Semi arid	*450*	70% Marls, 30% limestone	Max:480 Min:200	*77*	*50% cropland, 47% f*orest, 3% badlands.	contour bench terraces	***41.3***

821 Table 2. Mean annual hydrologic and sediment yield measurements in the five studied catchments.

Catchment	Periods	Area-specific sediment yield (SSY) (Mg ha^{-1} yr^{-1})	Annual rainfall (mm yr^{-1})	Erosivity index (MJ mm ha^{-1}h yr^{-1})	Runoff (mm yr^{-1})	Runoff coefficient (%)
El Hnach*	09/1992 – 02/2007*	15	372	525	28	7.5
El Melah	10/1995 – 08/1999	17	578	1201	38	6.6
Fidh Ali	06/1993 – 09/1999	38	279	469	18	6.5
Kamech	09/1994 – 11/2008	15	561	1063	114	20.3
Sbaihia	09/1993 – 11/2006	10	454	798	72	15.7

** Rainfall and runoff measurements for El Hnach catchment were only available for the period between 09/1994 and 08/1999 because of technical failures.*

Table 3. Mean and Standard deviation of potential fingerprinting properties and specific surface area (SSA) measured in sediment source and reservoir sediment samples (n=85) collected in the five studied catchments.

	Locations	**Number of samples /cores**	**^{137}Cs (Bq kg^{-1})**	**TOC (%)**	**SSA (m^{-1})**
El Hnach	Topsoil	6	7.8 ±10.3	1.2± 0.4	25823 ± 5360
	Gully/channel bank	5	0 ± 0.1	0.5 ± 0.1	24253 ±2945
	Upstream reservoir area	2	1.4 ± 0.1	0.7 ±0.3	17035 ± 846
	Downstream reservoir area	1	2.3	0.8	29329
El Melah	Topsoil	7	3.9 ± 2.5	0.7 ± 0.2	13083 ± 6783
	Gully/channel bank	4	0 ± 0.0	0.4 ± 0.1	13925 ± 8076
	Upstream reservoir area	3	4.9 ± 2.7	1.5± 0.1	18982 ± 6362
	Downstream reservoir area	1	5.7	1.17	23876
Fidh Ali	Topsoil	6	3.5± 2.8	0.5 ± 0.1	12065 ± 3513
	Gully/channel bank	4	0.1 ± 0.2	0.3 ± 0.04	15290 ± 3458
	Upstream reservoir area	1	2.1	0.7	11443
	Downstream reservoir area	1	3.1	0.5	14880
Kamech	Topsoil	8	3.7 ± 1.5	1.1 ± 0.1	29043 ± 3921
	Gully/channel bank	9	0.2 ± 0.3	0.5 ± 0.1	23540 ± 2146
	Upstream reservoir area	8	1.4 ± 0.4	0.7 ± 0.2	15695 ± 2607
	Downstream reservoir area	5	3.1 ± 0.6	1.0 ± 0.1	26253 ± 1725
Sbaihia	Topsoil	6	10.1 ± 4.2	2.5 ± 1.0	25968 ± 4484
	Gully/channel bank	6	0.7 ± 1.0	0.9± 0.8	25713 ± 3392
	Upstream reservoir area	1	2.2	0.8	20338
	Downstream reservoir area	1	2.9	0.8	26137

Table 4. Correlation coefficient values (R) between catchment sediment yield, rill/interrill and gully/channel erosion contribution to reservoir siltation and the tested factors in the 5 studied catchments.

	Catchment sediment yield	**Rill/interrill relative contribution**	**Rill/interrill erosion contribution**	**Gully/channel erosion contribution**
Area	-0.25	-0.66	-0.41	0.35
Mean Annual Rainfall	-0.66	0.27	-0.43	-0.95*
Erosivity Index	-0.50	0.39	-0.25	-0.91*
Runoff	-0.55	0.20	-0.34	-0.83
Runoff coefficient	-0.51	0.05	-0.35	-0.68
Global slope index	-0.47	-0.86	-0.69	0.40
% of tender lithology	0.45	0.09	0.39	0.36
% of badlands	0.77	-0.12	0.56	0.93*
Drainage density	0.89*	0.28	0.78	0.68
% of cropland	-0.64	0.35	-0.39	-0.98*[#]
% of total managed area	-0.45	-0.98*[#]	-0.68[#]	0.42

** Correlation is significant at the 0.05 level considering the 5 study catchments.*
[#] Correlation is significant at the 0.05 level considering 4 catchments only (Fidh Ali excluded).

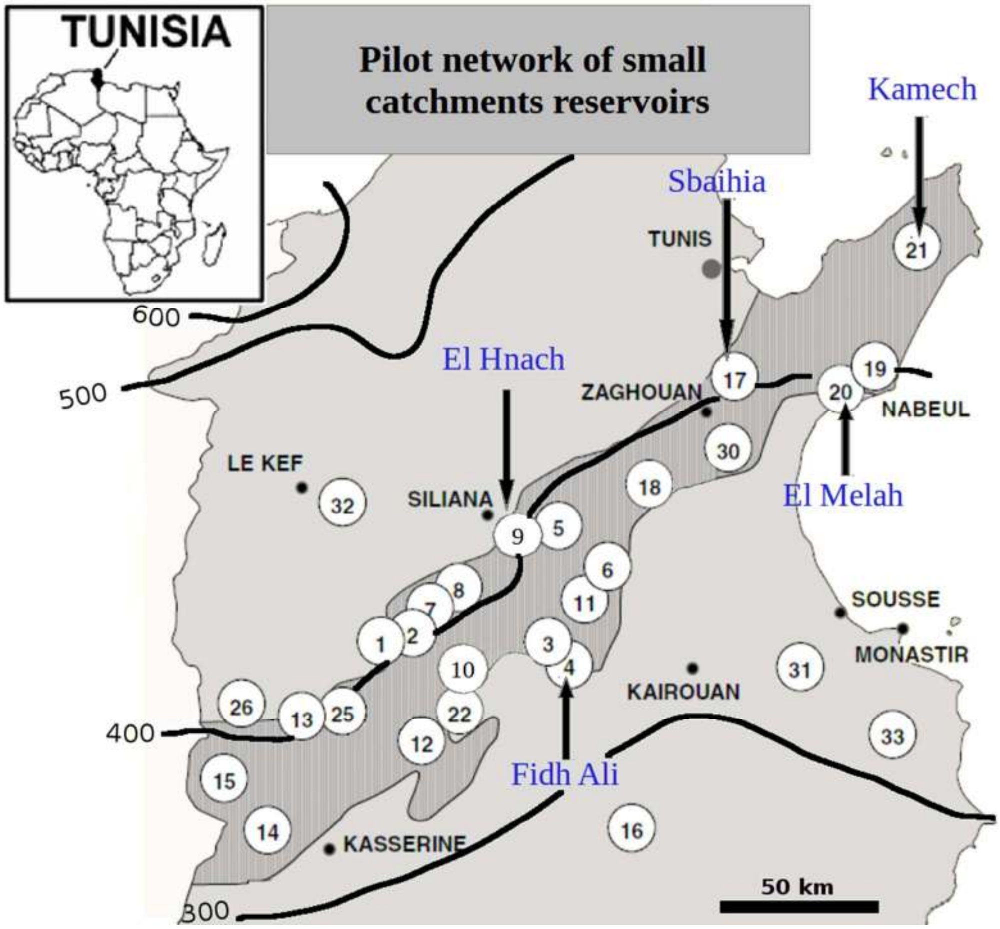

Figure 1. Location of the selected catchments within a pilot network of monitored catchment reservoirs along the Tunisian Ridge and the Cape Bon region (modified from Temple-Boyer et al., 2007). Rainfall information (isohyet) has been superimposed.
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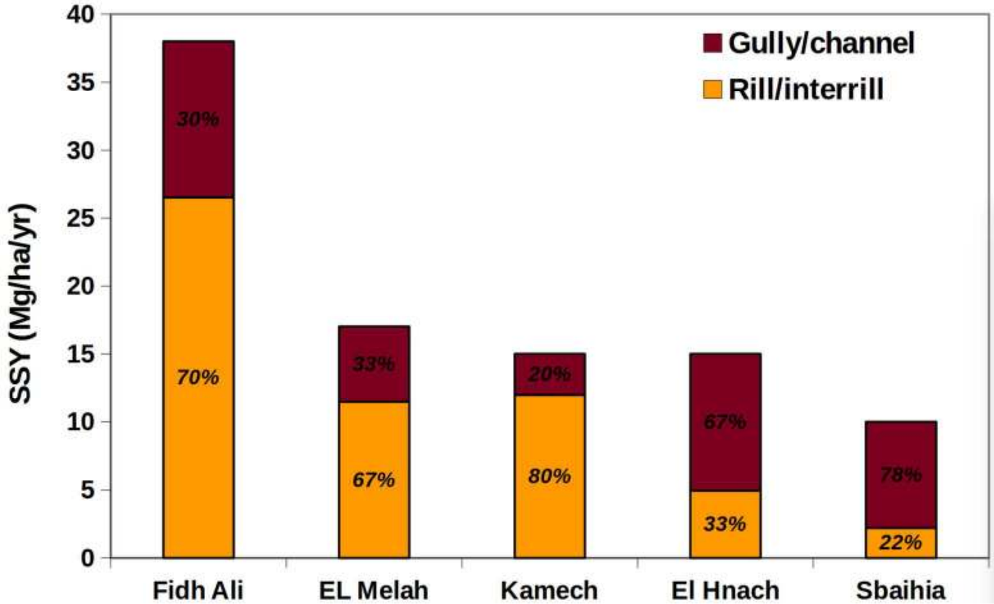

Figure 2. Catchment sediment yield, rill/interrill and gully/channel erosion contribution to reservoir siltation for the five study catchments.
417x256mm (96 x 96 DPI)

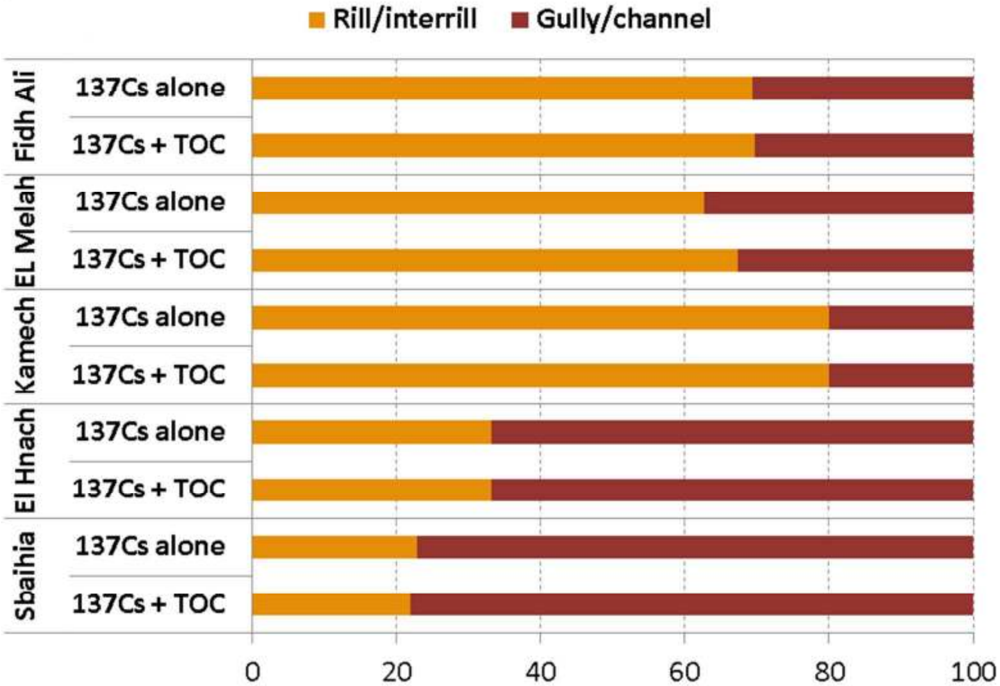

Figure 3. Sediment source apportionments for the five studied catchments using the mixing model either with the combination of 137Cs and TOC or with 137Cs only.
235x165mm (96 x 96 DPI)