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Relative contribution of Rill/Interrill and Gully/Channel erosion to small reservoir siltation in Mediterranean environments

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5 **1 RELATIVE CONTRIBUTION OF RILL/INTERRILL AND GULLY/CHANNEL**
6 **2 EROSION TO SMALL RESERVOIR SILTATION IN MEDITERRANEAN**
7 **3 ENVIRONMENTS**

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32 39 ABSTRACT
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35 40 Reservoir siltation due to water erosion is an important environmental issue in Mediterranean
36 41 countries where storage of clear surface water is crucial for their economic and agricultural
37 42 development. The high density of gully systems observed in Mediterranean regions raises
38 43 the question of their contribution to reservoir siltation. In this context, this study quantified the
39 44 absolute and relative contributions of rill/interrill and gully/channel erosion in sediment
40 45 accumulation at the outlet of small Tunisian catchments (0.1-10 km²) during the last 15 years
41 46 (1995-2010). To this end, a fingerprinting method based on measurements of cesium-137
42 47 and Total Organic Carbon combined with long-term field monitoring of catchment sediment
43 48 yield was applied to five catchments in order to cover the diversity of environmental
44 49 conditions found along the Tunisian Ridge and in the Cape Bon region. Results showed the
45 50 very large variability of erosion processes among the selected catchments, with rill/interrill
46 51 erosion contributions to sediment accumulated in outlet reservoirs ranging from 20 to 80%.

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5 52 Overall, rill/interrill erosion was the dominant process controlling reservoir siltation in three
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7 53 catchments whereas gully/channel erosion dominated in the other two catchments. We
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9 54 identified the presence of marly gypsum substrates and the proportion of catchment surface
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11 55 covered by soil management/conservation measures as the main drivers of erosion process
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13 56 variability at the catchment scale. These results provided a sound basis to propose
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15 57 guidelines for erosion mitigation in these Mediterranean environments and suggested to
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17 58 apply models simulating both rill/interrill and gully/channel erosion in catchments of the
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19 59 region.
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25 61 **Keywords:** Erosion. Gully. Rill and interrill. Sediment fingerprinting. Small Mediterranean
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27 62 reservoirs.
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64 INTRODUCTION

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34 65 Water erosion is considered to be one of the main causes of land degradation and is a major
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36 66 threat to the soils worldwide (Cerdan et al., 2010; Lal, 2001; Mendal & Sharda, 2013; Zhao et
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38 67 al., 2013). The Mediterranean region is particularly prone to erosion and higher sediment
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40 68 yields were reported in this environment than in many other regions across the world
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42 69 (Woodward, 1995; Vanmaercke et al., 2011, 2012). This situation is due to the specific
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44 70 Mediterranean context (Cerdà et al., 2010; Cantón et al., 2011; García-Ruiz et al., 2013)
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46 71 characterised by an erosive climate affecting steep catchments composed of poor soils and a
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48 72 very long history of intense cultivation including some inappropriate farming practices (Cerdà
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50 73 et al., 2009; Laudicina et al., 2014; Raclot et al., 2009). The severe soil losses observed in
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52 74 this region have direct on-site effects by affecting both soil sustainability and agricultural
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54 75 productivity (De Vente & Poesen, 2005) and off-site effects by increasing flood risk, and
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56 76 affecting water quality and quantity. The rapid siltation of numerous artificial reservoirs built
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58 77 during the last decades to mitigate water scarcity represents an important societal issue in
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5 78 North African countries, as the decline of surface water storage capacity may greatly impact
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7 79 their agricultural, economic and social development (Ayadi et al., 2010; Ben Mammou &
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9 80 Louati, 2007; Hentati et al., 2010; Habi & Morsli, 2011; Lahlou, 2000). The prediction of the
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11 81 main erosion processes occurring in catchments is therefore essential for guiding the
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13 82 implementation of erosion control measures adapted to the catchment context.
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16 83 The dominance of gully erosion as the main source of sediment in Mediterranean
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18 84 environments has been underlined by many authors. Studies conducted at the local scale, i.e.
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20 85 plot or gully scale, in Algeria (Collinet & Zante, 2005; Roose et al., 2000) showed that gully
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22 86 erosion could produce ten to one hundred times more sediment than sheet erosion. Similarly,
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24 87 when moving up to the catchment scale, several studies highlighted the important role of
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26 88 gullies controlling the reservoir siltation in Spain (De Vente et al., 2008) and in Italy (De
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28 89 Vente et al., 2006). In a review on gully contribution to total catchment erosion (Poesen et al.,
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30 90 2003), this feature appeared to provide the dominant source of sediment in all catchments
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32 91 located in Mediterranean regions. For example, in Spanish reservoirs, gully erosion supplied
33
34 92 83% (Poesen et al., 1996) of sediment and largely dominated compared to rill and inter-rill
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36 93 erosion. However, similar measurements detailing the respective contribution of individual
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38 94 erosion processes at the catchment scale are rarely available (Porto et al., 2014). Existing
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40 95 estimations are often given for a limited number of erosive events as the collection of
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42 96 required data through detailed topographic surveys is very difficult and time consuming to
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44 97 cover the entire catchment area. As a result, there is a lack of information regarding the
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46 98 contribution of gully erosion to sediment fluxes at the catchment scale over the mid to long-
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48 99 term. In addition, the factors explaining the differences of erosive behaviour (i.e., absolute
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50 100 and relative contribution of the rill/interrill and gully/channel erosion processes) between
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52 101 catchments are poorly understood.
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55 102 In this context, sediment fingerprinting may provide an alternative technique to quantify the
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57 103 relative contribution of individual erosion processes at the catchment scale. This approach
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5 104 aims to provide useful quantitative information on sources delivering sediment to rivers that is
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7 105 very difficult, time-consuming and expensive to assess using classic monitoring surveys in
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9 106 the field. This technique has been successfully applied to floodplain deposit samples (Collins
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11 107 et al., 2010; Wasson et al., 2010; Wilkinson et al., 2009); to suspended sediment (Collins et
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13 108 al., 1998; Devereux et al., 2010; Mukundan et al., 2010; Nagle et al., 2007; Walling, 2005), or
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15 109 to core reservoir samples (Ben Slimane et al., 2013; Juracek & Ziegler, 2009; Mourrier, 2008)
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17 110 to apportion the respective contributions of surface and subsurface soils as sediment
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19 111 sources. In these studies, the use of fallout radionuclides (in particular, caesium-137) alone,
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21 112 or in combination with other tracers has proven to be powerful in discriminating between
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23 113 subsoil and topsoil sources. Several recent papers (Guzmán et al., 2013; Haddadchi et al.,
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25 114 2013; Walling, 2013) have reviewed the current approaches, advantages and challenges of
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27 115 this technique.

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30 116 The objectives of this paper are to: 1/ quantify the mean inter-annual absolute (in $\text{Mg ha}^{-1} \text{yr}^{-1}$)
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32 117 and relative (in %) contribution of rill/interrill and gully/channel erosion processes to the outlet
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34 118 sediment yield of several Mediterranean catchments; 2/ investigate the main driving factors
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36 119 that may explain reservoir siltation, and check whether these driving factors change when
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38 120 considering total sediment yield (i.e., sediment providing from rill/interrill plus gully/channel
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40 121 erosion processes) or individual soil erosion processes (either rill/interrill or gully/channel)
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42 122 contribution to catchment sediment yield. To this end, we combined catchment sediment
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44 123 yield measurements derived from field monitoring with a fingerprinting approach applied to
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46 124 reservoir deposits accumulated at the outlet of five catchments covering a large range of
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48 125 environmental conditions found in Maghreb countries.

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127 MATERIAL AND METHODS

128 *Study sites*

129 Five rural catchments were selected among a pilot network of more than 30 small hillside
130 catchments with reservoirs (0.1-10 km²) distributed across the Tunisian Ridge and the Cape
131 Bon (Figure 1). These five catchments (El Hnach, El Melah, Fidh Ali, Kamech, and Sbahia)
132 were chosen because of their contrasted landscape characteristics as described in Table 1
133 and their continuous monitoring by the Tunisian Direction of Soil and Water Conservation
134 (DGAFTA-CES) and the French Research Institute for Development (IRD).

135 The surface area of these catchments ranges from 0.61 to 3.67 km². They drain into small
136 reservoirs built between 1991 and 1994 with an initial storage capacity ranging from 20,000
137 to 150,000 m³ where sediment has accumulated for more than 15 years. In 2009-2010, El
138 Melah, El Hnach and Fidh Ali reservoirs were completely filled with sediment, but Kamech
139 and Sbahia lakes were still operational. They are all associated with very low nutrient levels
140 as generally found in North African rural environments. The drainage density including both
141 wadis (i.e., dry creeks) and gullies ranges from 48.2 to 158.3 m ha⁻¹ (Rebai et al., 2012). The
142 catchments are distributed along an annual rainfall gradient comprised between 285 and 650
143 mm. The lithology mainly consists of marls (soft substrate), sandstones and limestones (hard
144 substrates), but their relative surface cover varies from one basin to another. Marly gypsum
145 was the most widely found in Fidh Ali catchment. Cropland occupied 10 to 70% of the total
146 surface depending on the catchment. The rest of the surface was covered by scrubland
147 devoted to grazing, by forests, by gullies/badlands and by a few houses. The main active
148 erosion processes in these catchments are related to either rill/interrill or gully/channel
149 (including bank) processes. Contribution of other processes such as mass movements is
150 negligible. Two catchments were equipped with a large panel of erosion control measures
151 covering between 30 and 40% of the surface area. They consist in contour bench terraces,
152 tree planting, small contour stone bunds and a few small stone check-dams installed across

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5 153 gullies in upstream positions. The main climate, lithology, topography and land cover
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7 154 characteristics of the studied catchments and their erosion control measures are synthesized
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9 155 in Table 1. An aerial view derived from Google Earth and ground-based photographs
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11 156 showing gullies, land cover, reservoirs and erosion mitigation measures are also provided for
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13 157 each catchment as supplementary material.
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19 159 *Hydrological and total sediment yield measurements*

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21 160 Monitoring in the reservoir of the five studied catchments was undertaken since the
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23 161 construction of the small reservoirs. This continuous monitoring consisted of instantaneous
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25 162 measurements of rainfall using a tipping bucket rain gauge (0.5 mm) and water levels with a
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27 163 1 cm precision water level gauge recorder. Between 3 and 10 precise bathymetric surveys
28
29 164 were also conducted in each reservoir to establish up-to-date depth/volume and
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31 165 depth/surface curves. Reservoir siltation volumes were quantified between successive
32
33 166 bathymetric surveys. Sediment concentrations during overflow through the spillway or
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35 167 emptying through bottom drain valve were also measured through manual sampling. All
36
37 168 these measurements enable the calculation of i) mean annual rainfall depth and mean
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39 169 rainfall erosivity by calculating the EI30 index (Wischmeier & Smith, 1958); ii) continuous
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41 170 variation of water level within the reservoir; iii) variation of sediment deposits between
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43 171 successive bathymetric surveys and iv) continuous outputs of water and sediment from the
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45 172 reservoir.
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49 173 Continuous runoff input into the reservoir was then quantified by drawing a hydrologic budget
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51 174 of the reservoir. In addition, sediment input into the reservoir was computed by drawing
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53 175 sediment budgets for successive bathymetric surveys following the method described in
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55 176 Albergel et al. (1998, 2005). Mean annual runoff (in mm yr⁻¹) and sediment yield (in Mg yr⁻¹)
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57 177 were finally quantified for each catchment and for the longest period of records available.
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5 178 In this study, catchment sediment yield is expressed as an area-specific yield (SSY in Mg ha⁻¹
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7 179 yr⁻¹) by dividing the reservoir sediment input by the contributing surface area of the
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9 180 catchment. The precision on the SSY evaluation then mainly depends on: (i) the precision of
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11 181 the DEM as derived from bathymetric surveys (estimated to about 10 %); (ii) the precision on
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13 182 volumes discharged over the spillway (5%) and on measured sediment concentrations (30%);
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15 183 (iii) the precision on average silt density (10%). As a result, global error on SSY was
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17 184 estimated to reach about 20% for these small Tunisian reservoirs (Raclot & Albergel, 2006).

185 *Field sampling*

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

197 Two to four sediment cores were also collected in 2009-2010 in each reservoir
198 simultaneously to the source material sampling (see supplementary material for sampling
199 core location). Each core covered the entire layer of sediment at the sampling locations in
200 the reservoirs and ranged from 0.60 to 2.50 m. This was confirmed by the presence of a
201 more compact soil layer at the base of the core. In addition, the core depths were consistent
202 with data provided by topographical surveys conducted immediately after the reservoir
203 construction. The number and location of cores in reservoir deposits were chosen in order to

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5 204 collect one core in the vicinity of the dam and additional cores at the outlet of each main
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7 205 tributary delivering material to the reservoir. Ben Slimane et al. (2013) showed that this type
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9 206 of sampling scheme where a limited number of sediment cores are collected at strategic
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11 207 locations within the reservoir offered a good compromise to reduce the cost of laboratory
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13 208 analyses while providing relevant and representative sediment fingerprinting results. Cores
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15 209 were then described at the laboratory before and after drying. A single composite sample of
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17 210 each core was then prepared.

211 *Laboratory analysis*

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

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

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

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5 230 After the preliminary destruction of organic matter and dispersion of soil and sediment
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7 231 particles, the grain-size distribution was determined based on the principle of laser diffraction
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9 232 using a Beckman Coulter LS 13320 particle size analyser at the *Laboratoire Géosciences*
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11 233 *Montpellier* (Montpellier, France). This device is equipped with an agitator and an adjustable
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13 234 ultrasonicator to maintain uniform suspension, which enables the analysis of particles with
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15 235 diameters comprised between 0.375 and 2,000 μm . Specific Surface Areas (SSA, square
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17 236 metres per cubic metre) were derived from these laser diffraction data.
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22 238 *Fingerprinting main steps*

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24 239 The fingerprinting properties were first corrected in order to take into account the grain size
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26 240 effects on their adsorption onto particles, as ^{137}Cs and TOC are known to be enriched in the
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28 241 finest (clay to loam-sized) particle fractions (Motha et al., 2003). He and Walling (1996)
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30 242 tested the particle size effects on the adsorption of ^{137}Cs on soils and sediments and showed
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32 243 that ^{137}Cs content can be closely represented by a power function of SSA values calculated
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34 244 for the samples, with exponent values varying between 0.6 and 0.8. In this study, the
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36 245 correction was performed using this power function with an exponent value of 0.7 and
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38 246 applied to both ^{137}Cs activities and TOC content values. Each soil source (i.e. surface topsoil
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40 247 and gully/channel bank) was subsequently characterised by its mean concentration/activity
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42 248 and the standard deviation of each of its fingerprint properties.
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45 249 The ability of individual fingerprinting properties to discriminate between the potential soil
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47 250 sources was then confirmed by conducting a non-parametric Kruskal-Wallis *H*-test as
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49 251 suggested by Collins & Walling (2002). A detailed description of this procedure is provided by
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51 252 Evrard et al. (2011). To characterise the properties of both groups of sources, we assumed
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53 253 that their concentrations ($c_{i,j}$) could be represented by a normal distribution (Eq. 1).
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$$55$$
$$56$$
$$57 \quad c_{i,j} \approx N(\mu, \sigma^2) \quad (1)$$
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$$60$$

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

$$258 \quad \hat{\sigma}^2 = \left(\frac{S.D.}{\sqrt{d}} \right)^2 \quad (2)$$

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

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

$$263 \quad \begin{bmatrix} \bar{c}_{1,1} & \bar{c}_{1,2} & \dots & \dots & \bar{c}_{1,S} \\ \bar{c}_{2,1} & \bar{c}_{2,2} & \dots & \dots & \bar{c}_{2,S} \\ \dots & \dots & \bar{c}_{i,j} & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \bar{c}_{V,1} & \dots & \dots & \dots & \bar{c}_{V,S} \end{bmatrix} \begin{bmatrix} \hat{\beta}_1 \\ \dots \\ \hat{\beta}_j \\ \dots \\ \hat{\beta}_S \end{bmatrix} = \begin{bmatrix} y_1 \\ \dots \\ y_j \\ \dots \\ y_V \end{bmatrix} \quad (3)$$

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

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

$$269 \quad \sum_{j=1}^S \hat{\beta}_j = 1; \quad 0 \leq \hat{\beta}_j \leq 1 \quad (4)$$

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

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

$$277 \quad GOF = 1 - \left\{ \frac{1}{p} \times \left(\sum_{i=1}^v \frac{|y_i - \sum_{j=1}^S \hat{\beta}_j \bar{c}_{i,j}|}{y_i} \right) \right\} \quad (5)$$

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

281

282 RESULTS

283 *Analysis of catchment sediment yield*

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

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

294 Three of the five catchments were characterised by very similar catchment sediment yields

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5 295 (between 15 and 17 Mg ha⁻¹ yr⁻¹), whereas Fidh Ali catchment showed a significantly larger
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7 296 sediment yield (38 Mg ha⁻¹ yr⁻¹) and Sbahia catchment a significantly lower sediment yields
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9 297 (10 Mg ha⁻¹ yr⁻¹). The lifetime of the reservoir (number of years to be completely silted) is
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11 298 about 11 years for Fidh Ali and El Hnach; 15 years for El Melah, and about 30 years for
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13 299 Kamech and Sbahia.

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19 301 *Quantification of the relative contribution of rill/interrill and gully/channel erosion to catchment*
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21 302 *sediment yield for the five catchments*

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24 303 Both ¹³⁷Cs and TOC passed the Kruskal-Wallis test and were used in combination for
25
26 304 discriminating sediments sources in the five studied catchments. Their values and the related
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28 305 specific surface areas (SSA) in both source material and composite sediment core samples
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30 306 collected in the different study sites are presented in Table 3.

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33 307 A significant difference in ¹³⁷Cs and TOC values between both potential sediment sources
34
35 308 was observed in all study catchments, with systematically higher values in the topsoil source
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37 309 than in the gully/channel material. Mean ¹³⁷Cs activities in the topsoil samples varied from 3.5
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39 310 Bq kg⁻¹ to 10.1 Bq kg⁻¹ whereas they were systematically lower than 0.7 Bq kg⁻¹ in
40
41 311 gully/channel samples. Values of ¹³⁷Cs exceeding 1 Bq kg⁻¹ in the topsoil samples indicate
42
43 312 that there has been significant caesium atmospheric fallout during the last decades across
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45 313 the entire Tunisian Ridge and Cape Bon. This confirmed previous ¹³⁷Cs measurements
46
47 314 conducted across the Maghreb region (Damnati et al., 2012; Faleh et al., 2005). The mean
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49 315 TOC value varied from 0.3% and 0.9% in gully/channel material and from 0.5% to 2.5% in
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51 316 topsoil. A recent study conducted in 25 soil samples collected under cropland and 10
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53 317 additional samples collected under forests in Tunisia showed that the organic carbon content
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55 318 of the topsoil ranged from 0.8 to 3.2% for all soils, with a median TOC value of 2.4% for
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57 319 forest soils and 1.4% for cultivated soils (Annabi et al., 2009). The topsoil samples analysed

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5 320 in the 5 study sites were characterised by TOC values that are usually found in Tunisian
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7 321 cultivated soils located in similar bioclimatic zones. Compared to TOC contents found in soils
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9 322 of many other parts of the world, the low values measured in Mediterranean environments
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11 323 can be explained by the low precipitation amounts and the high temperatures prevailing in
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13 324 this region, which are favourable to C mineralization. Among the five studied catchments,
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15 325 samples collected in both El Melah and Fidh Ali sites had TOC values < 1% which indicates
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17 326 a poor soil quality, even for Mediterranean areas (Jones et al., 2004). The very low TOC
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19 327 values measured in topsoil samples of these 2 catchments may also be explained by their
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21 328 coarser texture (i.e., lower SSA values in Table 3) that is known to be less effective to store
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23 329 soil organic carbon than fine-textured soils (Meersmans et al., 2012).

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26 330 The SSA values measured in core and source material samples of a given catchment
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28 331 remained very similar for 4 of the 5 study sites, which means that enrichment and depletion
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30 332 effects caused by selective mobilisation and transport of sediment were of limited magnitude.
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32 333 A significant enrichment of fine-grained sediment during erosion and transportation between
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34 334 soils and the reservoir was only observed in El Melah catchment.

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37 335 Fingerprinting results obtained for the different cores collected in each reservoir were
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39 336 extrapolated to the entire catchment scale by attributing to each core a weighting factor
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41 337 corresponding to its representativeness in terms of sediment volume accumulated in the
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43 338 reservoir as proposed by Ben Slimane et al. (2013). Figure 2 illustrates the results of the
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45 339 source apportionment for each catchment.

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48 340 Results showed the contrasted contribution of erosion processes within the five selected
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50 341 catchments, as the soil surface relative contribution to reservoir sediment ranged between 20%
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52 342 and 80% depending on the site. The surface topsoil was the dominant source of sediment in
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54 343 Fidh Ali, El Melah and Kamech sites, whereas gully/channel material dominated in El Hnach
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56 344 and Sbaihia catchments.

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78 346 *Rill/interrill and gully/channel erosion contributions to catchment sediment yield*
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10 347 Rill/interrill and gully/channel erosion contributions to catchment sediment yield were
11 348 calculated by applying the relative source contribution to the catchment sediment yields
12 349 measured in each catchment (Figure 2). Rill/interrill erosion contribution varied from 2.2 Mg
13 350 ha⁻¹ yr⁻¹ in Sbaihia catchment to 26.5 Mg ha⁻¹ yr⁻¹ in Fidh Ali catchment, whereas
14 351 gully/channel erosion contribution varied between 3 Mg ha⁻¹ yr⁻¹ for Kamech and 11.5 Mg ha⁻¹
15 352 yr⁻¹ in Fidh Ali. The lowest rill/interrill erosion contribution of 2.2 Mg ha⁻¹ yr⁻¹ obtained in
16 353 Sbaihia catchment remained significantly higher than the tolerable soil loss estimated to 1.4
17 354 Mg ha⁻¹ yr⁻¹ (Verheijen et al., 2009), indicating the severe levels reached by soil erosion along
18 355 the Tunisian Ridge and in the Cape Bon region.

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29 356 The range of variation of rill/interrill erosion contribution was larger (from 1 to 12) than
30 357 catchment sediment yields and gully/channel erosion contribution (from 1 to 4) considering
31 358 the five investigated catchments. Quantification of individual erosion process contributions
32 359 therefore provided important information that was not well reflected by catchment sediment
33 360 yields.

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40 361 Overall, Fidh Ali catchment was clearly characterized by the highest catchment sediment
41 362 yields and the highest rill/interrill and gully/channel erosion contributions. When considering
42 363 the other four catchments, the ranking was modified depending of the erosion type
43 364 considered. This is illustrated for instance by the fact that Kamech catchment had the second
44 365 most important rill/interrill erosion contributions but the lowest gully/channel erosion
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DISCUSSION

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5 369 *Selection of ¹³⁷Cs and TOC as sediment tracers in this study*

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7 370 One of the main challenges associated with the choice of tracers in fingerprinting technique
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9 371 still lies in the need for better accounting for the selectivity/conservative behaviour of
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11 372 sediment and fingerprint properties between the sources of sediments and the collected
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13 373 material (Koiter et al., 2013). A recent extensive review on sediment tracers in water erosion
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15 374 studies (Guzmán et al., 2013) showed that fallout radionuclides are the most extensively
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17 375 used soil redistribution tracers reported in the scientific literature and that ¹³⁷Cs is by far the
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19 376 dominant one, especially for medium time scales (tens of years) across a broad range of
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21 377 spatial scales from hillslope and small catchments to large basins. Its use in fingerprinting
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23 378 techniques -alone or in combination with other tracers- has proven to be effective in
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25 379 discriminating between subsoil and topsoil sources in several studies (Owens et al. 1999;
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27 380 Zhang & Walling, 2005, Juracek & Ziegler 2009; Smith et al. 2012). The conservative
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29 381 behaviour of ¹³⁷Cs in soil environments has been demonstrated in many studies and detailed
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31 382 arguments may be found in Guzmán et al. (2013) for instance. If biochemical properties have
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33 383 the potential to provide better spatial constraints for sediment sources compared to other
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35 384 fingerprint properties (Koiter et al., 2013), the use of organic constituents as soil redistribution
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37 385 tracers is less usual. One reason is that the behaviour of organic constituents may often be
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39 386 suspected as poorly conservative. Many arguments have been formulated by Ben Slimane et
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41 387 al (2013) regarding the ability of TOC to be used as an additional tracer to ¹³⁷Cs in the
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43 388 specific context of recent North African reservoirs (less than 20 years old) : i) autochthonous
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45 389 source of organic constituents in oligotrophic North African reservoir is negligible as proved
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47 390 in a series of more than 20 modern Tunisian reservoirs (Rahaingomanana 1998); ii) TOC
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49 391 degradation in the deposits is also negligible for recent reservoir as the kinetics of TOC
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51 392 degradation were proved to be very slow in oligotrophic lake deposits as demonstrated by
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53 393 Patience et al. (1995) for the Lac du Bouchet (France); iii) terrestrial organic residues
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55 394 probably did not experience major changes via bacterial alteration during their transport,
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57 395 settling and incorporation into the sediment because terrestrial higher plant debris had
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5 396 already been submitted to strong biotic as well as abiotic degradation under oxic conditions
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7 397 in soils (Vandenbroucke & Largeau 2007); iv) degradation during mobilisation and transport
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9 398 is also likely to be limited due to the very short sediment transport distances within the small
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11 399 studied catchment. The conservative behaviour of TOC was also corroborated by previous
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13 400 studies conducted in recent North African reservoirs. Albergel et al. (2006) demonstrated for
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15 401 instance that the majority of the organic matter found at two Tunisian reservoirs (El Gouazine
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17 402 and Fidh Ali) originated from upstream soil sources, and that this organic matter was not
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19 403 transformed in the recently accumulated sediment (approximately 10 years old in their
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21 404 studies). Ben Slimane et al. (2013) confirmed the terrestrial origin of TOC in the Kamech
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23 405 reservoir deposits using Rock-Eval analysis and $\delta^{13}\text{C}$ measurements to demonstrate the
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25 406 very low kinetics of TOC degradation through analysis of the entire sediment deposit
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27 407 sequence.

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30 408 Previous research and the very different TOC contents found in topsoil and subsoil sources
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32 409 (Table 3) support the relevance of using TOC in combination with ^{137}Cs as potential sediment
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34 410 tracers in the context of this study. It was verified by comparing results from fingerprinting
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36 411 approach using either the combination of ^{137}Cs and TOC or ^{137}Cs alone. Figure 3 shows that
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38 412 very similar results are obtained by both methods. As the use of multiple tracers in a mixing
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40 413 model allows for more reliable source apportionment than the use of only one tracer (Walling
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42 414 et al. 1993; Small et al. 2002; Martinez-Carreras et al. 2008) we finally focused our
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44 415 discussion on the fingerprinting results derived from the combined use of ^{137}Cs and TOC as
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46 416 tracers.

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50 417 *On the driving factors of reservoir siltation*

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52 418 Although Fidh Ali catchment is characterized by the lowest mean rainfall amount and the
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54 419 lowest rainfall erosivity index values, it clearly showed the highest erosion contributions
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56 420 whatever the erosion processes considered (Figure 2). The extreme intensity of erosion in
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58 421 Fidh Ali catchment can be explained by its soil composition that contains a very high
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5 422 percentage of marly gypsum showing intense swelling/shrinkage processes (clayey soils).
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7 423 They are known to increase soil sensitivity to erosion (Cantón et al., 2001; Sfar Felfoul et al.,
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9 424 1996, 1999) as they facilitate both aggregate dispersion and gully initiation. In this catchment,
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11 425 this specific lithological feature directly appears as the first-order factor driving the very high
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13 426 erosion rates. Areas covered with a large marly gypsum surface should therefore be
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15 427 considered as priority zones for implementing erosion protection measures in the Tunisian
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17 428 Ridge.

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20 429 A simple statistical analysis by means of linear regressions was performed in order to
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22 430 investigate the relationships between dominant erosion processes contributing to reservoir
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24 431 siltation and the following characteristics: total catchment area, mean annual rainfall, mean
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26 432 annual erosivity index, mean annual runoff, mean annual runoff coefficient, global slope
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28 433 index, drainage density, percentage of catchment surface covered by (i) soft lithological
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30 434 substrate types, (ii) badlands, (iii) cropland, (iv) equipped with soil conservation measures.
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32 435 Table 4 summarizes the correlation coefficient values obtained for each linear relationship
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34 436 tested when considering the 5 studied catchments. The significant correlations at the 0.05
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36 437 level are mentioned when considering the 5 catchments but also when excluding Fidh Ali as
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38 438 its extreme erosion values may greatly affect some correlations. As this analysis is restricted
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40 439 to a set of 4 or 5 catchments, its statistical significance is relatively low. Consequently only
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42 440 correlation values significant at the 0.05 level are discussed in the remainder of the text and
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44 441 further investigations will be required to confirm these preliminary findings regarding the
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46 442 identification of first-order factors controlling reservoir siltation.

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49 443 First, correlation coefficient values between potential driving factors and the contribution of a
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51 444 single individual erosion process (related to either rill/interrill or gully/channel sediment
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53 445 sources) were generally higher than the ones obtained between driving factors and SSY.
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55 446 This may indicate that the tested factors explain individual erosion process contributions
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57 447 rather than the combined effect of all erosion phenomena. Second, several correlations
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5 448 values were significant at the 0.05 level when considering the five studied catchments but
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7 449 non-significant when excluding Fidh Ali. This means that the significance of the correlations
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9 450 is mainly due to the extreme erosion values recorded in Fidh Ali catchment and not to the
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11 451 tested factor. On the contrary, a significant negative correlation was obtained between the
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13 452 percentage of catchment area under cropland and the gully/channel erosion contribution (at
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15 453 the 0.05 level) by both including and excluding the Fidh Ali site. This result can be interpreted
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17 454 as the fact that gully/channel erosion took place in a highly degraded environment unsuitable
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19 455 for cultivation. Finally, the percentage of total catchment area equipped with erosion control
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21 456 measures (% of total managed area) appeared to be the most relevant driving factor of
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23 457 reservoir siltation in the five studied catchments. It was significantly correlated with the
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25 458 relative contribution of individual erosion processes (with or without Fidh Ali) and with
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27 459 rill/interrill erosion rate (when excluding the Fidh Ali catchment), both in a negative way. This
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29 460 confirms that soil protection measures have a significant impact on surface erosion by
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31 461 limiting either soil detachment or sediment transportation from hillslopes to catchment outlet.
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33 462 This is a major finding of this study as this factor is anthropogenic and can therefore be
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35 463 controlled.
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41 465 *Main erosion processes contributing to reservoir siltation*

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44 466 Jebari et al. (2010) have proposed to use a rough direct relationship between rainfall
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46 467 characteristics (maximum 15-min duration rainfall intensity) and the respective contribution of
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48 468 rill, interrill and gully erosion processes to sediment siltation in 28 Tunisian small reservoirs.
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50 469 Their results indicated that rill/interrill erosion was largely dominant in the major part of the
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52 470 Tunisian Ridge as gully erosion contribution exceeded 20% in only 5 of the 28 studied
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54 471 catchments, and 50% in one single catchment. Considering the same sites of investigation
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56 472 used in this study, they found a dominant contribution of rill/interrill erosion with values
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58 473 between 82% and 90% for the five catchments. There is therefore a contradiction between
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5 474 the findings provided by Jebari et al. (2010) and our results as we found that two of the five
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7 475 investigated catchments were in fact dominated by gully/channel erosion processes. This
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9 476 inconsistency may arise from the fact that rainfall characteristics are important but not
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11 477 sufficient to explain the dominant erosion processes in a catchment and that we need to take
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13 478 into account human activities such as soil conservation measures as major driving factors to
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15 479 understand and characterize properly the erosive processes in a catchment.
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18 480 To a wider extent, the predominance of gully/channel erosion contribution in two of the five
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20 481 studied catchments confirms the significant contribution of subsuperficial erosion processes
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22 482 (other than sheet and rill erosion) to catchment sediment yield in the Mediterranean zone as
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24 483 recently underlined by Vanmaercke et al. (2012) who compared sheet/rill erosion rates and
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26 484 sediment yield in a large number (n = 1794) of European catchments. This result is likely
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28 485 valid in other regions of the world as for the Alpine zone (Vanmaercke et al., 2012) or in
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30 486 Northern Ethiopia (Haregeweyn et al., 2013).
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36 488 *Implications for catchment management*

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38 489 A simple sediment source apportionment method conducted at the catchment scale showed
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40 490 that the variability observed for individual (i.e., rill/interrill or gully/channel) erosion process
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42 491 magnitude was two or three times higher than the variability observed for total erosion. The
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44 492 explicit consideration of different erosion processes provided a more efficient way to outline
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46 493 the high variability of erosion processes between catchments than the simple calculation of
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48 494 specific sediment yields (SSY). Moreover, the ranking of catchments following an order of
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50 495 increasing/decreasing erosion contributions proved to be significantly modified depending on
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52 496 the type of erosion processes considered. Identification and quantification of the dominant
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54 497 sediment sources is crucial for our understanding of human impacts on catchment SY and
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56 498 for the design of efficient management strategies to reduce SY at the catchment scale
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5 499 (Vanmaercke et al., 2012). In Tunisia, implementation of conservation farming practices
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7 500 should be encouraged in catchments characterised by similar features as Kamech, Fidh Ali
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9 501 and El Melah sites. In these environments, maintaining a minimal vegetation cover of the soil
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11 502 during autumn may provide a good solution to protect it from sheet and rill erosion (Crosaz,
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13 503 1995; Maetens et al., 2012; Menashe, 1998; Rey & Berger, 2002). In contrast, measures
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15 504 dealing with gully and channel erosion should be targeted on sites similar to El Hnach and
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17 505 Sbaihia catchments. To a wider extent, installation of any erosion protection measure must
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19 506 be carefully designed as it is well-known that complex interactions exist between these
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21 507 different types of erosion processes at the catchment scale (Bryan, 2000; de Figueiredo &
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23 508 Fonseca, 1997; Romkens et al., 2001; Roose et al., 2010). In our study, we showed that the
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25 509 use of conservation measure was efficient in decreasing both relative (in %) and absolute (in
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27 510 $\text{Mg ha}^{-1} \text{ yr}^{-1}$) rill/interrill erosion contributions to reservoir siltation. These measures that were
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29 511 targeted to reduce rill/interrill erosion therefore fulfilled their objective. However, the
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31 512 significant correlation between the percentage of total managed area and the relative
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33 513 contributions of individual erosion processes (including or excluding Fidh Ali) also means that
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35 514 the implementation of soil conservation measures has a negative effect on the contribution of
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37 515 gully/channel erosion processes. This result suggests that measures aimed to control topsoil
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39 516 erosion must be implemented in association with complementary measures aimed to gully
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41 517 stabilization. Such a combination is especially required when topsoil conservation measures
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43 518 aim to reduce sediment detachment or to enhance sediment trapping without decreasing
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45 519 runoff as it is the case for contour stone bunds for instance. This confirms the need for
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47 520 combining several types of measures (vegetative and structural) to increase sediment
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49 521 trapping and protect reservoir from siltation (Mekonnen et al., 2014).

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52 522 Identification and quantification of the dominant sediment sources are also crucial to identify
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54 523 the most appropriate models to simulate erosion at the catchment scale (De Vente et al.,
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56 524 2013; Morgan, 2011; Vanmaercke at al, 2012) and avoid their misapplication (Govers, 2011).
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58 525 Poor modelling results are frequently obtained when a single model is applied to a wide
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5 526 series of catchments, as most models are generally designed for describing a limited number
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7 527 of processes (either sheet and rill erosion or gully and bank erosion) but they are rarely
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9 528 designed to simulate the complete range of phenomena (De Vente & Poesen, 2005; De
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11 529 Vente et al., 2013, Haregeweyn et al., 2013). In Mediterranean environments, the occurrence
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13 530 of severe catchment sediment yield was explained by a complex combination of rill/interrill
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15 531 and gully/channel erosion processes. In the light of these results, we suggest that
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17 532 interactions between both processes need to be further investigated and integrated into soil
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19 533 erosion models.
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CONCLUSIONS

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27 536 This work confirmed the relevance of using a fingerprinting method based on the
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29 537 measurement of ^{137}Cs and TOC to estimate the relative contribution of rill/interrill vs.
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31 538 gully/channel erosion processes to reservoir siltation in Northern Africa catchments. Among
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33 539 the five investigated catchments, three of them were characterized by dominant rill/interrill
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35 540 erosion contribution, whereas gully/channel erosion contribution prevailed in the two other
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37 541 sites. The results also showed that a very large variability of erosion processes contributed to
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39 542 reservoir siltation in catchments located along the Tunisian Ridge even when similar
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41 543 catchment specific sediment yields were recorded. The presence of a large surface cover of
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43 544 marly gypsum material was confirmed to enhance both rill/interrill and gully/channel erosion
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45 545 processes. Furthermore, the implementation of soil protection measures was also identified
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47 546 as a main factor driving erosion in this region. This work also corroborated the existence of
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49 547 complex interactions between rill/interrill and gully processes. Consequently, implementation
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51 548 of soil conservation measures must be carefully designed at the catchment scale. Indeed soil
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53 549 conservation measures aimed to prevent particle detachment on cultivated hillslopes and
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55 550 their downstream transportation seemed to have negative feedback by amplifying
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57 551 downstream gully/channel erosion. In catchments where rill/interrill erosion contribution
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5 552 dominates, we therefore suggest to implement topsoil protection measures that significantly
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7 553 reduce sediment concentration and runoff at the same time. To a wider extent, this work also
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9 554 corroborated the interest to combine different types of conservation measures (vegetative
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11 555 and structural, in both the fields and gullies/channels) to limit reservoir siltation.
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14 556 Overall, our results also suggest the need to develop erosion models simulating interactions
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16 557 between rill/interrill and gully/channel processes in order to guide the implementation of
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18 558 erosion control measures in Mediterranean catchments.
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11 803 Figure 1. Location of the selected catchments within a pilot network of monitored catchment
12 reservoirs along the Tunisian Ridge and the Cape Bon region (modified from Temple-Boyer
13 et al., 2007). Rainfall information (isohyet) has been superimposed.
14
15 805 et al., 2007). Rainfall information (isohyet) has been superimposed.
16

17 806 Figure 2. Catchment sediment yield, rill/interrill and gully/channel erosion contribution to
18 reservoir siltation for the five study catchments.
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20 807 reservoir siltation for the five study catchments.
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22 808 Figure 3. Sediment source apportionments for the five studied catchments using the mixing
23 model either with the combination of ^{137}Cs and TOC or with ^{137}Cs only.
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25 809 model either with the combination of ^{137}Cs and TOC or with ^{137}Cs only.
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817 Table 1. Characteristics of the five studied catchments as of 2010. The bioclimatic zones were extracted from the bioclimatic map of Tunisia
 818 (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
 819 catchment surface and the length of the equivalent rectangle (km).

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Catchments	Description				Characteristics / Factors								
	Name	Area (km^2)	Drainage density ($m\ ha^{-1}$)	Reservoir		Regional climate		Lithology	Topography		Land cover	Catchment management	
				Building year	Initial volume (m^3)	Bioclimatic zones	Mean annual rainfall (mm)		Altitude range (m)	Global slope index ($m\ km^{-1}$)		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% limestone 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% forest, 3% badlands.	contour bench terraces	41.3	

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

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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
Sbailia	09/1993 – 11/2006	10	454	798	72	15.7

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

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828

829 Table 3. Mean and Standard deviation of potential fingerprinting properties and specific
 830 surface area (SSA) measured in sediment source and reservoir sediment samples (n=85)
 831 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

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

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	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).

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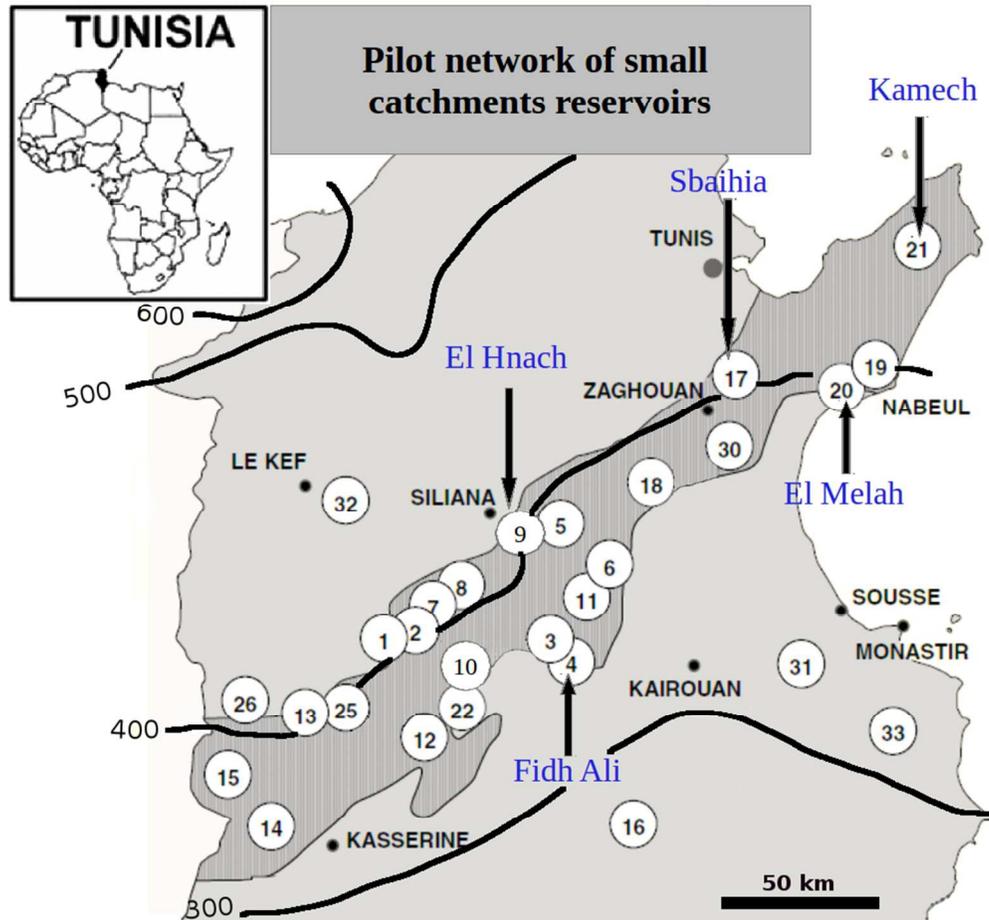


Figure 1. Location of the selected catchments within a pilot network of monitored catchment reservoirs along the Tunisian Ridge and the Cape Bon region (modified from Temple-Boyer et al., 2007). Rainfall information (isohyet) has been superimposed.
258x238mm (96 x 96 DPI)



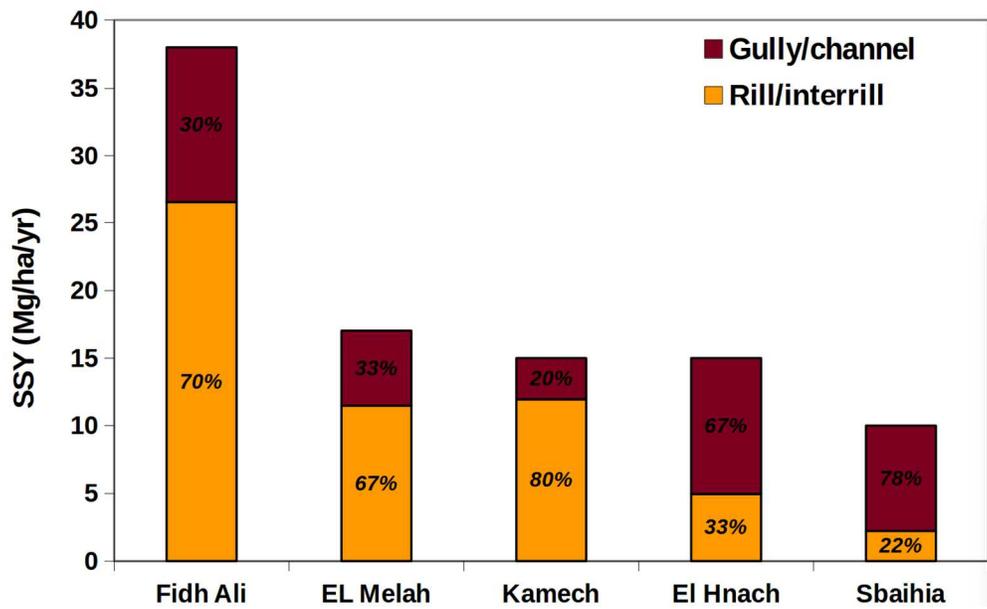


Figure 2. Catchment sediment yield, rill/interrill and gully/channel erosion contribution to reservoir siltation for the five study catchments.
417x256mm (96 x 96 DPI)

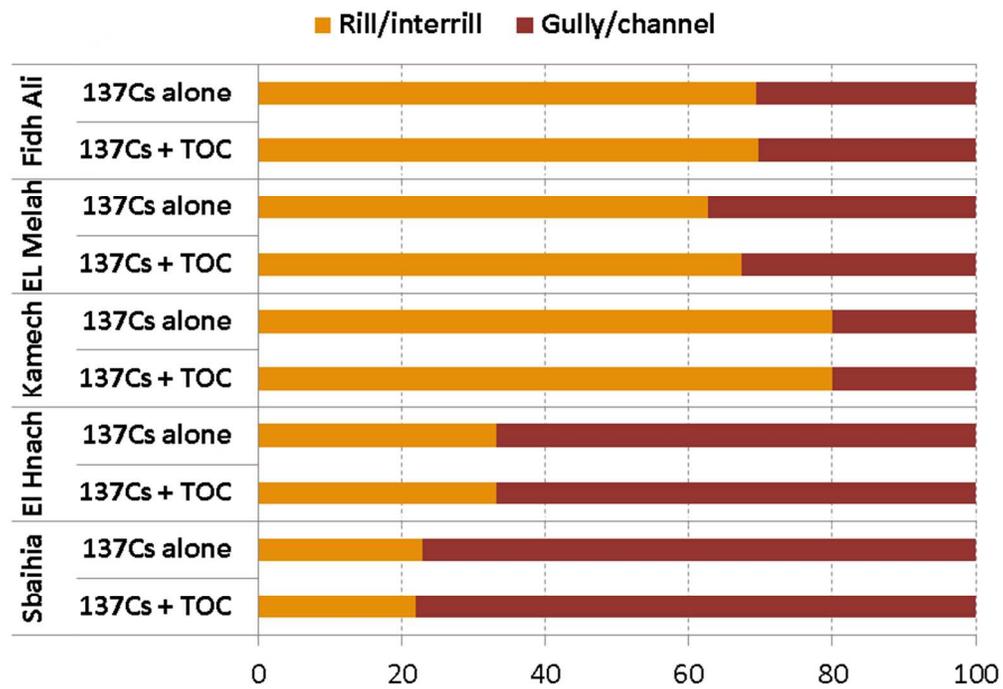


Figure 3. Sediment source apportionments for the five studied catchments using the mixing model either with the combination of ^{137}Cs and TOC or with ^{137}Cs only.
235x165mm (96 x 96 DPI)