



HAL
open science

Spring mounds of the Nefzaoua oases in Tunisia : irreversible degradation of exceptional geomorphic structures

A. Raddadi, Pascal Podwojewski

► **To cite this version:**

A. Raddadi, Pascal Podwojewski. Spring mounds of the Nefzaoua oases in Tunisia : irreversible degradation of exceptional geomorphic structures. *Journal of Arid Environments*, 2022, 205, 104806 [10 p.]. 10.1016/j.jaridenv.2022.104806 . hal-03741903

HAL Id: hal-03741903

<https://hal.science/hal-03741903>

Submitted on 22 Jul 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Spring mounds of the Nefzaoua oases in Tunisia: irreversible degradation of exceptional**
2 **geomorphic structures**

3 **Afef Raddadi¹, Pascal Podwojewski^{*2}**

4 1. UMR ARCHEORIENT Environnements et Sociétés de l’Orient ancien, UMR 5133,
5 Université Lumière Lyon 2. Berges du Rhône, Maison de l’Orient et de la Méditerranée, 7,
6 rue Raulin 69365 Lyon cedex 7, France.

7 2. UMR IEES-Paris, IRD, SU, INRAE, CNRS, UP, UPEC. IRD, délégation régionale Île de
8 France, 32 av. H. Varagnat, 93143 Bondy cedex, France.

9 *corresponding author: pascal.podwojewski@ird.fr

10 **Keywords:** spring mound, degradation, oases, geomorphosite, Tunisia

11 **Highlights:**

- 12 • The oases of the Nefzaoua Region in Tunisia are associated with spring mounds.
13 • Artesian springs emerging from spring mounds were at the base of oasian settlements.
14 • Spring mounds are exceptional geomorphic structures of arid lands.
15 • Spring mounds are endangered with natural and anthropic degradation.
16 • Some selected mounds could be preserved from destruction as geomorphosite.

17 **Abstract**

18 The oases in the arid the Nefzaoua region in central-western Tunisia are associated with
19 spring mounds. Spring mounds result from an exceptional succession of geomorphological,
20 hydrogeological and climatic conditions and processes that follow each other in a specific
21 order. They look like small volcanoes that range from 200 m to more than 2 000 m in
22 diameter and 3-30 m in height, which centres were once occupied by a pond fed by an
23 artesian spring. They are at the origin of each oasis’s irrigation system, which radiates from
24 the mound’s foot. Due to intense irrigation of intensive date palm plantations (*Phoenix*

25 *dactylifera*) in recent decades, all artesian springs dried out. We established a complete
26 inventory and typology (i.e. location, dimension, and types of degradation) of all spring
27 mounds in the Nefzaoua region. Overall, in an area of 3 000 km², 126 spring mounds of 7
28 types were identified, of which 112 (89%) were degraded. Due to the low salt content in
29 spring mound sediments, they are excavated and used as a soil amendment to expand new
30 palm plantations. Only 14 mounds (11%) are presently preserved. Their qualification as a
31 geomorphosite could preserve them from complete destruction.

32 **1. Introduction**

33 While land degradation is considered a major cause of loss of biodiversity (IPBES, 2018),
34 salinisation caused by mismanaged irrigation is considered a major cause of land degradation
35 and desertification in arid regions, especially oasis environments (UNCCD, 1994, FAO and
36 ITPS, 2015). This type of land degradation is well documented, especially in Saharan
37 environments such as the oasis complex of the Nefzaoua region in central-western Tunisia
38 (Zammouri and al., 1997; King and Thomas, 2014). In 1998, the surface of Nefzaoua oases
39 covered 15 300 ha (Sghaier, 1999), corresponding to 48% of all Tunisian oases area.

40 However, another recent form of land degradation not well documented occurs; the complete
41 and recent anthropic destruction of spring mounds associated with oasis springs. Spring
42 mounds are natural rounded geomorphological small hills that range from 200 m to more than
43 2 000 m in diameter and 3-30 m in height. They are associated with artesian springs that
44 emerge from the ground and are well known in a variety of arid environments, especially the
45 Great Artesian Basin in Australia (Watts, 1973; Ponder, 1986; Clarke and al., 2007; Powell
46 and al., 2015; Harris, 2020) and oases in western Egypt (Brookes, 1993; Idris, 1996;
47 Adelsberger and Smith, 2010; Torab, 2021).

48 More than 600 springs have been identified in the Great Artesian Basin (1.7 million km²)
49 (Ponder, 1986), with more than 60 of them active in the Dalhousie Mound Spring Complex

50 (Clarke, 2007). In comparison, in the Nefzaoua region alone, 126 spring mounds have been
51 identified in an area of less than 3 000 km², 0.18% the size of the Great Artesian Basin
52 (Raddadi, 2021). In the Nefzaoua region, each spring lay at the centre of a permanent oasis
53 settlement for more than 2 000 years (Bédoucha-Albergoni, 1976). In 1884, Tissot observed
54 that more than 100 artesian springs were exploited in an area 100 km in diameter (*70 leagues*
55 *in circumference*) in the Nefzaoua region. Currently, all irrigated plantations radiate out
56 around these mounds (Figure 1). Surprisingly, only one major reference mentions the
57 presence and importance of spring mounds in Tunisia (Robert and Mitchell, 1987), and no
58 inventory of their presence, size, location and status has ever been made.

59 Because the level of the water table decreased due to excessive artificial pumping for
60 irrigation (Sghaier, 1999; Brochier-Puig, 2004), all artesian springs in the Nefzaoua region
61 have dried up. Thus, spring mounds no longer lie at the centre the irrigation networks of oasis
62 agricultural systems and can no longer maintain themselves; their structure is only a relic of a
63 past based on sedentary settlements. Today, the existence of these geomorphological features
64 is at risk. Most of these spring mounds will disappear within a few decades due to natural
65 sand invasion or anthropic excavation. Local farmers use the sediments of these mounds,
66 which have a low salt content, as a soil additive to expand intensive cultivation of mono-
67 specific date palms (*Phoenix dactylifera*, variety *deglet nour*), which are exported.

68 The recent excavation of some mounds has exposed stratigraphic features of limnic deposits
69 associated with capillary rise of neoformed carbonate and gypsum layers in the upper part of
70 the mounds from evaporated groundwater (Raddadi, 2021), and confirmed their origin already
71 described by Ponder (1986) or Clarke and al., (2007) in Australia. The uneven extent of this
72 degradation was the first reason to establish a complete inventory and status of the mounds of
73 the province. We present in this article different methodologies used to establish an inventory

74 and a typology of all 126 visible spring mounds in the Nefzaoua region. With these tools, we
75 have established their location, size, and seven paths of evolution based on their current state.
76 To preserve some spring mounds from complete destruction, they should be classified as
77 geomorphosites (Reynald and Panizza, 2005). According to Reynard (2009) and Reynard et
78 al., (2015), the first step before the management of a geomorphosite is a complete inventory
79 of the sites. From this first step we would be able i) to select sites for complete sediment
80 sampling to study the formation process of the mounds from their origin through all steps in
81 their evolution, ii) to establish the importance of spring mound excavation associated with the
82 extension of cultivated lands, iii) to provide suggestions for protecting them and preventing
83 their complete destruction in relation of scientifically, cultural, historical and aesthetic values
84 (Raddadi et al., 2022).

85 **2. Materials and methods**

86 ***2.1 Study sites***

87 *2.2.1 Geological and hydrogeological context*

88 The geology of the Nefzaoua region is composed of sedimentary rocks (e.g. limestone,
89 siltstone, dolomite, gypsum) from a Cretaceous monoclinical structure part of the southern
90 alpine Atlas Mountain chain, to Pleistocene sub-horizontal deposits, with active tectonics. The
91 province has two extended captive aquifers, the lower one of Turonian age (*Continental*
92 *intercalaire*) composed with limestone and clayey dolomite and the upper one (*Complexe*
93 *terminal*) of late Senonian age composed with gypsum marls (OSS, 2003; Gonzalvez and al.,
94 2014; Hadj Ammar et al., 2014). Due to tectonic movements, artesian springs emerged at the
95 surface (Swezey, 1996), nearly 300 of which were recorded at the beginning of the 20th
96 century (Raddadi, 2021).

97 The chemical composition of water from multiple boreholes in the province has low to
98 moderate salt content (total dissolved solids of 600-3 700 mg l⁻¹); however, the salt content

99 increases with irrigation and leaching of salts. The Water compositions reveal that the
100 mineralization is mainly regulated by water/rock interaction through mineral dissolution and
101 probably by ions exchange processes enhanced by long groundwater residence time (Kraiem
102 et al., 2014; Hadj Ammar et al., 2014). Intensive irrigation decreases the level of the water
103 table, which increases the risk of salinity (Zammouri and al., 2007; Marlet and al., 2009).

104 2.2.2 Geomorphological context

105 The Nefzaoua region corresponds to the governorate of Kebili in the central west part of
106 Tunisia (Figure 2). The spring mounds in the Nefzaoua region in central-western Tunisia are
107 found in a large set of oases shaped like a crescent in the extreme east of the Chott el Jerid,
108 including the cities of Kebili and Douz, at the crossroads of four geomorphological entities
109 and landforms (Figure 2). In the North lies the Djebel Tabagha mountain chain, which is a
110 oriented East-West. and reaches 470 m.a.s.l. In the East lies the piedmont of the Jurassic
111 monoclinical structure of Djebel Dahar, which reaches 713 m.a.s.l., is oriented North-South and
112 declines into a gentle slope oriented to the West. In the South-West lies the large desert sand
113 dunes of the *Grand Erg Oriental*. Finally in the West lies a vast playa locally designated as
114 *sabkha* of 5 860 km² called Chott el Jerid, which is a saline and endoreic depression with an
115 elevation of 15 m.a.s.l. There is no direct influence of evaporitic deposits in the *sebkhas* on
116 the chemical composition of the major water-tables (Kraiem et al., 2014; Hadj Ammar et al.,
117 2014).

118 2.2.3 Climate

119 The climate is arid and hot (BWh in the Köppen classification), with mean rainfall of <100
120 mm year⁻¹ (80 mm year⁻¹ in the past 20 years). The mean annual temperature is 20.9°C, with
121 extreme daily, monthly and seasonal extremes (48°C in summer to -5°C in winter). Annual
122 evapotranspiration exceeds 1 600 mm, with a strong water deficit. In arid environments, wind
123 is the main source of erosion and a geomorphological agent. Most strong winds originate

124 from the north-east, and 40% of those measured in Kebili exceed 3 m s⁻¹ (Khatelli and
125 Gabriels, 2000; data from the Tunisian National Meteorological Office).

126 2.2.4 Land occupation

127 Evidence of sedentary settlements around these springs (i.e. *aioun*) on top of the spring
128 mounds are indicated by the remains of Roman construction. Irrigation canals (i.e. *seguia*),
129 tunnels and collectors reveal a highly developed agricultural system based on irrigation
130 around the mounds (Idoux, 1902; Trouset, 1986). Since the end of 19th century, the local
131 population in the Nefzaoua region has grown from 18 000 to 160 000 (in 2015), from partially
132 nomadic to completely sedentary (Sghaier, 1999), and was concentrated around 300 artesian
133 springs. Not all of them are developing spring mounds but all spring mounds are associated
134 with artesian springs.

135 The irrigated agricultural system was sustained by sharing irrigation time, maintaining the
136 infrastructure and cleaning the springs frequently (Lasram, 1990). Three-level gardens (date
137 palm on top; fruit trees such as fig or pomegranate in the middle; and vegetables, fodder and
138 barley at the bottom) radiated around the mounds. Currently, due to the development and use
139 of solar-powered pumps, the area of irrigated intensive date palm plantations in the past 40
140 years increased from 5 000 to 20 000 ha (Raddadi, 2021). At the same time, the level of the
141 water table decreased greatly. Wells fed by artesian springs have not been active since 1995
142 (Zammouri et al., 2007) and the mounds are no longer sustained by regular flooding.

143 2.2 Methodology

144 To locate spring mounds and assess their recent evolution, we used three data sets:

- 145 - Eight topographic maps of the area were combined, digitised, projected into an image in
146 UTM coordinates and geo-referenced (Table S1). On these maps, 399 springs associated
147 with spring mounds were identified, 2 springs were described as filled, 1 had dried up and
148 31 were located north of Djebel Tebaga. Not all of these springs were spring mounds.

- 149 - The Timelapse project of Google Earth™ allows users to visualise and measure the
150 evolution of a landscape since 1984. It uses GigaPan Time Machine technology (Carnegie
151 Mellon University, USA), which allows for high-definition examination of mosaics of
152 cloud-free images that consider the incidence of shade in relation of the season. Most
153 images are provided by Landsat satellites (NASA). Since 2016, Landsat 8 images have
154 been combined with Sentinel-2 images (European Space Agency)
- 155 - A digital elevation model was provided by two TanDEM-X twin satellites from the
156 German Research Centre for Astronomy (DLR Deutsches Zentrum für Luft and
157 Raumfahrt) and the EADS Atrium group (Airbus Defense and Space). These satellites can
158 be used to create radar images and digital elevation models with a relative precision of 10
159 m in horizontal resolution and 2.0 m in vertical resolution. The digital elevation model
160 enabled us to measure the diameter and height of most of the spring mounds, especially
161 when their boundaries were unclear in the field (Figure 4). When the radius is mentioned
162 for the size of a spring mound it is for an easier evaluation of the slope value.

163 **3. Results**

164 Based on recent observations (since 2019), 126 spring mounds (Table S2; Raddadi and
165 Podwojewski, 2022) have been identified in an area of 3 000 km² (60 km north-south and 50
166 km east-west) that includes the cities of Debabcha in the north and Kebili, Douz and Sabia in
167 the south (Figure 3B). In the north, the Djebel Tabagha mountain chain represents the
168 northern limit of the mounds. North of this chain, the spring mounds associated with former
169 springs are extremely small and difficult to identify. The 126 mounds were classified into
170 seven types (Table 1). This relatively subjective typology considered evolution of the mounds
171 only over the past 10 years (2010-2020) and allowed mounds to be assigned a secondary type
172 in addition to the dominant type. However, the process of evolution/degradation is clear for
173 the seven types of mounds (Figure 5) :

- 174 • *silted*: a naturally degraded mound whose original morphology is covered by sand and
175 whose summit is no longer visible. Of the 18 mounds (14.3%) identified, 12 (9.5%) had no
176 secondary type (Table 2). In comparison, 18 other mounds (14.3%) were silted as a
177 secondary type.
- 178 • *levelled*, which is subdivided into *naturally levelled* or *anthropically levelled*.
- 179 - *naturally levelled* (N): a mound with a naturally flat surface on top. The spring is silted,
180 and the basin is no longer visible. Of the 28 mounds (22.2%) identified, 12 (9.1%) had no
181 secondary type, while 14 (11.1%) were silted as a secondary type (Table 2). They are
182 located on the edge of the study area, where all spring mounds are concentrated in a
183 crescent from the south of the chott to north-east of Douz. These mounds are difficult to
184 identify on satellite images. Only 14 (50% of this type) had clear circular boundaries that
185 were easy to measure with the digital elevation model.
- 186 - *anthropically levelled* (A): a mound whose original structure and features no longer
187 exist. The mound has been stripped, and some of it has been transformed into fields. Of
188 the 14 mounds (11.1%) identified, 11 were considered seriously degraded, including 3 in
189 the process of being dismantled and 1 which was urbanised and silted (Table 2). These
190 mounds are considered the most degraded.
- 191 • *dismantled*: a mound which has been partially excavated or levelled with mechanical
192 shovels. The sand removed is used to fill depressions near the chott and to expand new
193 cultivated land in the chott using sediments with low salt content (i.e. low electrical
194 conductivity). A dismantled spring mound also clears land on which to create new fields
195 for plantations. Of the 39 mounds (31%) identified, 5 were strongly degraded and 10
196 were weakly degraded (Table 2), but the irreversible process is underway. The secondary
197 type was urbanised for 8, silted for 2 and naturally levelled for 1. This type is located
198 mainly near the eastern edge of the chott, where most of the spring mounds occur.

- 199 • *urbanised*: a mound currently or formerly occupied by a village. This is the case for
200 largest mounds, which have a mean radius of 657 m, compared to the overall mean radius
201 of 364 m (Table 3). All villages in Nefzaoua were built on a mound whose spring
202 irrigated the mound's foot. Of the 9 mounds (7.1%) identified, 4 were being destroyed by
203 anthropic levelling.
- 204 • *equipped*: a mound whose spring water was usually collected in a constructed circular
205 pool. The pool collects water around the natural spring vent, and some were used as fish
206 ponds. All 4 mounds (3.2%) identified had urbanised as a secondary type.
- 207 • *preserved*: a mound which has kept its initial morphology and has little natural or
208 anthropic degradation. Of the 14 mounds (11.1%) identified, the secondary type was
209 silted for 2 and urbanised for 1. Some showed evidence of natural hydric erosion, with
210 rills along the slope.

211 **4. Discussion**

212 ***4.1 Formation and composition of spring mounds***

213 Spring mounds result from an exceptional combination of geomorphological, geological,
214 tectonic and climatic conditions that follow each other in a specific order (Raddadi, 2021).
215 Many sources have documented the steps involved in their formation typical of arid or semi-
216 arid environments: the collection of rainwater to fill water tables (Kraiem et al., 2014),
217 neotectonic and faults (Swezey, 1996) with emerging artesian springs (Harris, 1981; Ponder,
218 1986), the influence of vegetation to trap fine aeolian particles (e.g. Adelsberger and Smith,
219 2010) and the presence of fine sediments layers deposited in the pond in the centre of a
220 geomorphological structure similar to a little volcano (Harris, 1981; Ponder, 1986; Clarke and
221 al., 2007).

222 The mounds are composed at their base of fine centimetric horizontal sediment layers, with
223 low salt content ($< 2 \text{ mS cm}^{-1}$ in the 1/5 water extract), which are subjected to pedogenesis

224 processes with oxido-reduction features and carbonate precipitation A thick layer of indurated
225 gypsum covers the top of the mounds (Raddadi, 2021).

226 ***4.2 Spring mound dimensions in the Nefzaoua region***

227 The size (diameter and height) of a spring mound depends on the morphology of the basement
228 of the spring. A flat area will create a large pond whose edge can be colonised by vegetation.
229 The artesian pressure will determine the flow and the height of the mound. Chemical
230 properties of the spring water influence both the precipitation of certain salts (carbonates and
231 sulphates), which elevates the mound, and the growth of the vegetation, which traps aeolian
232 sand depending on the intensity and direction of the wind.

233 The size of 88 (70%) of the 126 mounds could be measured (Raddadi and Podwojewski,
234 2022). The mean size and variability in sizes of the mounds in the Nefzaoua region are much
235 larger than those in the Great Artesian Basin (180 m in diameter and 6 m in height) (Clarke,
236 2007) or the Dakhla oasis in Egypt (< 15 m in diameter and 7.9 m in height) (Torab and al.,
237 2021). In the Nefzaoua region, the diameter ranged from 250-2 430 m and the height ranged
238 from 2-28 m.

239 The mounds had a mean slope of $2.9\% \pm 1.23\%$, which is gentle (Table 3). However, in these
240 flat areas near the Chott el Jerid, the mounds clearly emerge from the landscape. The largest
241 mounds were urbanised (657 ± 192 m radius, 19 ± 6 m in height) (Figure 6). The smallest
242 mounds were naturally levelled (274 ± 127 m radius) while the shortest mounds and those
243 with the lowest slope were anthropically levelled (8 ± 4 m in height and $2.3\% \pm 1.15\%$,
244 respectively).

245 ***4.3 Spring mounds, indigenous settlements and degradation processes***

246 Spring mounds are particularly abundant in the Great Artesian Basin in Australia (Ponder,
247 1986; Clark and al., 2007). Even though indigenous activity is well documented around these

248 springs, the poor water quality, nomadic activities of indigenous people and cultural
249 importance of these springs were always underestimated (Harris, 2020). Overuse of artesian
250 springs decreased the pressure of aquifers, which led to the loss of artesian springs at the
251 beginning of the 20th century. However, in the past 10 years, under the Great Artesian
252 Sustainability Initiative and other related bore-capping programs, considerable progress has
253 been made in restoring aquifer pressure (Powell and al., 2015, Brake et al., 2019).

254 In the hyper arid Libyan Desert in Egypt, the oases of Kargha and Dakhla were associated
255 with spring mounds and human settlements during the Pleistocene (Idris, 1996; Adelsberger
256 and Smith, 2010; Crepy and Callot, 2016). Archaeological studies in these areas showed that
257 the degradation and rapid demise of springs were due mainly to aridification of the climate
258 during the Holocene (Bravard and al., 2016; Torab, 2021) and current excessive pumping
259 from fossil aquifers, which is the result of modern irrigation schemes (Powell and Fensham,
260 2015).

261 Nefzaoua has likely been occupied since the Neolithic (Moreau, 1947; Monaco et al,
262 2000). Many Roman vestiges, such as in the equipped urbanised mound of Ain el Relig (TRT
263 14), north and east of Kebili, confirm the use and equipment of the springs (i.e. *ayoun*) since
264 Antiquity, with basins and vestiges of surface channels (i.e. *sâgya*) (Idoux, 1902; Moreau,
265 1947; Troussset, 1986). The oldest mounds are likely those that were naturally levelled, which
266 are concentrated in a line from Douz to Kebili. Many fragments of stone points, ceramics,
267 ostrich shells and blocks of Roman walls have been found in top of these mounds (Raddadi,
268 2021). The local population also built tunnels (i.e. *khargias*, similar to *foggaras*) through
269 these mounds to drain the water directly from the spring inside to the oasis plantations at the
270 foot of each mound (Figure S1A).

271 Currently, the irrigation systems of all spring mounds are being degraded rapidly, in three
272 ways. First, the artesian springs have not been active for 30 years due to excessive pumping

273 and siltation or natural levelling affected 14.3% and 22.2% of the mounds, respectively
274 (36.5% of the total). Second, the salinisation of cultivated soils due to uncontrolled irrigation
275 without adequate drainage is frequently documented in this area (e.g. [Zammouri and al., 2007](#),
276 [Marlet and al., 2009](#); [Kraiem et al., 2014](#); [Haj-Amor and al., 2017](#)). Third, because sediment
277 at the bottom of mounds has a low salt content ([Raddadi, 2021](#)), mounds have been and
278 continue to be excavated by heavy machinery: 11.1% have been completely levelled, and
279 31.0% are being destroyed (Figure S1B). Spring mounds are used as sediment “mines” to
280 expand newly cultivated areas over former unproductive areas. Counting dismantled mounds
281 and those with other anthropic degradation (i.e. levelled, urbanised or equipped), over half
282 have been deeply and permanently degraded by human activity. The mounds, which were the
283 historical basis of Nefzaoua oasis culture, have largely disappeared. Only 14 (11.1%) of the
284 126 mounds were relatively well preserved. These erosion and destruction processes have not
285 been previously observed or documented.

286 ***4.4 Potential for conservation***

287 In the Nefzaoua region, controlling pumping (legal or illegal) and protecting ancient
288 springs, as in Australia ([Brake and al., 2019](#)), is unlikely ([Brochier-Puig, 2004](#)). The spring
289 mounds in the Nefzaoua region are a model of complex geomorphologic processes that are
290 exceptional in their density. They testify to many centuries of technological skill and
291 collective management of water and irrigation infrastructure for sustainable agriculture
292 production in highly arid conditions.

293 According to [Panizza \(2001\)](#), the spring mounds in the Nefzaoua region can be considered
294 geomorphosites. A geomorphological resource is a geomorphosite that society can use. The
295 attributes that may confer value are scenic, socio-economic, cultural and scientific ([Reynard
296 and Panizza, 2005](#)). When possible, the time scales of a geomorphosite should be
297 distinguished: the deep past of geology, the Quaternary Period, the distant past of prehistory

298 and postglacial environments, the near past of history and recent history, and the present time
299 of active geotopes, during which the dynamic interaction of internal or external geodynamics,
300 including anthropogenic factors, has an influence (Giusti and Calvet, 2010).

301 To be protected as geomorphological heritage, the mounds cannot belong only to the
302 scientific community. The concept of this geomorphosite would be linked to “*emphasis on*
303 *community involvement for sustainability*”, one of the four concepts in the recent synthesis of
304 Németh et al. (2021). Therefore, this heritage could be preserved successfully if the local
305 population could own it and become its guardians. Unfortunately, the local population
306 perceives the mounds as a mining resource for short-term unsustainable agricultural activity.
307 According to Reynard (2009) and Reynard et al., (2015), after a complete inventory of the
308 different sites, about ten spring mounds could be selected as potential geomorphosites to be
309 protected (Raddadi et al., 2022), with suggestions for protecting them and preventing their
310 complete destruction.

311 **5. Conclusion**

312 Of the 399 spring mounds identified in 1933 in the Nefzaoua region, only 126 could be
313 identified there in 2020. Only 14 were considered not to be degraded. The irreversible
314 decrease in the level of the water table caused by intense pumping of groundwater and
315 irrigation of palm tree plantations has dried up all of the artesian springs, which are now only
316 geomorphological relics. Associated with this, the establishment of villages on top of the
317 mounds, construction of water collectors in ponds, irrigation channels and tunnels at the foot
318 of the mounds testify to ancient maintenance and water management, which comprise the
319 cultural heritage.

320 As 42% of the mounds have been or are being excavated, for example to provide a soil
321 amendment to expand new date palm plantations, they are at risk of complete destruction. The

322 spring mounds in the Nefzaoua region in Tunisia can be considered as geomorphosites, with
323 geomorphological, scientific, cultural and societal value, and some of them could be protected
324 according to the required criteria. However, no protection can be sustained without the
325 acceptance and participation of the local population.

326 **Acknowledgements**

327 This project was supported by the French laboratory Archéorient Environnements et sociétés
328 de l'Orient ancien, UMR 5133. We are very grateful to the Pr. Yann Callot for the initiation
329 and advices for this work, to the Institute of Arid Region of Medenine in south Tunisia for
330 facilities and field access and in memory of his director Houcine Khatteli. We thank also the
331 anonymous reviewers.

332

333 **Conflict of Interest**

334 The authors declare no conflict of interest.

335 **References**

- 336 Adelsberger, K. A., and Smith, J. R., 2010. Paleolandscape and paleoenvironmental
337 interpretation of spring-deposited sediments in Dakhleh Oasis, Western Desert of
338 Egypt. *Catena*, 83(1), 7-22. doi:10.1016/j.catena.2010.06.009
- 339 Bédoucha-Albergoni, G., 1976. Système hydraulique et société dans une oasis tunisienne.
340 *Études rurales*, no. 62, 1976. pp. 39-72. doi: <https://doi.org/10.3406/rural.1976.2155>
- 341 Brake, L., Harris, C., Jensen, A., Keppel, M., Lewis, M. and Lewis S., 2019. Great Artesian
342 Basin Springs: a Plan for the Future. Evidence-based methodologies for managing risks to
343 spring values. Prepared for the Australian Government Department of Agriculture, South
344 Australian Department for Environment and Water, Queensland Department of Natural
345 Resources, Mines and Energy, New South Wales Department of Planning, Industry and

346 Environment, and the Northern Territory Department of Environment and Natural
347 Resources.
348 [https://www.researchgate.net/publication/340826030_Great_Artesian_Basin_Springs_a_Plan_for_t](https://www.researchgate.net/publication/340826030_Great_Artesian_Basin_Springs_a_Plan_for_the_Future_Evidence-based_Methodologies_for_Managing_Risks_to_Spring_Values)
349 [he_Future_Evidence-based_Methodologies_for_Managing_Risks_to_Spring_Values](https://www.researchgate.net/publication/340826030_Great_Artesian_Basin_Springs_a_Plan_for_the_Future_Evidence-based_Methodologies_for_Managing_Risks_to_Spring_Values)

350 Brochier-Puig J., 2004. Société locale et Etat face aux limites de la ressource eau (Nefzaoua,
351 sud-ouest tunisien). In: Picouet, M., Sghaier, M., Genin, D., Abaab, A., Guillaume, H., and
352 Elloumi, M. (Eds.). Environnement et sociétés rurales en mutation: approches alternatives.
353 Paris: IRD, Latitudes 23, 307-321.

354 Bravard, J. P., Mostafa, A., Garcier, R., Tallet, G., Ballet, P., Chevalier Y. and Tronchère H.,
355 2016. Rise and fall of an Egyptian oasis: Artesian flow, irrigation soils, and historical
356 agricultural development in El deir, Kharga Depression, western desert of Egypt.
357 *Geoarchaeology*, 31(6), 467-486. doi 10.1002/gea.21566

358 Brookes, I. A., 1993. Geomorphology and Quaternary geology of the Dakhla Oasis region,
359 Egypt. *Quaternary Science Reviews*, 12(7), 529-552.

360 Clarke, J., Bourke, M., Nelson, P., Manga, M. and Fonseca, J., 2007. The Dalhousie Mound
361 Spring Complex as a guide to Martian landforms, processes, and exploration. In *Mars*
362 *Society Australia Clifton Hill, Proceedings of the 7th Australian Mars Exploration*
363 *Conference. Australia*, 14.

364 Crépy, M., and Callot, Y., 2016. Les dépôts de sédiments fins dans le sud de la dépression de
365 Kharga (désert libyque, Égypte): indices d'une morphogenèse éolienne et anthropique.
366 *Géomorphologie: relief, processus, environnement*, 22(3).
367 <https://journals.openedition.org/geomorphologie/11499>

368 FAO and ITPS., 2015. Status of the World's Soil Resources (SWSR) – Main Report. Rome.

369 Giusti, C. and Calvet, M., 2010. The inventory of French geomorphosites and the problem of
370 nested scales and landscape complexity, *Géomorphologie: relief, processus,*

371 environnement, 16(2), 223-244. <http://journals.openedition.org/geomorphologie/7947>; doi:
372 <https://doi.org/10.4000/geomorphologie.7947>

373 Gonçalves, J., Petersen, J., Deschamps, P., Hamelin, B., and Baba Sy, O., 2013. Quantifying
374 the modern recharge of the “fossil” Sahara aquifers. *Geophysical Research Letters*, 40(11),
375 2673-2678. doi:10.1002/grl.50478

376 Hadj Ammar, F., Chkir N., Zouari, K., Hamelin B., Deschamps, P. and Aigoun, A., 2014.
377 Hydro-geochemical processes in the Complexe Terminal aquifer of southern Tunisia: An
378 integrated investigation based on geochemical and multivariate statistical methods. *Journal*
379 *of African Earth Sciences*, 100, 81-95. <http://dx.doi.org/10.1016/j.jafrearsci.2014.06.015>

380 Haj-Amor, Z., Tóth, T., Ibrahimi, M. K., and Bouri, S., 2017. Effects of excessive irrigation
381 of date palm on soil salinization, shallow groundwater properties, and water use in a
382 Saharan oasis. *Environmental Earth Sciences*, 76(17), 1-13. doi: 10.1007/s12665-017-
383 6935-8

384 Harris, C., 1981. Oases in the desert: the spring of northern south Australia. *Proceedings of*
385 *the Royal Geographical Society Australasia (SA Branch)*, 81, 26–39.

386 Harris, C., 2020. Five decades of watching mound springs in South Australia. *Proceedings of*
387 *the Royal Society of Queensland, The*, 126, 213-224.
388 <https://search.informit.org/doi/abs/10.3316/informit.626738639867267>

389 Idris, H., 1996. Springs in Egypt. *Environmental geology*, 27(2), 99-104.

390 IPBES, 2018. The IPBES assessment report on land degradation and restoration.
391 Montanarella, L., Scholes, R., and Brainich, A. (eds.). Secretariat of the Intergovernmental
392 Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 744 p.
393 <https://doi.org/10.5281/zenodo.3237392>

394 Idoux, M., 1902. Notes sur le Nefzaoua (Tunisie méridionale). *Annales de Géographie*, t. 11,
395 no. 60, 439-447; doi: <https://doi.org/10.3406/geo.1902.18193>

396 King, C., and Thomas, D. S., 2014. Monitoring environmental change and degradation in the
397 irrigated oases of the Northern Sahara. *Journal of Arid Environments*, 103, 36-45.
398 <http://dx.doi.org/10.1016/j.jaridenv.2013.12.009>

399 Khatelli, H., and Gabriels, D., 2000. Effect of wind direction on aeolian sand transport in
400 southern Tunisia. *International Agrophysics*, 14(3), 291-296.

401 Kraiem, Z., Zouari, K., Chkir, N., and Agoune, A., 2014. Geochemical characteristics of arid
402 shallow aquifers in Chott Djerid, south-western Tunisia. *Journal of Hydro-environment*
403 *research*, 8(4), 460-473. <http://dx.doi.org/10.1016/j.jher.2013.06.002>

404 Lasram, M., 1990. Les systèmes agricoles oasiens dans le Sud de la Tunisie. *Revue options*
405 *méditerranéennes*, CIHEAM, 21-27. <https://om.ciheam.org/om/pdf/a11/CI901480.pdf>

406 Marlet, S., Bouksila, F., and Bahri, A., 2009. Water and salt balance at irrigation scheme
407 scale: A comprehensive approach for salinity assessment in a Saharan oasis. *Agricultural*
408 *Water Management*, 96(9), 1311-1322. doi: <https://doi.org/10.1016/j.agwat.2009.04.016>.

409 Monaco, A., Belhouchet, L., Brahim, H. B. H., Fraj, T. B., Nasr, J. B., Boussoffara, R.,
410 Cancellieri, E., Jnen, M., Lucci, E., Rotunno, R., di Lernia, S., 2020. Megalithic Structures
411 of the northern Sahara (Chott el Jérid, Tunisia). *Cartagine. Studi e Ricerche*, 5. doi:
412 [10.13125/caster/4078](https://doi.org/10.13125/caster/4078)

413 Moreau, P., 1947. Des lacs de sel aux chaos de sable. Le pays des Nefzaouas. Institut des
414 Belles Lettres Arabes, Tunis, impr. Bascone et Muscat, 206 p.

415 Németh, B., Németh, K., Procter, J. N., and Farrelly, T., 2021. Geoheritage Conservation:
416 Systematic Mapping Study for Conceptual Synthesis. *Geoheritage*, 13(2), 1-21.
417 <https://doi.org/10.1007/s12371-021-00561-z>

418 OSS, 2003. Hydrogéologie, volume II. Observatoire du Sahara et du Sahel, 130p. Tunis.
419 [http://www.oss-online.org/sites/default/files/publications/OSS-SASSHYDROGEOLOGIE-](http://www.oss-online.org/sites/default/files/publications/OSS-SASSHYDROGEOLOGIE-II.pdf)
420 [II.pdf](http://www.oss-online.org/sites/default/files/publications/OSS-SASSHYDROGEOLOGIE-II.pdf)

421 Panizza, M., 2001. Geomorphosites: concepts, methods and examples of geomorphological
422 survey. Chinese science bulletin, 46(1), 4-5. <https://doi.org/10.1007/BF03187227>

423 Ponder W. F., 1986. Mound springs of the great artesian basin. In *Limnology in Australia* (pp.
424 403-420). Springer, Dordrecht.

425 Powell O., Silcock J., and Fensham R., 2015. Oases to oblivion: The rapid demise of springs
426 in the south-eastern Great Artesian Basin, Australia. *Groundwater*, 53(1), 171-178.
427 <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.834.3475&rep=rep1&type=pdf>
428 df

429 Powell O. and Fensham R., 2016. The history and fate of the Nubian Sandstone Aquifer
430 springs in the oasis depressions of the Western Desert, Egypt. *Hydrogeology Journal*,
431 24(2), 395-406. Doi: 10.1007/s10040-015-1335-1

432 Raddadi A., 2021. Les paysages du Nefzaoua, une interaction entre l'eau, le vent et les
433 hommes. Ph.D. thesis, Université Lumière Lyon 2, Ecole doctorale des sciences sociales,
434 UFR Temps et territoires, Département de géographie. Lyon.
435 <https://drive.google.com/file/d/1rtMsMtqAVW7NWYIBXgwRtDd9jSssIy-3/view>

436 Raddadi A., Callot, Y., Podwojewski P., 2021. Un patrimoine en péril : les tertres du
437 Nefzaoua dans le sud tunisien. In: Reynard, E. et Bussard J. (Eds.) *Géopatrimoines et*
438 *territoires*. Geo-Regards, 14, 95-118. DOI : 10.33055/Geo Regards.2021.014.01

439 Raddadi, A., Podwojewski, P., 2022, Location and morphological status of spring mounds in
440 the Nefzaoua Province in western Tunisia in 2020., <https://doi.org/10.23708/U9GR0C>,
441 DataSuds, V1.

442 Reynard, E., 2009. The assessment of geomorphosites. In: Reynard E., Coratza P. et Regolini-
443 Bissig G. (Eds.), «Geomorphosites». Pfeil München, 63-71.

444 Reynard, E. and Panizza, M., 2005. Geomorphosites: definition, assessment and mapping,
445 *Géomorphologie: relief, processus, environnement*, 11, 3, 177-180.

446 <https://doi.org/10.4000/geomorphologie.337>

447 Reynard, E., Perret, A., Bussard, J., Grangier, L., and Martin, S., 2015. Integrated approach
448 for the inventory and management of geomorphological heritage at the regional scale.
449 *Geoheritage*, 8(1), 43-60.

450 Roberts, C. R., and Mitchell, C. W., 1987. Spring mounds in southern Tunisia. Geological
451 Society, London, Special Publications, 35(1), 321-334.

452 Sghaier, M., 1999. Les Oasis de la Région de Nefzaoua. Interaction between Migration, Land
453 and Water Management and Resource Exploitation in the Oases of the Maghreb,
454 IMAROM, Working paper series, no. 3. Univ. of Amsterdam, The Netherlands. 37 p.

455 Swezey, C. S., 1996. Structural controls on Quaternary depocentres within the Chotts Trough
456 region of southern Tunisia. *Journal of African Earth Sciences*, 22(3), 335-347.

457 Torab, M., 2021. Geomorphology of Fossil Spring Mounds near El Gedida Village, Dakhla
458 Oasis, Western Desert of Egypt. *Egyptian Journal of Environment Change*, 13(1), 23-32.
459 doi : 10.21608/ejec.2021.149015

460 Tissot, C.J., 1884. Exploration scientifique de la Tunisie: Géographie comparée de la
461 province romaine d’Afrique. Impr. nationale, 697 p.

462 Troussset, P., 1986. Les oasis présahariennes dans l’Antiquité: partage de l’eau et division du
463 temps. *Antiquités Africaines*, 22(1), 163-193.
464 doi: <https://doi.org/10.3406/antaf.1986.1130>.

465 UNCCD, 1994. About the convention to combat desertification. United Nation convention to
466 combat desertification. <https://www.unccd.int/convention/about-convention>.

467 Watts, S.H., 1973. Mound springs, *Australian geographer*, 13, 52-53.

468 Zammouri, M., Siegfried, T., El-Fahem, T., Kriâa, S., and Kinzelbach, W., 2007. Salinization
469 of groundwater in the Nefzawa oases region, Tunisia: results of a regional-scale
470 hydrogeologic approach. *Hydrogeology Journal*, 15(7), 1357-1375.

471 doi: <https://doi.org/10.1007/s10040-007-0185-x>.

472 **Captions – No colour printing**

473 Figure 1: Satellite image of a set of spring mounds without vegetation around the city of
474 Blidet (West of Douz) on the south East of the Chott el Jerid showing the radiating
475 structure of the palm tree plantations at the foothill of the mounds. The typology of the
476 mounds is described in Table S2.

477 Figure 2A: Location of the Nefzaoua region in Tunisia, isohyet lines, and the limit of the pre
478 Saharian Tunisia; 2B: the cities of Kebili and Douz, and the four geomorphological units.

479 Figure 3A: Location of springs and spring mounds on the 1933 topographic map of Nefzaoua
480 province. 3B: Location of the 7 types of the 126 spring mounds in the Nefzaoua region.
481 Mounds TRT 118 (naturally levelled) and TRT 119 (silted), located south-west of the city
482 of Sabria, lie outside of the map. For levelled mounds, “N” denotes “naturally” and “A”
483 denotes “anthropically”.

484 Figure 4 Example of the determination of the size of two spring mounds. 4A: Satellite image
485 of the West-East section that crosses spring mounds TRT 77 ($33^{\circ}32'38\text{ N}$, $8^{\circ}58'33\text{ E}$) and 78
486 ($33^{\circ}33'25\text{ N}$ $8^{\circ}59'28\text{ E}$). 4B: Satellites TanDEM-X image of the lateral extension of the two
487 mounds, which appear in light colour; 4C: digital elevation model of the two mounds
488 calculated by TanDEM-X satellites.

489 Figure 5: The seven types of spring mounds and their evolution over time. The North is facing
490 down to emphasize the contrast of the shadow effect.

491 Figure 6; Relation between the height and radius of the spring mounds identified. The solid
492 oval indicates the largest mounds (urbanised and equipped), and the dotted oval indicates
493 the smallest mounds (naturally levelled). For levelled mounds, “N” denotes “naturally” and
494 “A” denotes “anthropically”.

495

496 Table 1. The seven types of spring mounds identified in 2020.


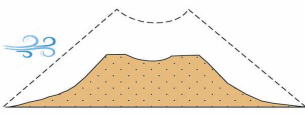


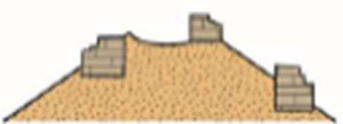
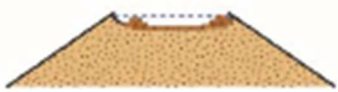
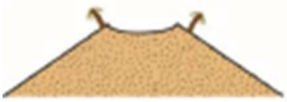
Name	Type	Morphology	Description
Silted	S		Stage 1: Covered by recent aeolian deposits of different shapes (e.g. aeolian veil, <i>nebka</i>); Stage2: Completely silted; the original morphology of the summit is no longer visible.
Levelled, naturally or anthropically	N		Naturally levelled surface; the crater is silted, and the remaining palm stipes are down.
	A		The entire top has been stripped and levelled by humans.
Dismantled	D		Partly or completely excavated by mechanical shovels.
Urbanised	U		Modified by urban interference: a village was built on top of the mound, which contains the ruins of buildings
Equipped	E		Equipped with a pool to collect the water of the artesian spring.
Preserved	P		Little degradation, and its original morphology is maintained, with little peripheral damage or excavation. Intact and visible water basin in the centre.

Table 2. Number and percentages of dominant and secondary types of spring mound. See Table 1 for definitions of the types.

		Secondary type (number)							
Dominant type	Number	None	Silted	N levelled	A levelled	Dismantled	Urbanised	Equipped	Preserved
Silted	18	12	-	0	2	3	1	0	0
N levelled	26	14	10	-	0	0	1	0	1
A levelled	16	11	0.5	1	-	3	0.5	0	0
Dismantled	39	28	2	1	0	-	8	0	0
Urbanised	9	5	0	0	1	4	-	0	0
Equipped	4	0	0	0	0	0	4	-	0
Preserved	14	11	2	0	0	0	1	0	-
TOTAL	126	80	18	1	3	8	16	0	1

		Secondary type (percentage of total)							
Dominant type	Percentage	None	Silted	N levelled	A levelled	Dismantled	Urbanised	Equipped	Preserved
Silted	14.3	9.5	-	0.0	1.6	2.4	0.8	0.0	0.0
N levelled	22.2	11.1	7.9	-	0.0	0.0	0.8	0.0	0.8
A levelled	11.1	8.7	0.4	0.8	-	2.4	0.4	0.0	0.0
Dismantled	31.0	22.2	1.6	0.8	0.0	-	6.3	0.0	0.0
Urbanised	7.1	4.0	0.0	0.0	0.8	3.2	-	0.0	0.0
Equipped	3.2	0.0	0.0	0.0	0.0	0.0	3.2	-	0.0
Preserved	11.1	8.7	1.6	0.0	0.0	0.0	0.8	0.0	-
TOTAL %	100.0	63.5	14.3	0.8	2.4	6.3	12.7	0.0	0.8

- 1 Table 3. Mean and standard deviation (SD) of the radius and slope of the seven types of
- 2 spring mounds. See Table 1 for definitions of the types.

Type	Number	Measured (n)	% Measured	Radius (m)	SD	Height (m)	SD	Slope (%)	SD
Silted	18	13	72	584	276	14	5	2.77	1.34
N levelled	26	14	54	274	127	10	4	3.93	1.51
A levelled	16	14	88	364	145	8	4	2.31	1.15
Dismantled	39	30	77	411	186	11	4	2.95	0.95
Urbanised	9	5	56	657	192	19	6	2.95	1.15
Equipped	4	2	50	-	-			-	-
Preserved	14	12	86	457	275	11	6	2.65	0.91
TOTAL	126	88		364	233			2.91	1.23

3