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ScienceDirect
C. R. Geoscience 340 (2008) 38–48
Comptes Rendus Geoscience
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Surface Geosciences (Hydrology–Hydrogeology)

Efficiency of contour benches, filling-in and silting-up of a hillside reservoir in a semi-arid climate in Tunisia

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Received 22 June 2007; accepted after revision 27 September 2007
Available online 26 November 2007

Presented by Ghislain de Marily

Abstract

The El Gouazine catchment area (18.1 km^2), located in semi-arid central Tunisia (average annual rainfall 350 mm), was equipped with total retention contour benches on 43% of its surface area between June 1996 and July 1997. In order to analyze the efficiency of these benches on the catchment area, different thematic maps (slope, lithology, land use, hydrographic network) were crossed using GIS with a map that located the benches and their breaks. Specific topographical surveys were also carried out on a series of 14 benches' in order to characterize the development of their holding capacities. To evaluate the impact of the contour bench installation on the catchment area, the change of liquid and solid inflow was measured at the catchment area outlet two years before and eight years after the bench installation. On-site surveys showed that contour bench dysfunction in the El Gouazine catchment area could not have been caused by man. However, three main physical causes could explain the dysfunction: placement of benches on gypsum clay soils, location of breaks on the hydrographic network, and slope greater than 25%. Topographic surveys showed that the benches initial holding capacity varied between 1 and 3 m^3 per linear metre for a construction standard fixed at 2.28 m^3. These surveys also showed that, nine years after their construction, the benches had lost 10 to 50% of their initial holding capacity. After installing benches in the El Gouazine catchment area, solid inflow was only reduced by 30%, whereas liquid inflow was reduced seven to eight times during a four-year period, which greatly limited the possibility of downstream irrigation. Annual runoff coefficients, at 4.5% before bench installation, were again at 5.1% in 2002–2003, and the silting-up rate was evaluated, in June 2005, as identical to its value before installation. Bench breakage and silting up of upstream canals explain these changes. The results of this study should serve to improve contour bench installation plans of catchment areas in semi-arid climates by both increasing bench efficiency and, at the same time, conserving sufficient water flow to hillside reservoirs. ***To cite this article: N. Baccari et al., C. R. Geoscience 340 (2007).***
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Résumé

Efficience des banquettes de courbe de niveau, remplissage et envasement d'un réservoir collinaire sous climat semi-aride en Tunisie. Le bassin versant d'El Gouazine (18,1 km^2), localisé en Tunisie centrale semi-aride (350 mm de pluie annuelle en moyenne) a été aménagé en banquettes à rétention totale sur 43 % de sa superficie entre juin 1996 et juillet 1997. Pour analyser

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doi:10.1016/j.crte.2007.09.020

l'efficience de ces banquettes sur le bassin versant, différentes cartes thématiques (pente, lithologie, occupation des sols, réseau hydrographique ont été croisées, en utilisant un système GIS avec une carte qui indique la localisation des banquettes et de leur rupture. Des contrôles topographiques spécifiques ont également été effectués sur une série de 14 banquettes, pour caractériser le développement de leur capacité de rétention. Pour évaluer l'impact de l'installation de telles banquettes sur le bassin versant, le changement d'apport liquide et solide a été mesuré au débouché du bassin d'alimentation, deux ans avant et huit ans après l'installation des banquettes. Des contrôles sur le site montrent que le dysfonctionnement des banquettes dans le bassin d'alimentation d'El Gouazine ne peut avoir été provoqué par l'homme. Cependant, trois principales causes physiques pourraient expliquer le dysfonctionnement constaté : l'installation des banquettes sur des sols argileux et gypseux, la localisation des ruptures sur le réseau hydrographique et une pente supérieure à 25 %. Les mesures topographiques montrent que la capacité initiale de rétention des banquettes varie entre 1 et 3 m^2 par mètre linéaire pour une construction standard à 2,28 m^3 ; elles montrent également que, neuf ans après leur construction, les banquettes ont perdu 10 à 50 % de leur capacité de rétention initiale. Après l'installation des banquettes dans le bassin d'alimentation d'El Gouazine, l'apport solide était seulement réduit de 30 %, tandis que l'apport liquide l'était de sept à huit fois pendant une période de quatre ans, ce qui limite beaucoup les possibilités d'irrigation aval. Les coefficients de ruissellement annuel, de 4,5 % avant l'installation des banquettes, étaient à nouveau de 5,1 % en 2002–2003, et le taux d'ensablement était identique, en juin 2005, à ce qu'il était avant l'installation des banquettes. La rupture des banquettes et l'ensablement des canaux amont expliquent ces changements. Les résultats de cette étude pourraient servir à améliorer les plans d'installation de banquettes de courbes de niveau dans les bassins d'alimentation en climat semi-aride, à la fois en augmentant l'efficience des banquettes et en maintenant un débit d'eau suffisant aux réservoirs collinaires. ***Pour citer cet article : N. Baccari et al., C. R. Geoscience 340 (2007).***

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Keywords: Soil conservation; Contour bench breakage; Gypsum soils; Semi-arid climate; Tunisia

Mots clés : Conservation des sols ; Rupture des banquettes de courbe de niveau ; Sols gypseux ; Climat semi-aride ; Tunisie

1. Introduction

For the last three decades, approximately one million hectares of agricultural land have been installed with machine-made anti-erosive contour benches in the semi-arid climate zone of Tunisia [6]. These installations help prevent water erosion of the land and promote runoff water retention and infiltration in the catchment area. However, the durability of these installations and their impact on reducing water and sediment inflow in a dam or hillside reservoir downstream are still not well known [2,11].

However, already in 1973, Hudson [9] described the dangers for soil protection caused by lack of maintenance of machine-made installations. In Algeria, Heusch [7] showed that, from 1947 to 1968, contour benches had no influence on the sedimentation rate in the Oued Fodda dam. Likewise, in Tunisia, Bannour [4] noted that contour benches did not stop gullying and that gullied areas increased 12% between 1963 and 1973 in the Oued el Foul catchment area.

After surveys in the Maghreb (Morocco, Algeria and Tunisia), Heusch [8] noted that the objectives of the contour bench installations were met on silty soils during brief heavy summer storms. In Algeria, Tamaghoult [18] came to the same conclusion in studying soil permeability on contour bench networks surrounding the Hamiz dam near Algiers. This also confirmed Kerriou's observations [10] on landslides caused by contour bench networks in the Oued Arbatach catchment area (Boumerdes country, Algeria). According to Arabi and Asla [1], the factors explaining these slides are the nature of clay rocks, prone to sliding, and livestock movement along them. In a similar circumstance, Boudjadi [5] reported that contour benches on the Djebala perimeter (Tlemcen, Algeria) were notched at the bottom, this deterioration being most often caused by underground soils (marl and clay) and by the risk of water overflow accumulated in certain parts of the bench.

In Oran, Taabni and Kouti [17] noted that benches that were not kept up became a factor for increased erosion, since the slightest break that was not repaired led to a chain-like reaction from bench to bench during prolonged torrential rainfall. Moreover, Roose et al. [12,13] found that Algerian small farmers object to contour benches on their lands and refuse to see to their upkeep, believing that the benches hinder free movement and waste useable agricultural land, which is not compensated enough by the increase in crop output.

On the marl catchment areas of pre-Rif (Morocco), Sabir and Boudhar [14] carried out a survey on eight olive tree and vineyard plantations equipped with benches since 1950. They found that two of the plantations disappeared and that the six remaining ones had a 50% rate of success. Gullies formed and landslides occurred on the marl catchment areas with a slope greater than 25%. Lack of maintenance was responsible for the failure.

In northern Thailand, Sang-Arun et al. [15] studied the impact of the plant cover and of the structure of graded terraces on erosion. They showed that rivulets and gullies rarely formed on terraces well covered by natural plants or by crop remnants. However, on bare soil, rivulets turned into gullies from the upstream to the downstream terraces. On the high volcanic lands of Java, Van Dijk and Brujnzeel [19] studied the erosion process on hillside catchment areas cultivated with terraces and showed that erosion on the terraced catchment areas was due, on the one hand, to a temporary lack of plants on the terrace talus and, on the other hand, to the poor sizing of runoff evacuation drains.

Research done on machine-made anti-erosive installations in many countries around the world thus proves that the efficiency of these benches depends not only on local physical conditions such as lithology and slope or on the density of vegetation protecting the soil from heavy rainfall and runoff, but also on the construction and maintenance of the benches with participation from the local population. In the light of these works, this article proposes to analyze the causes of bench breakage in a small catchment area in a semi-arid area in Tunisia and to evaluate the impact of benches on water flow and silting up of the hillside reservoir at the catchment area outlet.

2. Study site and methods

2.1. Study site

The El Gouazine catchment area (18.1 km^2) is located in semi-arid central Tunisia (Fig. 1) with an average annual rainfall of 350 mm. It is 12 km east of

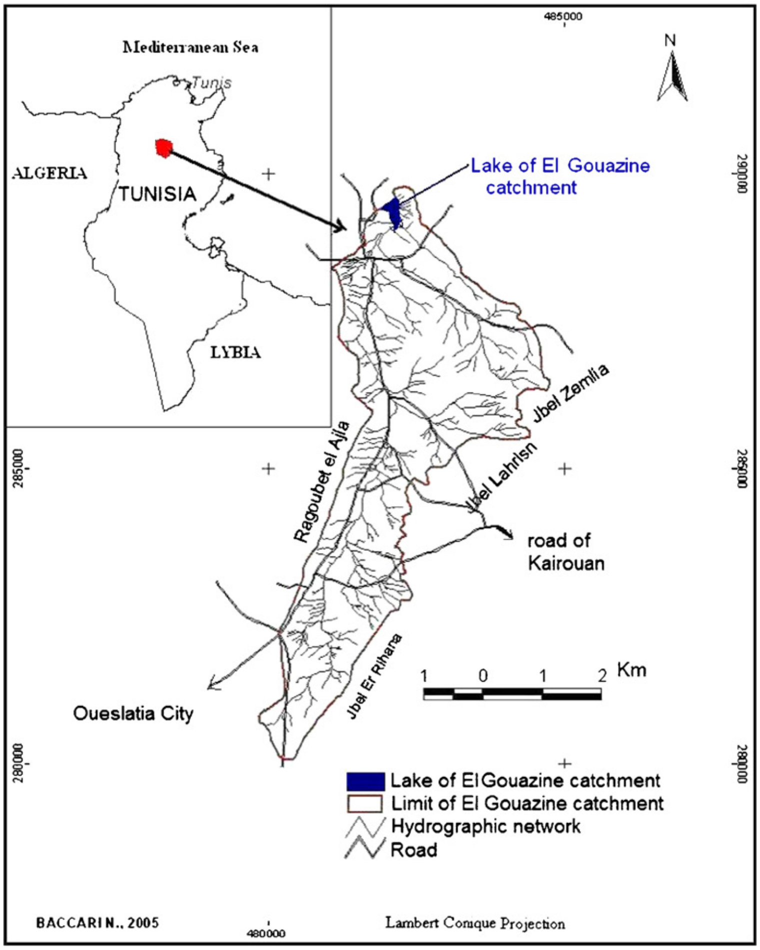

Fig. 1. Map of the El Gouazine catchment area location.

Fig. 1. Carte de localisation du bassin versant d'El Gouazine.

Oueslatia, between Mount Es-Serj to the northwest and Mount Er-Rihana to the southwest. The catchment area altitude ranges between 575 m at the southern end and 375 m to the north at its outlet. Its longitudinal slope is 1.8%. From a topographical point of view, 28% of the surface area has a low slope, less than 5%, and 60% has a slope from 5 to 35%. It should be noted that 5 and 35% represent the minimum and maximum limits for an anti-erosive bench installation according to the standards set by Bahri et al. [3].

Approximately 35% of the catchment area surface is covered by an Aleppo pine forest, 24% by scrubland, and the remainder (41%) by cereal crops. Between June 1996 and July 1997, the catchment area was installed with total retention contour benches on its cultivated part, approximately 43% of its surface area (Fig. 2).

At the catchment area outlet, a hillside reservoir was constructed in 1993. Since then, hydrological records of rainfall and water inflow have been taken on a regular basis. At the same time, lake sedimentation has been monitored, with periodical bathymetrical measurements between 1993 and 2005. This series of hydrological and bathymetrical measurements shows the impact of the benches on the catchment area in terms of runoff reduction and silting up of the reservoir.

2.2. Description of the contour benches

The contour benches installed in the El Gouazine catchment area are levees constructed parallel to contour lines (Fig. 3). Each bench part is done perpendicular to the slope of the land with trapezoidal

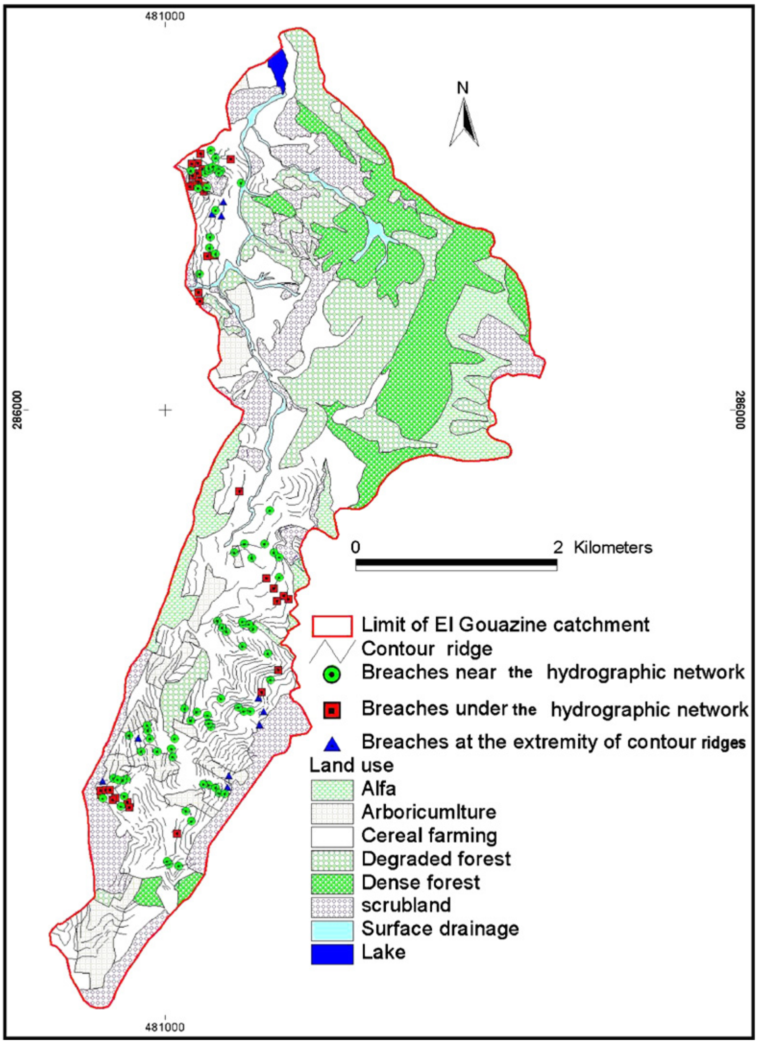

Fig. 2. Land use map of the El Gouazine catchment area.

Fig. 2. Carte d'occupation du sol du bassin versant d'El Gouazine.

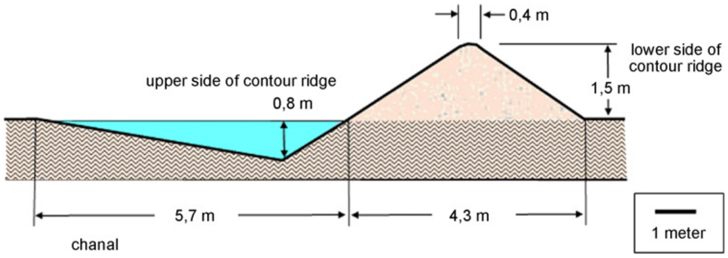

Fig. 3. Cross section of a contour bench.

Fig. 3. Section transversale d'une banquette.

ballast and a flared ditch forming a canal upstream. The objective of the benches is to intercept runoff water and prevent its concentration [8]. These installations, when they are designed for total retention, as those at El Gouazine, are generally sized for holding daily runoff for a period of 10 years [3], and bench ends are lower than the embankment average height, so that discharge is generally on one of the bench ends. For passing vehicles, access ways were planned and benches close up each side of the path (Fig. 4). Livestock are not a cause of bench breakage because they are only present on the crops temporarily during the dry season. Ploughing contributes little by little to reduce the base of the benches, but, given the size of the machine-made benches, it would take several dozen years for ploughing to have a significant effect on the benches transversal profile. The El Gouazine benches are naturally grass-covered, which provides the talus with some protection against erosion. The benches, constructed in the El Gouazine catchment area in 1996–1997, could be subjected, however, either to a partial or total filling-in of their holding canals by sediments coming from their impluviums or to breaks in their talus (Fig. 6), testifying to a hydrological dysfunction that reduces

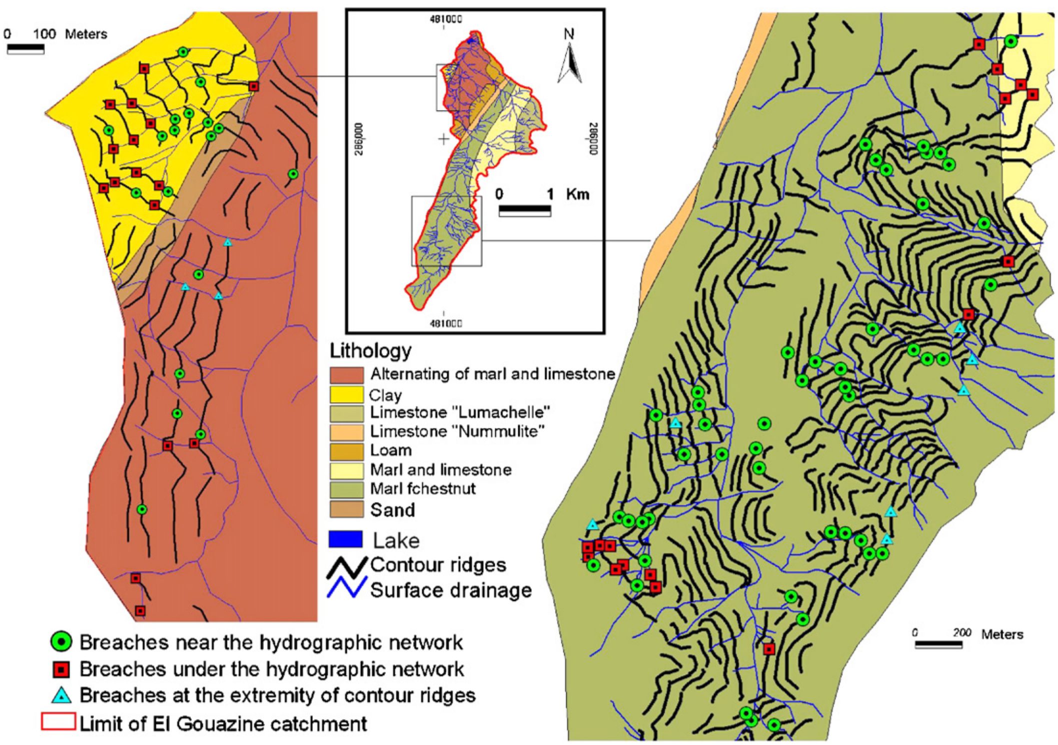

Fig. 4. Lithological map of the El Gouazine catchment area.

Fig. 4. Carte lithologique du bassin versant d'El Gouazine.

the anti-erosive role of these installations and increases the risk of overflow and gulling.

2.3. Methods

On-site surveys not having revealed any obvious impact of human activities on bench deterioration in the El Gouazine catchment area, four physical efficiency indicators were selected to analyze the causes of bench dysfunction:

- lithology;
- slope of the land;
- hydrographic network layout;
- holding capacity of the benches.

Two indicators were also chosen to evaluate the long-term impact of the benches on the catchment area: annual liquid and solid inflow at the outlet.

Eight high-resolution (2 m) aerial images were used to create a three-dimensional orthoimage introducing for each image the Lambert standard conic projection system and six fulcrums per aerial image. The visual interpretation of the orthoimages was used to draw up maps of land use, the hydrographic network, and bench alignment. Bench element ends and talus breaks were located using on-site surveys with a GPS with a planimetric precision of 5 m. The break location map will be used by crossing it with other thematic maps using the GIS Arcview software to analyze dysfunction causes.

The interpretation of the geological map, lithological levees and aerial photographs were combined and used to develop the lithological map of the catchment area. By superimposing the bench-installation dysfunction map with the lithological map, four values could be determined for each lithological formation: the number of bench elements, their length, the number of breaks, and the number of breaks per kilometre of benches.

Contour lines were digitalized from the topographical map of Djbel Es-Serj at 1:50,000 in order to analyze the causes of bench breakage compared with slope. Then, the break location map was crossed with the slope map to ascertain again for each slope class the same four values: the number of bench elements, their length, the number of breaks, and the number of breaks per kilometre of benches.

Crossing the bench-installation dysfunction map with that of the hydrographic network made the role of the hydrographic network in bank breakage clearer. On average, a break was considered near the hydrographic network when the distance between the two was not greater than 5 m, or two pixels on the orthoimage.

The initial holding capacity of the benches was defined by the Tunisian administration for water and soil conservation according to FAO standards [3] to hold runoff water on the bench impluvium for a decade. However, these standards are not always respected on site and, since their construction, the upstream canal of each bench regularly receives sediment from its impluvium by the runoff water. The bench holding capacity will therefore be reduced over time due to sedimentation in upstream canals. To study this phenomenon, very precise topographical levelling was done using a laser theodolite on a series of 14 benches located on the same marl catchment. In order to estimate the current capacities of the upstream canals of the benches, levelling was done on transversal sections 2.5 m apart, each section being levelled at 1 m. The initial capacity of the canal was calculated by determining the volume of sediment deposited in the upstream canal using the difference between excavated sediment volume and current canal volumes. The excavated volumes were determined by considering that the mass of the backfill that was used to construct the bench is the same as that of the excavated material taken upstream from the bench. The densities of the excavated material and backfill being different, 1.4 to 1.5 and 1.1, respectively, this difference was taken into account when determining the initial volume of the canal from the volume of the embankment for each one of its sections. Adding the sediment volume obtained to the current holding capacity of the canal gives the initial holding capacity.

Finally, analysis of the change in liquid and solid inflow to the El Gouazine hillside reservoir from 1994 to 2005, two years before bench construction work began and eight years after its completion, will help to evaluate the impact of the benches on water inflow and on silting-up of the hillside reservoir, because the evolution of the impact will have been followed over a long period. This data is taken from hydrological records published since 1995 by the DCES, the DGACTA, and the IRD. The calculations resulting from the hydrological assessment of the El Gouazine reservoir can be said to have a precision of between 5 and 10%.

3. Results and discussions

On-site work carried out in July 2005 on the El Gouazine catchment area identified 109 breaches on 90 benches out of a total of 439 constructed contour

Table 1
Contour bench and breakage statistics according to the lithological formation
Tableau 1
Statistiques des banquettes et des brèches par formation lithologique

Lithology	Number of benches	Bench length in kilometres	Number of breaks	Number of breaks per kilometre
Gypsum clay	16	2.590	22	8.5
Marl limestone	40	6.480	11	1.7
Marl	359	58.200	64	1.1
Limestone and sand	24	3.890	12	3.1
Total	439	71.160	109	1.5

benches there: an average breakage percentage of 21%, on average 1.5 breaks per kilometre of bench, the average length of each bench element being 162 m.

Crossing the bench dysfunction map with the lithological map gave the results presented in Table 1.

Analysis of Table 1 shows that the gypsum clay formation presents the greatest risk of bench breakage: 2.7 times higher than on limestone and sand formations, 5.7 times higher than marl-limestone, and 7.7 times higher than on marl. The gypsum clay therefore seems to pose the most serious problems in bench stability. It also appears that limestone and sand formations at the top of the catchment area have a breakage risk twice that of the average risk.

Crossing the bench dysfunction map with that of slope gave the results presented in Table 2.

Analysis of this table shows that the very high slope class presents the greatest risk of contour bench breakage. This risk is in fact 2.4 times higher than the average risk of bench breakage on the entire El Gouazine catchment area. This observation confirms the standard established by the FAO, which discourages contour bench construction on very high slopes.

Crossing the bench dysfunction map with that of the hydrographic network showed that 33% of the breaches are located on former waterways, 47% are near the network (less than 5 m), and 20% are on the bench ends (Fig. 4). In El Gouazine, 80% of the observed breaches are thus associated with the layout of the hydrographic network.

The results of the measurements of current and initial holding capacities of the 14 benches of the small marl catchment area located downstream and on the left bank of El Gouazine are presented in Table 3.

Table 3 shows that the initial average holding capacity of the 14 benches is 2.0 m^3 per linear metre, but that it varies between 1 and 3 m^3/m, whereas the standard set by the Tunisian administration for water and soil conservation is 2.28 m^3/m. Moreover, Table 3 shows that sedimentation rates in the upstream canals are low, between 0.09 and 0.03 m^3/m yr. It can thus be concluded that, after nine years in operation, these benches lost between 10 and 50% of their holding capacities, with an average loss of 28%. Filling-in of the upstream canals with sediments coming from impluviums is a factor that increases the risk of bench breakage as they get older.

Table 4 presents the results from the calculations of the water hydrologic balance from the El Gouazine reservoir per hydrological year from September 1994 to August 2005.

A close examination of this table shows that, in low-rainfall years (300 mm), runoff from the catchment area is seven to eight times less than after bench construc-

Table 2
Contour bench and breakage statistics according to the slope class
Tableau 2
Statistiques des banquettes et des brèches par classe de pente

Slope class (%)	Number of benches	Length of benches in kilometres	Number of breaks	Number of breaks per kilometre
Very low <5	307	49.770	70	1.4
Low 5–10	29	4.700	10	2.1
Medium 10–15	58	9.400	10	1.1
High 15–25	38	6.160	15	2.4
Very high >25	07	1.130	4	3.5
Total	439	71.160	109	1.5

Table 3
Contour bench holding capacities and sedimentation rates of a small marl catchment area

Tableau 3
Capacités de stockage des banquettes et taux de sédimentation sur un petit sous-bassin versant marneux

Order number	Backfill length (m)	Current capacity in 2006 (m^3/m)	Initial capacity in 1997 (m^3/m)	Sedimentation rate (m^3/m yr)	Loss of holding capacity after nine years (%)
1	106	1.96	2.51	0.06	24
2	162	1.64	2.12	0.05	25
3	127	0.79	1.16	0.04	35
4	83	0.78	1.03	0.03	27
5	116	1.75	2.27	0.06	25
6	116	0.82	1.15	0.04	32
7	113	2.19	2.96	0.09	29
8	146	1.39	1.71	0.04	21
9	124	1.10	1.53	0.05	31
10	152	1.88	2.36	0.05	23
11	113	1.90	2.38	0.05	22
12	186	2.77	3.06	0.03	11
13	132	1.53	2.07	0.06	29
14	303	0.92	1.70	0.09	51
Total and averages	1979	1.53	2.0	0.05	28

tion. It also shows that rises in the water level of the same volume are obtained for storms 30 mm before construction (1994–1995) and 80 mm (1998–1999) or 54 mm (2002–2003) after construction, since the maximum runoff coefficient was two to three times lower after construction. However, four years later, for almost identical annual rainfall, an increase can be noted in the annual runoff coefficient from 0.8% (1996–1997) to 1.6% (2000–2001) and from 2.7% (1998–1999) to 5.1% (2002–2003) and 6.5% (2004–2005).

Fig. 5 represents the relationship between the average annual rainfall in the El Gouazine catchment area and the runoff swell at the outlet. It shows that bench installation on only 43% of the surface area led to a change in annual retention capacity of the catchment area from 100 mm to 240 mm for a period of five years following bench construction. However, bench installation does not seem to modify the increase coefficient of the annual runoff swell compared to annual rainfall; this coefficient remained steady at 0.06. The difference between the two annual retention values of the catchment area corresponds to a volume of 2,534,000 m^3, this amount being retained by benches constructed on only 43% of the total surface area. This volume is 10 times the holding capacity of the reservoir (237,000 m^3 at normal level). Five years after bench

Table 4
Water inflow through runoff before and after contour bench construction in the El Gouazine catchment area

Tableau 4
Apports d'eau par ruissellement avant et après aménagement en banquettes du bassin versant d'El Gouazine

	Annual runoff				Maximum runoff			
Year	Annual rainfall	Volume	Swell	Coefficient	Maximum rainfall	Volume	Swell	Coefficient
	mm	thousand m^3	mm	%	mm	thousand m^3	mm	%
94–95	299	236	13	4.37	30	129	7.12	23.7
95–96	576	478	26	4.59	27	150	8.29	30.7
96–97	245	35.4	2	0.80	51	30.6	1.69	3.3
97–98	339	75.8	4	1.23	25	22.2	1.23	4.9
98–99	408	200	11	2.71	80	128	7.07	8.8
99–00	304	11.7	1	0.21	56	6.4	0.35	0.6
00–01	262	77.1	4	1.63	64	21.1	1.17	1.8
01–02	222	62.9	3	1.57	33	29.8	1.65	5.0
02–03	421	389	21	5.11	54	137	7.60	14.1
03–04	407	31.2	1.7	0.42	40.7	23.6	1.31	3.2
04–05	456	532	29.4	6.45	108.4	352	19	18

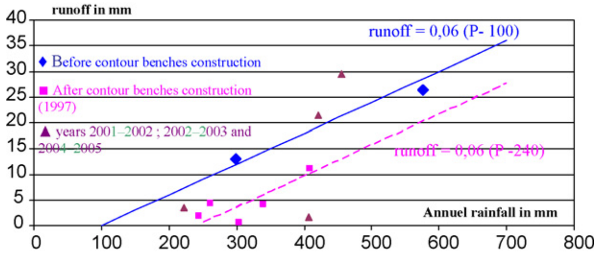

Fig. 5. Relationship between annual runoff swell and rainfall in the El Gouazine catchment area.

Fig. 5. Relations entre la lame ruisselée annuelle sur le bassin versant d'El Gouazine et la pluie annuelle.

installation, a change in the hydrological behaviour of the catchment area can be observed by an increase in runoff swells for the same annual rainfall. However, the year 2003–2004 is an exception to this tendency due to mild winter storms, whereas the rise in the water level in semi-arid climates is usually caused by heavy autumn storms.

Concerning solid inflow, the specific rate of silting-up of the lake according to Nasri et al. [11] decreased from 1.55 in 1996 to 1.1 m^3/ha yr in 1998. Nevertheless, since October 2000, water and sediment inflows to the lake have again increased, mainly due to bench breaks. The runoff coefficients reached 33% in 2003 and the silting-up rate was evaluated in June 2005 at 1.46 m^3/ha yr for the period 2002–2005.

4. Recommendations

First of all, taking into account the results obtained by the analysis of contour bench efficiency on different lithological formations in the El Gouazine catchment area, it is useless to think of constructing benches on gypsum clay formations, since the probability of breakage is extremely high, 7.7 times higher than on marl. On gypsum clay, breakage is the consequence of a strong tendency in clay soil to runoff and to dissolving the gypsum contained in the soil used to construct the benches, which leads to the formation of tunnels called piping. Moreover, on this type of formation, bench breakage creates gullies [16]. In order to avoid the overdeepening of these gullies (Fig. 6), benches on this geological formation should be taken out and replaced by grassy strips alternating with crops or by direct plantation.

Secondly, the risk of bench breakage clearly seems to be associated with benches crossing the hydrographic network (80% of the breaks). In order to limit this type of risk, it is possible to close the benches on both sides with small thalwegs or to make outlets out of dry rock, which would allow excess water to run off without causing a risk of breakage. These projects could be carried out during bench maintenance four or five years after their construction, realizing that the probability of bench breakage due to crossing the hydrographic network is only 20%, even though 80% of the breaks are situated on the network or less than 5 m from it.

Knowing that the risk of bench breakage is considerably greater on very high slopes (more than 25%), it would be preferable to replace the bench installations on very high slopes with reforestation or to forbid access to grazing animals to avoid overgrazing.

Concerning the holding capacity, it is essential to adapt the size of the impluviums to the holding capacity

Fig. 6. Example of a breach on a contour bench at the El Gouazine catchment area.

Fig. 6. Exemple d'une brèche sur une banquette dans le bassin versant d'El Gouazine.

Fig. 7. A cascade of contour benches on a marly slope in the El Gouazine catchment area.

Fig. 7. Une cascade des banquettes sur un versant marneux du bassin versant d'El Gouazine.

of the benches by taking into account, on the one hand, the runoff capacity of the impluviums and, on the other hand, the soil susceptibility to erosion. Given no breakage, soil erosion in fact influences the life span of the works by a gradual filling-in of the upstream canals of each bench. For those benches located upstream, extra special care must be taken for impluvium size or for treatment against erosion and runoff, since rupture of these upstream benches can lead to a series of breaks (Fig. 7) on the benches located downstream of them.

In addition, if the catchment area includes not only anti-erosive installations, but also construction of hillside reservoirs, it is important to evaluate the impact of the anti-erosive installations on the water flow to the hillside reservoir. Benches on only 43% of the El Gouazine surface area reduced annual runoff from the catchment area seven or eight times for a period of four years, thus limiting the use of irrigation water by farmers with irrigated crops downstream of the reservoir. It is therefore sometimes necessary to limit the extent of anti-erosive installations in a catchment area in order to protect surface water resources downstream.

5. Conclusion

In the El Gouazine catchment area, eight years after their construction, the average risk of bench breakage was evaluated at 21%, or 1.5 breaks per kilometre of bench. By examining the location of the breaks compared to the hydrographic network, to different lithological formations, and to slope classes, it was possible to show that there exist three main causes of bench dysfunction. In order of importance, we find: presence of gypsum clay (8.5 breaks per kilometre of bench), hydrographic network (80% of breaks on or near the network), and very high slopes, greater than 25% (3.5 breaks per kilometre of bench). Compared to the average risk of bench breakage in the area, the risk is thus 2.4 times higher on a very high slope and five times higher on gypsum clay.

The analysis of bench efficiency compared to the holding capacity of their upstream canals was carried out on a series of 14 benches on marl. Whereas the standard set by the Tunisian administration of water and soil conservation is 2.28 m^3/m, the topographical levees showed that the initial average holding capacity of the 14 benches was 2.0 m^3/m, but that this varied between 1 and 3 m^3/m. The topographical levees also showed that, nine years after their construction, the benches had lost 10 to 50% of their holding capacity. Although it was not possible to extend this analysis to a greater sampling of benches, two important pieces of information can be deduced: a high uncertainty about the actual initial holding capacity of the benches and a reduction in holding capacity compared to erosion of upstream impluviums of each bench.

Evaluating the impact of bench installations in El Gouazine shows that the benches result in an increased retention capacity of the catchment area to a water height of 140 mm, that is to say a volume of 2,534,000 m^3, equal to 10 times the holding capacity of the hillside reservoir. Five years after bench construction, examination of annual runoff shows a gradual return to the situation prevalent before installation. This return to previous runoff conditions is in part due to bench breakage and partly to the loss of holding capacity because of sedimentation in the upstream bench canals.

The results of this study should be used to improve bench installation plans for catchment areas in semi-arid climates and eventually to maintain existing installations with the objective of improving contour bench efficiency while conserving sufficient water inflow to hillside reservoirs and protecting them against silting up.

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