

CHEMICAL EROSION OF A GULLY HEAD: RAINFALL SIMULATION EXPERIMENT ON A GYPSIC MEDITERRANEAN SOIL (FIDH ALI WATERSHED, CENTRAL TUNISIA).

Grünberger O.*, Reyes Gomez V.** , Montoroi J.P*, Dridi B.*** & Agrebaoui

* IRD (Institut de recherche pour le développement), Centre de recherches d'Ile-de-France, 32 rue Henri Varagnat, 93143 Bondy, France.

** Instituto de Ecologia de Mexico, AP 632, 34100 DGO, Durango, Mexico.

ABSTRACT

The backward erosion of gypsic soils in the Fidh Ali watershed causes important problems for downstream reservoirs. The upper parts of the gullies are associated with the piping process. Two long rainfall simulation experiments (more than 5 hours) were applied to characterize internal hydrodynamic features and solute transport. Minidisk infiltrometer measurements and adjustment of the infiltration curve demonstrated that soil without piping has an impermeable layer at about 35 cm while the closeness of the piping phenomena implies that a drainage flux of 10 mm h⁻¹ appears at about 60 cm above surface level. The temporal and spatial evolutions of the runoff and drainage fluxes show a contrasting behavior for the 2 plots. Apparently, piping takes rarely place, only after various successive runoff events. As the chloride content of the reservoir and the runoff water is similar, the contribution of the drainage water, in contact with the saline soil layers, is less than a few per cent. In turn, the comparison of reservoir and runoff water in terms of sulfate leads to a relative contribution, from 24 to 30%, of the superficial drainage water in contact with the upper soil layers.

KEYWORDS

Rainfall simulation, salinity, solute transport, leaching, piping, gypsic soils, Tunisia

INTRODUCTION

The construction of one thousand small reservoirs is planned by the state authorities of Tunisia with the central aim of providing appropriate water supply for habitation, breeding and small irrigation in mountainous semi arid zones. Other expected effects are enhancement of aquifer recharge, retaining of erosion products and better flood regulation.

Beside hydrologic problems, such as excessive water loss by infiltration, a relative failure of the water management is sometimes occurring when the solute content of the stored water exceeds useful range and when the erosion deposits tend to quickly fill up the reservoir (Albergel and Rejeb, 1997). This is the case for Fidh Ali reservoir in which an erosion is occurring. The gully network is mainly formed by gypsum dissolution and piping process occurring in gypsic soils. Therefore, reservoir water salinity reaches a value often too high for irrigation use (Rahaingomanana, 1998).

As the piping process is clearly a consequence of gypsum dissolution, the objective of the present work is to determine the relationships between the hydrodynamic soil behavior and the chemical content of the soil solution, these mechanisms contributing to the water quality and the replenishing of a downstream reservoir.

MATERIAL AND METHODS

The 412.5 ha Fidh Ali watershed (34°42'40''N, 9°36'13''E) is located on Eocene sedimentary material. The deposits are formed by a succession of gypsic clayey and calcareous layers. Soil survey at 1/20 000 scale was carried out by Collinet and Zante (1999). Experimental site is located in Unit 5 defined by these authors as immature calcimagnesian soils containing quartz, gypsum, calcite and 2:1 clay mineral representing about a 22% weight rate. Erosion is intense and the volume of erosion products, deposited in the reservoir during the last 8 years, as of 1999 was 37% of the reservoir initial volume. Gullies are well developed in the upper part of the watershed where they reach 6 meters in depth (Collinet and Zante, 1999). The head of the gully is often an overhanging erosion front. Marks of chemical dissolution appears in the gully wall as the outlets of

cavities, pipes and fissures and the collapsed cavities produce small depressions in the soil surface, These phenomena are common in gypsum deposit (Gutiérrez and Santolalla, 1998).

A DeltaLab® mini rainfall simulator was used on two 1 m² plots. Both the plots were nearby an eroded gully head in the upper part of the watershed. One of the plots (plot 1) was situated in the talweg where gypsum dissolution and piping process were clearly observed (Fig. 1). The other plot (plot 2) was located laterally in a place where there was no indications of piping process. The two plots were equipped with horizontal PVC drainage pipes at 3 distinctive depths according to soil layer configuration.

Before rainfall simulation, soil profile was described and sampled. Soil water content was measured by gravity method and diluted soil solution (1:5) was extracted.

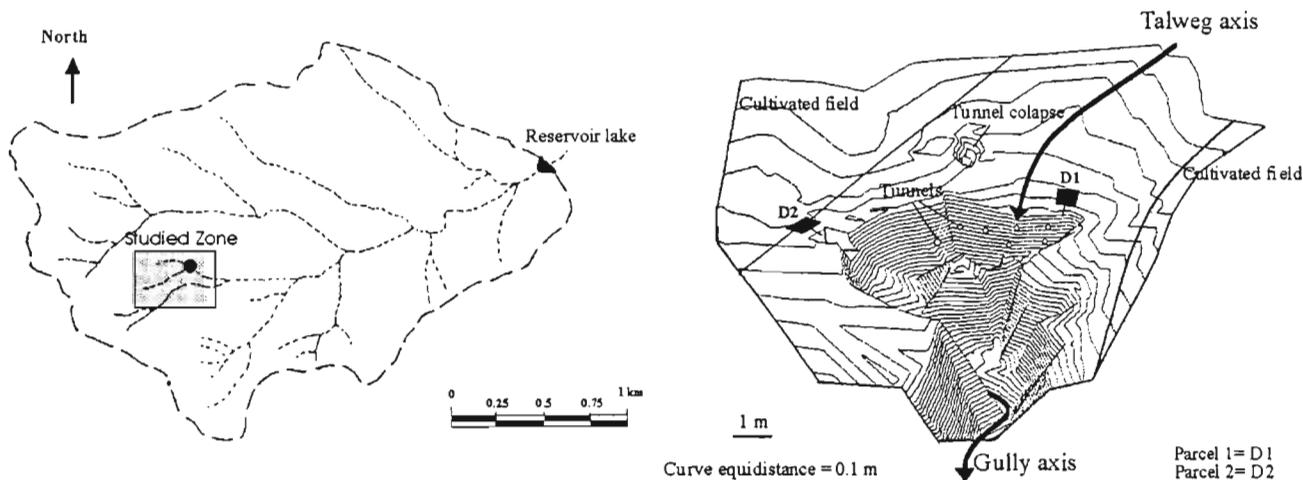


Fig. 1 : Location of the studied zone in Fidh Ali watershed (left) and the experimental plots (D1 = plot 1 and D2 = plot 2) above the erosion front (right).

Rainfall experiments were performed to simultaneously obtain soil solution from the surface plot outlet (runoff flow) and, from most of the artificial drainage pipes, to monitor the temporal evolution of the water quality and the chemical content. The applied intensity was 31 mm h⁻¹ at the beginning of the experiment and was exhausted at 42.6 mm h⁻¹ after 1 h for the plot 1 because of the insufficient volume of runoff water. The rainfall simulation was delimited to the annual rainfall range of the ten driest years observed at the nearest meteorological station (231 mm). The applied rainfall water was chosen to have the lowest solute content, the electrical conductivity (EC) equal to 0.349 dS m⁻¹.

During the rainfall simulation, three TDR moisture probes were monitored at distinctive levels to follow the soil water front. Although for plot 1, the temporal moisture monitoring was completed, in the case of plot 2, when water front reached the probes, an error signal due to a highly soil salinity was delivered preventing the measurement. All the sampled solutions of the runoff and the drainage water were immediately filtered at 45 μm. Electrical conductivity (EC), pH, alkalinity were measured in field. Major elements (SO₄²⁻, Cl⁻, Ca²⁺, Mg²⁺) were firstly determined using a Hatch® DR/2010 portable spectrophotometer and secondarily confirmed at IRD laboratory using a Dionex® HPLC and an atomic spectrometer for Na⁺, K⁺. Mineral saturation indexes were computed using the WateqF calculation program (Truesdell, 1974)

After the rainfall simulation, 62 measurements (37 for plot 1, 25 for plot 2) of the soil sorptivity were carried out at each soil layer using a minidisk infiltrometer and the Zang method (1997) for calculating hydraulic conductivity. The soil salinity using the diluted soil solution extraction (1:5 ratio), the water content using the gravity method and the bulk density using the cylinder method were also measured.

RESULTS

Hydrodynamic behavior

Rainfall amounts were nearly the same in the two simulation experiments (Table 1). Although a similar runoff rate was observed and the initial water content was higher for plot 2, the infiltration, drainage and "escaping" water rates were twice as high for plot 1. The infiltration evolution during the experiments (Fig. 2 and Fig. 3) confirm that plot 1 has a hydrodynamic behavior strongly different from plot 2. After 4 h rainfall, infiltration rate was about 15 mm h^{-1} for plot 1 and 0.3 mm h^{-1} for plot 2. Artificial drainage started at 2 h 54 mn for plot 2 and at 3 h 10 mn for plot 1. For plot 1, the drainage flow was twice as high and a 60 cm soil layer was saturated when the artificial drainage pipes started flowing. At this time, cumulative infiltration was 50.3 mm for plot 2 (close to 57 mm soil water content in Table 1) and 84 mm for plot 1 (close to 87.1 mm soil water content in Table 1). Thus, gravity drainage was the only flow appearing in cavities, natural pipes and fissures, formed by piping process, and starting with the water saturation of the superficial layers.

TABLE 1: External and internal water balance for piping affected plot (plot 1) and non-piping affected plot (plot 2) during rainfall simulation

SIMULATION TIME	Volume (mm or l m^{-2})		Mean intensity (mm h^{-1})	
	Plot 1	Plot 2	Plot 1	Plot 2
5 h 27 mn (plot 1) 8 h 13 mn (plot 2)				
EXTERNAL WATER BALANCE				
Simulated rainfall (P)	231.9	252.3	42.6	30.7
Runoff (R)	107.2	169.3	19.7	20.0
Infiltration ($I = P - R$)	124.6	83.0	22.8	10.7
INTERNAL WATER BALANCE				
Initial water content [0-72cm] (S_0)	173.2	276.8		
Final water content [0-72cm] (S_f)	260.3	333.5		
Water content variation [0-72cm] ($\Delta S = S_f - S_0$)	87.1	57.0	16.0	6.9
Drainage water [0-72cm] (D_t)	2.2	1.5	0.4	0.2
Water loss (infiltration flux below 72 cm level and lateral flux) ($I - \Delta S - D_t$)	35.3	24.5	6.5	3.0

Soil hydraulic conductivity decreased with depth in both the plots (Fig. 4). The main difference between the plots was found at the 25 cm layer which the mode class is $14\text{-}16 \text{ mm h}^{-1}$ for plot 1 and $0\text{-}4 \text{ mm h}^{-1}$ for plot 2. For the 50 cm deep layer of plot 1, the $16\text{-}20 \text{ mm.h}^{-1}$ class was still valid, while for plot 2 the only valid class was $0\text{-}4 \text{ mm h}^{-1}$. The infiltrometer measurements carried out layer by layer are in accordance with the infiltration curves obtained by rainfall simulation for the assumption that hydraulic conductivity is independent of water content.

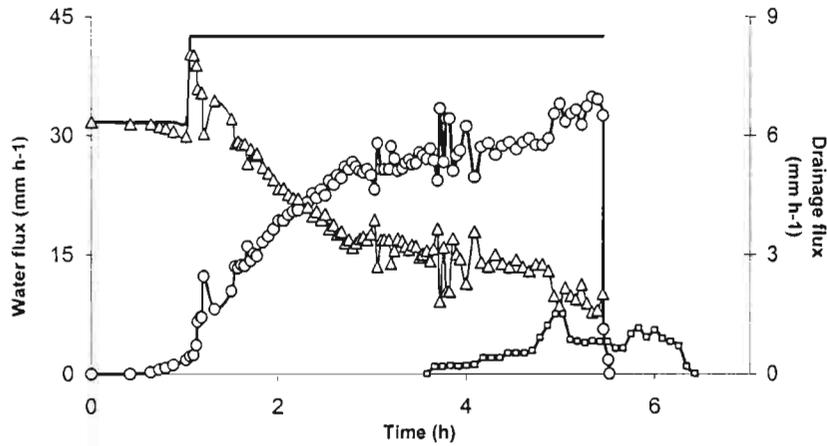


Fig. 2 : Surface water and drainage fluxes in plot 1 during rainfall simulation: open triangle for infiltration rate ; open circle for runoff rate, full line for rainfall rate; open square for drainage rate.

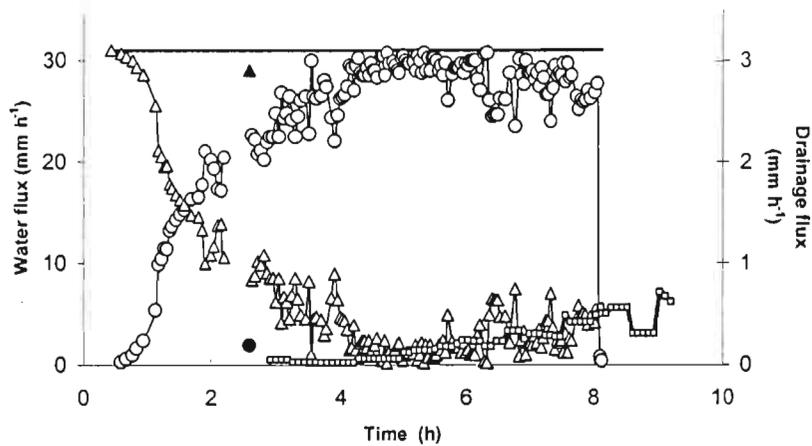


Fig. 3 : Surface water and drainage fluxes in plot 2 during rainfall simulation: open triangle for infiltration rate ; open circle for runoff rate, full line for rainfall rate; open square for drainage rate; full triangle for simulator disfunctioning.

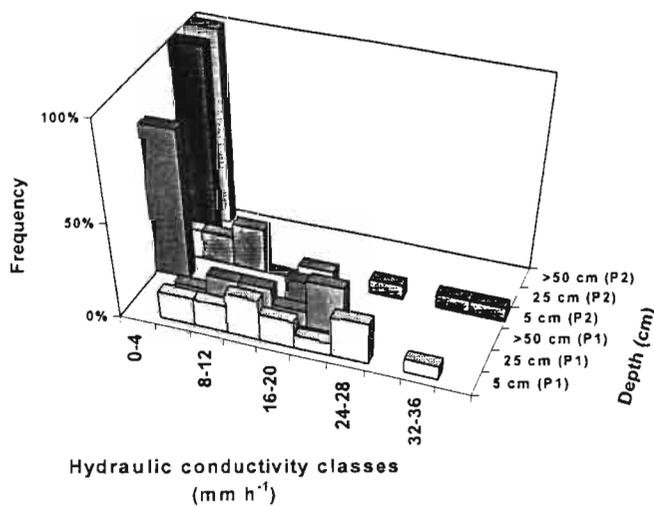


Fig. 4 : Hydraulic conductivity measurements in piping affected (plot 1) and non-piping affected (plot 2) plots

Chemical behavior of solutions

For the runoff solution, the evolution of the electrical conductivity (EC) versus time (Fig. 5) shows a characteristic pattern already observed in saline soils of Mexico (Reyes, 1998). Initial value decreases and tends to be stabilized in relation with hydrologic behavior. After 2 h runoff, a weak linear downward trend is discerned for the 2 plots, even if, for plot 2, runoff evolution seems to stabilize. When rainfall stops, the last EC value is increasing. Observed EC values are higher for plot 2 ($> 600 \mu\text{S cm}^{-1}$) than for plot 1 ($< 500 \mu\text{S cm}^{-1}$). The solute content of the runoff water leads to a thermodynamic saturation with respect to calcite and dolomite minerals and is in accordance with the CO_2 partial pressure of a natural soil, $\log(p\text{CO}_2)$ ranging from -2.69 to -2.45.

For the drainage solution, EC is about 10 times higher than EC in the runoff solution. EC evolution (Fig.5) do not show the same pattern for the two plots, even if mean solution salinity relies in the two cases on the depth of the artificial drainage pipe. For plot 1, EC values are weakly decreasing with time, this effect being more accentuated for the deepest solution. For plot 2, the EC curve versus time evolution is bell-shaped, the initial and final stages corresponding to the highest values. The drainage solution at 20 cm depth is oversaturated with respect to gypsum for both the plots. Sulfate content is increasing with depth while calcium and magnesium contents are identical, CO_2 partial pressure being stable. Sodium and chloride contents are increasing with depth for the two plots (Table 2).

TABLE 2 : Chemical content and volume of reservoir, rainfall, runoff and drainage waters

Water type	pH	CE	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	Volume
Reservoir water										
28/09/94 ¹	-	-	0.7	21.2	5.1	11.2	3.0	18.7	0.7	14400
18/10/94 ¹	-	3.10	0.8	17.2	1.1	10.5	2.1	10.5	0.5	82400
04/04/95 ¹	-	4.06	1.9	23.4	2.3	12.5	6.0	17.5	0.5	68200
15/05/98 ²	9.73	5.51	0.9	43.0	4.4	22.7	4.4	44.7	0.7	6000
Experimental rainfall water										
Rainfall water (stored in cement tank)	7.82	0.34	3.0	2.2	0.5	3.2	0.3	0.7	0.3	0.232 0.252
Plot 1 (mean values)										
Runoff water	7.71	0.48	3.2	4.5	0.9	5.2	0.8	0.8	0.3	0.107
Drainage water (20 cm)	7.76	3.28	2.8	45.5	1.0	33.3	8.5	11.0	0.3	
Drainage water (51 cm)	7.62	6.71	2.8	56.6	11.3	29.0	6.8	55.3	0.4	0.035
Plot 2 (mean values)										
Runoff water	7.87	0.71	3.2	8.6	0.9	8.9	1.3	0.8	0.3	0.169
Drainage water (20 cm)	7.57	8.44	3.2	54.8	35.6	32.0	12.2	59.7	0.4	
Drainage water (35 cm)	7.53	12.77	2.8	65.0	68.6	34.3	8.9	114.8	0.4	0.024

¹ after Rahaingomanana (1998) ; ² after Montoroi et al. (2000); - for no measurement

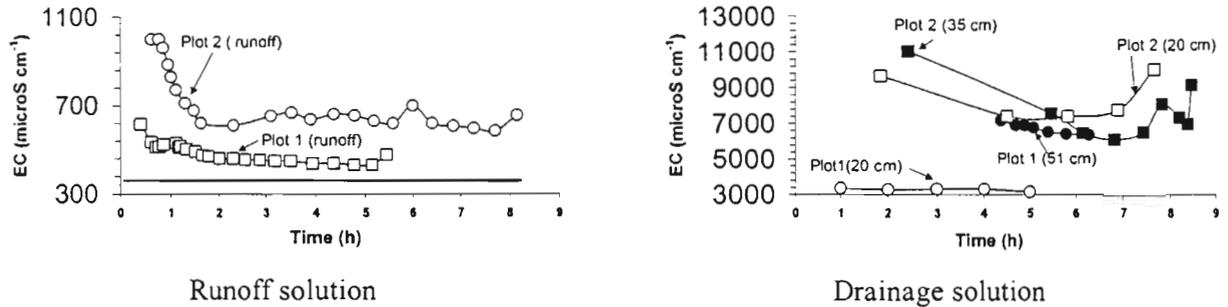


Fig 5 : Evolution of electrical conductivity (EC) versus time for runoff and drainage solutions during rainfall simulation.

Comparison with reservoir water

The chemical quality of the reservoir water is influenced by the evaporation. The 18/10/94 date corresponds to the fullest reservoir stage which is assumed to be the more representative stage for the water quality generally reached by reservoir water before an evaporation period. We consider that the chloride content of the reservoir water (1.1 mmol L^{-1}) is the result of a perfect chemical mixing between direct runoff water, with a chloride content of 0.9 mmol L^{-1} , and hypodermic drainage water. For plot 1, the chloride content of the drainage water is 11.3 mmol L^{-1} and the contribution of this hypodermic flux to the mixing reservoir water is evaluated at 1.8% by computing. Applying the same procedure for plot 2 with a 20 cm deep drainage water containing 35.6 mmol L^{-1} of chloride, the proportion reaches 0.6%.

The sulfate content of the reservoir water being 17.2 mmol L^{-1} can be interpreted as the mixing of direct runoff water with a 4.5 mmol L^{-1} sulfate content and hypodermic (20 cm) drainage water with a 45.5 mmol L^{-1} for plot 1. This leads to a 30% contribution of hypodermic flux whereas, for plot 2, the contribution is about 24% with a 20 cm deep drainage water containing 54.8 mmol L^{-1} of chloride.

CONCLUSION

The existence of a piping net with pipes, cavities, funnels and fissures implies the presence of free water at a depth of more than 60 cm. In the two rainfall plots, this condition could be reached when the cumulative infiltration amount was larger than 60 mm depending on the initial stage of the soil moisture in the superficial layers. Apparently, piping process takes place at few occasions and after various successive runoff events. In presence of piping phenomena, soil infiltration capacity is enhanced not only for the intermediate layer [20-40 cm] but also for deeper layers. In non-affected soil, the infiltration capacity of the deeper layer is negligible, whereas the likely flux to underground piping cavities is 10 mm h^{-1} (if the collapsed depressions are not taken in account).

The salinity of the runoff water is dependent on hydrological conditions but is stabilized after 1.5 h. The chemical content of the runoff water already respects the thermodynamic equilibrium with calcite, dolomite and soil CO_2 . Drainage water oversaturates the thermodynamic equilibrium with gypsum. Therefore, the salinity contrast is mainly due to the chloride and sodium contents. A salinity stratification of the drainage water is observed in the soil profile. Water salinity evolution with time is drastically different in the two experiment plots: for plot 1 affected by piping, EC is weakly decreasing which is in accordance with a leaching process, whereas, for the non-affected plot 2, after a previous decrease period, EC is increasing by a concentration process due to the infiltration drop in depth.

The chloride content of the reservoir water, at the fullest stage, is very similar to the chloride content of the runoff water which signifies that the dissolution of the Cl-rich minerals by drainage water is negligible. In turn, calculation based on the sulfate contents of the reservoir water, the runoff water and the 20 cm drainage water show that drainage water has a significant contribution, ranging from 24 to 30%, to the mixing reservoir water, the gypsum dissolution being a relevant process.

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