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Assessment of Clogging of Managed Aquifer Recharge in a Semi-Arid Region

Mohammed ZAIDI[1, 2], Nasre-Dine AHFIR[1*], Abdellah ALEM[1], Bouabid EL MANSOURI[2], Huaqing WANG[1], Said TAIBI[1], Benoît DUCHEMIN[1], Abdesselam MERZOUK[2]

[1]Normandie Univ., UNIHAVRE, UMR 6294 CNRS, LOMC, 76600 Le Havre, France.

[2]Laboratory of Geosciences of Natural Resources, Hydroinformatic section, Faculty of Sciences, Ibn Tofail University, Maamora Campus, BP.133, 14000 Kénitra, Morocco.

*Corresponding Author: Nasre-Dine AHFIR (ahfirn@univ-lehavre.fr)

Normandie Univ, UNIHAVRE, UMR 6294 CNRS, LOMC, 76600 Le Havre, France.

Phone number: +33 (0) 235-217-117, fax number: +33 (0) 235-217-198

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Abstract

To overcome water scarcity issues in arid and semi-arid regions, Managed Aquifer Recharge (MAR) remains a viable and suitable solution to manage and restore aquifers. However, clogging represents a major issue that can affect the durability and efficiency of MAR structures. The aim of this study was to evaluate the extent of clogging in MAR sites (Berrechid, Morocco). To achieve this objective, two field-based studies were undertaken: the first one consists of implantation of sand-filled columns in the recharge sites to evaluate the surface and subsurface clogging. The second one consists of the implantation of pickets over a 750 m^2 area in each recharge site to measure the extent of deposit thickness on the surface of the wadi bed. Results show that, despite the low rainfall (less than 1.4 mm/day) and the short period (91 days) of the study, the deposits thickness exceeds 3 cm in a large part of the MAR. The suspended solids concentrations measured in recharge sites ranged from 1.1 to 1.4 g/L. Due to the particles retention, the estimation of the saturated hydraulic conductivity (k) of the sand declines over 90% in the immediate entrance of the columns. The k values measured *in situ* during the drying period ranged from 10^{-5} to 10^{-6} m/s. The k values of the cake formed, without cracks, was about 10^{-8} m/s. The presence of cracks drives the entire infiltration. However, due to the high plasticity index of the MAR soil, a slight reduction of cracks opening during wetting cycles is observed. In addition, particles deposited in these cracks, would contribute actively to the reduction of infiltration. The results of this study clearly showed the MAR sites vulnerability in semi-arid regions due to physical clogging.

Keywords: semi-arid region; Managed Aquifer Recharge; particles transfer; hydraulic conductivity; clogging; soil cracks

Introduction

In water-limited environments, population growth has led to amplified water demand stressing aquifers and streams (Treese et al., 2009). Arid and semi-arid climates are particularly susceptible, often relying on groundwater to support the needs of large urban centres or irrigated agriculture in the absence of sufficient surface water resources (Famiglietti, 2014). Also, natural recharge is intrinsically limited in these climates, and the predicted effects of climate change on recharge in these regions are highly uncertain (Taylor et al., 2012). In order to increase the security of groundwater resources, managed aquifer recharge (MAR) programs have been developed and implemented globally (Stefan and Ansems, 2018). MAR is an engineering system that aims to increase groundwater supplies by water injection (well) into aquifers and also by infiltration being carried out from large and accessible surface structures (constructed basins, and perfectly dimensioned or natural wadi beds) (Bouwer, 2002; Missimer et al., 2015). Other objectives of this technique include reducing marine intrusions, storing water and improving surface water quality (Dillon, 2005; Dillon et al., 2009). Managed aquifer recharge was the subject of several research studies that addressed its various technical and economic aspects (Marino, 1975; Detay, 1995).

The soil infiltration rate decreased due to the high rate of sedimentation during flow periods. The study of Hatch et al., (2010) of Pajaro River in California, showed that the hydraulic conductivity of the streambed ranged from 10^{-6} to 10^{-4} m/s within the experimental site, with lower hydraulic conductivity determined later in the dry season, as deposits were accumulated on the streambed during periods of low flow. For the Danube River (Vienna), Blaschke et al., (2003) reported a reduction of the seepage rate by about 40% to 60% over a period of 4.5 years. The experiment conducted by Pholkern et al., (2015) at the Mae Rim site

(Thailand) indicates that during the 22-day period of the experiment, with channel flow (0.05 m/s) and turbidity (200-950 NTU), vertical hydraulic conductivity decreased significantly from 5.6×10^{-6} to 7.3×10^{-7} m/s between 0 and 0.03 m in depth.

Clogging has long been an issue in managed aquifer recharge (Dillon et al., 2016). The main operational challenge of infiltration systems is usually management of clogging, which causes a decrease in permeability. As a consequence, the recharge rate decreases, leading to the failure of managed recharge system (Jeong et al., 2018). A study conducted by Pavelic and Dillon (1997) found that clogging was the dominant reason for abandonment of Aquifer Storage and Recovery projects. Clogging of surface infiltration has multiple impacts, counting: i) decreasing infiltration rates (Schubert, 2002) and ii) reducing soil infiltrability efficiency, which involves a regular maintenance (Siegrist, 1987). In porous media, the clogging layer (cake) is the part of the medium over which a sharp drop in hydraulic head occurs as water infiltrates a sedimentary profile (Houston et.,1999). There are two distinct kinds of clogging layers that can be formed in the infiltration surface: i) a top layer consisting of suspended particles material, algae and/or microbes accumulating above native material and ii) a lower layer containing the autochthon sediment with organic and inorganic solids trapped in the pore space (Hutchison et al., 2013).

Clogging can be the result of chemical, biological or physical mechanisms or some combination of the three: (i) chemical clogging, which depends on chemical factors that control the colloidal stability of the particles and minerals precipitated from water (Mays and Hunt, 2007); (ii) biological by the growth of microorganisms (algae, biofilm and bacteria) at the infiltration surface or on a thin layer (Nie et al., 2011) and (iii) physical or mechanical related to solid particles inputs (Rinck-Pfeiffer et al., 2000; Siriwardene at al., 2007) and environmental compaction related to basin activities, water loads when the basin is filled and settling of sediment deposits themselves (Gonzalez-Merchan et al., 2012). In nature,

sediments carried by flows can have several origins but mainly erosion of crumbly geological formations (Gaskin et al., 2003) or by human activities, such as the extractive industry (gravel and clay extraction), agricultural activities and construction projects (Ryan, 1991). Hydraulic conductivity is one of the most significant soil properties that controls water infiltration from the surface to subsurface. The hydraulic conductivity is largely dependent on the soil proprieties and can therefore vary considerably in space and time (Viviani and Iovino, 2004; Sepaskhah and Sokoot, 2010;). For clayey soils, desiccation cracking is a phenomenon that may considerably increase the hydraulic conductivity. However, as shown by Rayhani et al. (2008), under cyclic drying and wetting, for some highly plastic soils, hydraulic conductivity decreased with an increase in permeation time, which is attributed to the cracks self-healing.

Many studies have been undertaken to study the clogging phenomenon *in situ*. Skolasińska (2006) identified the post-depositional changes that have occurred in river deposits affected by forced infiltration of river water and concluded that the decomposition of organic matter present in deposits or in infiltrating water is a very important factor controlling clogging. Casas-Mulet et al. (2017) studied the main hydraulic factors and trends in fine sediment accumulation on a river by installing sediment collectors in a lateral gravel bar subject to irregular flow fluctuations in the river. They estimated that an important horizontal inter-gravel transport contributed to a significant accumulation of fine sediments. Fetzer et al. (2017) investigated the dynamics of clogging by comparing infiltration of silty fine particles and sandy fine particles and by comparing the results between laboratory and field experiments. They showed that clogging is rather pronounced in the field due to a highly fluctuating water regime, a polydispersed suspension and a high concentration of suspended particles in comparison to laboratory conditions.

In Morocco, the techniques of artificial recharge started since 1958 (Sadiki et al., 2019). The first experiments were carried out on the Charf El Akab aquifer in the North-

Western area. Then these techniques were generalised to all unconfined aquifers that suffer from excessive exploitation of groundwater resources. There were 40 projects carried out, of which 96% are on the embankments constructed on streams, alimented by rainwater and dam releases. The clogging of recharge areas represents the common issue between these projects, induced by sediments mobilised during flows.

Until now and to our knowledge, there have been no studies on the clogging processes in artificial recharge facilities in Morocco (semi-arid region) according to hydro-meteorological conditions of the field. Thus, an investigation in that optic was carried out. The aim of this study was to evaluate the extent of clogging in the field by measuring the amount of fine particles infiltrating in depth and the thickness of sediments deposited on the bed surface in recharge sites. This was accomplished by using an original approach that consists of implanting pickets and sand-filled columns in recharge sites for assessing particle deposition on the soil surface and subsurface. Saturated hydraulic conductivity measurements were made, *in situ* and in the laboratory, to evaluate the effect of deposit accumulation on infiltration. Deposited particles, in the surface and subsurface, characteristics (particles size and composition of the organic and inorganic matter) were determined.

1. Materials and Methods

1.1. Description of study area

Berrechid Plain is located in the centre of Morocco (Fig. 1). It extends to 1,500 km². This region is characterised by an arid to semi-arid climate, with an average temperature of 18°C. The annual average rainfall varies from 280 to 310 mm/year (El Assaoui et al., 2015). The plain is marked by intense industrial activity, particularly the ceramics industry and the development of agriculture based on the exploitation of groundwater resources. According to the Bouregregreg and Chaouia Hydraulic Basin Agency (ABHBC), the water balance deficit

124 increased from 20 Mm^3 in 2010 to 30 Mm^3/year in 2016, which was linked to withdrawals
125 from about 3,000 wells and boreholes, where 96% of the total volume pumped is for
126 agricultural use (Ouassissou et al., 2019). For many years, this aquifer has been the subject of
127 many geological and hydrogeological studies (Hazan and Moullard, 1962; Ruhard, 1975; El
128 Mansouri, 1993). Berrechid Plain takes the form of a subsidence basin in which Triassic,
129 Cretaceous, Pliocene and Quaternary geologic formations have been deposited on the
130 Paleozoic basement (Hazan and Moullard, 1962). The aquifer is supplied mainly by lateral
131 flows from the Phosphate Plateau in the southern part of the basin, mainly Boumoussa,
132 Tamedrost, Mazer and El Himmer (27 km length) wadies (Fig. 1) and by direct infiltration
133 from rainfall and the return of irrigation flow (El Ghali et al. 2020).

134 **Fig.1**

135 The surface deposits in the study area are generally dominated by aggregates topped
136 with silty red clay, gravel and cobble (El Mansouri, 1993). In the southern section of the
137 aquifer, El Himmer wadi has been equipped since 2008 by a managed aquifer recharge
138 (MAR) system: two percolation tanks (S1 and S3), which retard flood water to facilitate
139 infiltration of the underlying aquifer during runoff, as well as two recharge releases (S2 and
140 S4), which are used to retain dam's releases inducing slow drainage of water into the
141 streambed to ameliorate the infiltration rate (Cf. Fig. 1; photos a and b). Note that outside the
142 rainy period and dam’s releases, El Himmer wadi remains dry. After more than ten years of
143 use and despite some curing operations carried out by the authorities to remove sediments
144 carried by the flows, a high volume of fine soils transported by flows each year settles along
145 the wadi, particularly in percolation basins, thereby limiting groundwater recharge.

146 **1.2. Rainfall**

147 The daily rainfall time series, provided by ABHBC, covering a period of eight months
148 (from August, 2018 to March 2019) is depicted in Fig. 2. Rainfall data was collected from El

149 Mers climate station (x=320,050 m; y=279,150 m) located at 10 km from the study area (Cf.
150 Fig. 1). The observation of the daily rainfall histogram (Fig. 2) distinguishes two typical
151 periods: one was from October to November with 151.8 mm, and another was relatively dry
152 between December and January with rainfall about 25.4 mm. During the study period (from
153 October 20th, 2018 to January 19th, 2019), the total rainfall was less than 122.6 mm, with an
154 average of 1.34 mm/day. The mean daily temperature was around 18°C (Fig. 2).
155 **Fig.2**

156 **1.3. Field investigations**

157 As mentioned above, the objective of this study was to assess the physical clogging in
158 MAR sites (S1, S2, S3, and S4) located along the El Himmer Wadi (Fig. 1). To achieve this
159 objective, at each studied site and over an area of 750 m² (15*50), pickets and sand-filled
160 columns were implanted in different positions (Fig. 3c). The implantation of these pickets and
161 columns was done on October 20th, 2018. More than 60 pickets have been implanted. The top
162 of each picket remained uncovered by 10 cm, which makes it possible to measure the
163 thickness of the deposits after 91 days of exposure to hydro-meteorological conditions (until
164 January 19th, 2019). The implanted PVC columns were 7.5 cm in inner diameter and 30 cm in
165 length. The sand filling the columns was sieved and cleaned to remove all organic matter and
166 fine particles attached to the grains. The grain-size distribution of the sieved sand ranged from
167 140 to 1,200 µm, with a mean diameter of 520 µm and a uniformity coefficient of 2.1. The
168 average porosity and saturated hydraulic conductivity of the sand filling columns were 0.38
169 (±0.01) and k =2.2×10^{-3} m/s (± 2×10^{-4}), respectively. A total of 24 columns were buried
170 (Figs. 3b and c) in the four recharge sites. The top of each column was on the same level of
171 the wadi bed. The positions of the pickets and the columns were recorded by GPS. After 91
172 days of exposure to natural conditions of the field (from October 20, 2018 to January 19th,
173 2019), 12 columns and 43 pickets were recovered successfully, while the others were found

damaged. Notice that all implanted columns and pickets in site S4 were damaged. The columns were dig up and carefully transported to the laboratory for treatment and analysed. Each column was divided into 1 cm layers. For each layer, the quantity of fine particles retained was determined by washing, drying and weighing (Alem et al., 2013). The particles deposition profile along the length of each column was determined. The deposited particles collected from sand during the washing process were stored in vials for granulometric analysis in order to determine the particle size distribution, using a laser diffraction particle size analyser.

Fig.3

In this study, saturated hydraulic conductivity measurements were performed in recharge sites using the double-ring infiltrometer test (NF X 30-418, 2012). It's a classic method that is widely used (Sidiras and Roth, 1987; Arriaga et al., 2010; Fatehnia et al., 2016). Thus, 30 measurements were carried out. It should be noted that, as shown in Fig. 4a, the soil surface constituting the first centimetres (from 5 to 10 cm depth) of the wadi bed is completely cracked. That is why during field measurements, and to prevent preferential flow paths, the part of the cracked soil is completely cleared. Thus, the soil surface hydraulic conductivity was measured at a depth between 5 and 10 cm. It is assumed that, at these depths, the hydraulic conductivity measured is that of the older deposits induced by the dam's release and/or rainfall. There were 30 other measurements that were made in the same positions, by digging holes around 100 cm in depth, in order to evaluate the water infiltration in the subsurface without surface deposits. As shown in Fig. 4b, even at depths beyond 50 cm, cracks persist. In addition, 30 turbid water samples were taken from the retained water in percolation tanks S1 and S3 for measuring their suspended solids concentrations.

Fig.4

199

200 **1.4. Laboratory investigations**

201 Laboratory analyses were performed on samples collected in the field. Among the
202 analyses carried out were

203 *i*) measurement of the saturated hydraulic conductivity of the layers formed on soil surface
204 (cake) using a triaxial permeameter according to ASTM D5084-10 (2010);

205 *ii*) percentage of organic matter (OM) in the cake. To evaluate this, the loss-on-ignition (LOI)
206 method was used. The LOI method consists of a known soil mass being placed in a ceramic
207 crucible (≤10g), which is then heated at 440°C overnight (ASTM D2974-14, 2014). Then they
208 are cooled in a desiccator and weighed. The OM content is determined as the difference
209 between the initial mass and the final mass of the sample divided by the initial mass of the
210 sample multiplied by 100%. A dozen of samples were tested;

211 *iii*) particle size distribution (PSD) of the deposited particles in the surface and subsurface
212 (columns depth); the PSD is measured using laser granulometer (Mastersizer, 2000);

213 *iv*) Atterberg limits. The liquid limit w_L and plastic limit w_P of the soil covering the surface of
214 the recharge sites, before and after the studied period, were measured according to NF EN
215 ISO 17892-12 (E), 2018 and *v*) mineralogical characterisation of the deposited particles using
216 X-ray diffraction (XRD). XRD was performed on a PANalytical X'Pert powder
217 diffractometer equipped with a CoKα anode (λ = 1.7903 Å) powered at 40 kV and 40 mA.
218 The detector was a linear PIXcel 1D detector equipped with 0.04 rad Soller slits. A powder
219 scan was performed on a sample that was back-loaded in a specific sample holder.
220 Programmable anti-scatter slits had a fixed aperture of 1/2°, whereas the anti-diffusion slits
221 had an aperture of 1°. A 15 mm mask was selected. The scans were performed in the 5–100°
222 range in steps of 0.0131° (399 s/step). The samples were also continually rotated at 8 sec/turn
223 in order to minimise preferred orientation. In order to characterise the clay fraction, oriented

mounts were also prepared from the supernatant of a clay/ultrapure water fraction. The supernatant was dropped on microscope glass slides and allowed to dry. These mounts were then measured by XRD as prepared, after exposure to ethylene glycol or after heating to 550°C for 5 h in a furnace. Measurements were performed in duplicates. The weight fractions were estimated using the Relative Intensity Ratio (RIR) method implemented in software PANalytical high score (v.3.0.5).

Hydraulic conductivity estimation

To display the clogging of the sand filled columns, the saturated hydraulic conductivity drop as a consequence of the particles deposition is estimated on the basis of the Kozeny-Carman equation as follows:

$$\frac{k}{k_0} = \frac{\emptyset^3}{\emptyset_0^3}\frac{(1-\emptyset_0)^2}{(1-\emptyset)^2}\frac{S_0^2}{S^2}\left(\frac{T_0}{T}\right)^2 \quad (1)$$

k_0 and k are the initial and reduced hydraulic conductivity values, respectively. S_0 and S are the specific surface area of the clean sand and the clogged sand, respectively. T_0 and T are, respectively, the tortuosity of the clean and clogged sand.

The specific surface area S of the clogged sand is estimated as follows (Alem et al., 2013):

$$S = \frac{1}{1-\emptyset}\left[(1-\emptyset_0)S_0 + (1-\emptyset_d)\frac{\sigma}{\rho_p}S_p\right] \quad (2)$$

ϕ_d, ρ_p and S_p are the porosity, the particles specific density and the specific surface area of the deposited particles. σ is the retention defined as the volume of deposited particles per unit of porous-medium volume. The deposit porosity ϕ_d is derived from the average density of deposited particles as follows (Boller and Kavanaugh, 1995):

$$\emptyset_d = 1 - \frac{\rho_d}{\rho_p} = 1 - \left[\frac{\rho_w}{\rho_p} + \left(1 - \frac{\rho_w}{\rho_p}\right)\frac{1}{a}N^{1-b}\right] \quad (3)$$

ρ_d is the average deposit density, ρ_w is the fluid density, N is the number of particles in a deposit layer and a and b are constants, taken as equal to 1 and 1.3, respectively.

Tortuosity is related to porosity as follows (De Marsily, 1986):

$$T = F\emptyset \quad (4)$$

where $F = \phi^{-m}$ is the formation factor (Archie, 1942) given empirically as a function of porosity, with m=1.3 for a sandy medium.

2. Results and Discussion

2.1. Assessment of columns clogging

2.1.1. Subsurface clogging

At the end of the study period (91 days), the implanted columns were recovered (January 19, 2019). The results observed accumulation of fine particles in all columns filled sand. As mentioned above (Section 1.3), each column was divided into 1 cm layers in order to determine the mass of the particles deposited as a function of depth. Clogging that occurred in columns could be divided into two types: superficial and internal clogging. The superficial (surface) deposit (cake) on each column is discussed below in section 2.1.2.

Fig. 5a shows the particles deposition profiles in three columns (C_1, C_2 and C_5) implanted in recharge site S1. For clarity, only three profiles are represented for this site (S1). Profiles illustrate that the amount of infiltrated particles is important in the column inlet and decreases with depth. It means that suspended particles were trapped largely in the near-surface layer that corresponds to the first 3 cm thick (internal clogging). In the study presented by Page et al. (2014), a similar result was obtained. They showed that clogging was concentrated in the top 3 cm of the columns.

Table 1 summarises the masses of the deposited particles in the first 3 centimetres and those in the rest of the columns (from 3 to 30 cm). The average masses of the retained particles in the first 3 cm thick layer of the columns implanted in sites S1, S2 and S3 equal 21 g, 15 g and 9g, respectively. Beyond 3 cm depth, the amount of retained particles (by sand)

ranges between 0 to 3 g/cm (Fig. 5a). It can be seen that the deposits in the first 3 centimetres can reach over 30% of the total deposit measured in the columns.

Table 1

The damage to the porous medium, after 91 days of exposure to hydro-meteorological conditions, as a result of particle deposition, was assessed by observing declines in either the porosity or the hydraulic conductivity. Knowing the mass of the deposited particles in each layer, the current porosity ϕ of the porous medium (sand + deposited particles) was estimated. Porosity variation of the porous medium as a consequence of the particles deposition is depicted in Fig. 5b, c and d. ϕ_0 is the initial porosity of the clean sand (ϕ_0=0.38). The results show that the porosity declines, on average, by 10 to 30% in the first 3 centimetres from the top of the sand filled columns. Beyond this depth, the decrease in porosity varies between 2 and 8%.

Fig.5

Fig.6

The results plotted in Fig. 6 show variation of (k/k_0) predicted by equation (1) as a function of the columns depth. For clarity, only three profiles are presented. Fig. 6 shows clearly that the damage is not uniform in the sand-filled columns. Damage is important at the inlet to the column and decreases with depth. In the first centimetres of the sand-filled columns, k/k_0 reduced drastically, which is owed to the high amount of deposited particles in the entrance of the columns and clogged up pores. This reduction can exceed 95% in the immediate entrance of the columns. Beyond the first 10 centimetres, hydraulic conductivity reduction varies between 10 and 40%. The same order of magnitude of hydraulic conductivity reduction has been observed by Pavelic et al. (2011). They showed that physical clogging was more significant than other forms of clogging and that the relative hydraulic conductivity (k/k_0) declined to around 90% in some columns.

2.1.2. Surface clogging

Surface clogging (or external clogging) occurs when the suspended particles with size larger than the pore diameters are intercepted in the surface. On the surface of the columns implanted in the wadi bed, a layer due the particles deposition was developed. The measurement of the solid particles concentration was done in the Percolation tanks (S1 and S3) for the turbid water before it cross the embankment were ranged from 1.1 to 1.4 g/L.

The thickness and the mass of the deposited particles (cake) on surface of each column are presented in Table 2. The thickness of the cake formed above each column filled with sand ranged from 0 to 7 cm. Indeed, an average cake thickness of 2.2 cm can be retained. Notice that when the thicknesses of the formed cake were measured, their average water content was about 29%. The results show that the cake thickness depends on the position of the implanted columns. Thus, columns C_1, C_6, C_7 and C_{10}, implanted near the embankments facilities, receive a high deposit volume, caused by embankments-break flows charged by suspended particles.

Table 2

This important deposit generates a total clogging of the implanted columns. As shown above (section 2.1.1), the deposition in the first 3 centimetres of the sand-filled columns drastically reduces its hydraulic conductivity (a drop more than 50%, on average, was measured). Thus, one can assume that the cake completely controls the hydraulic conductivity of the sand, which can be considered as totally clogged.

2.1.3. Characterisation of the cake's particles

In this section, the percentage of organic matter (OM) and the mineralogical characterisation of the particles constituting the cake formed on the surface are presented.

322 Results indicate an average percentage of OM around 3%. Thus, it can be considered that the
323 amount of total organic carbon in the total mass analysed is low.

324 Analysis of cake particles by X-ray diffraction (XRD) was used to achieve two main
325 objectives: i) obtaining a general idea of the mineralogical composition of the particles
326 constituting the cake and ii) evaluating the presence of certain clay minerals, which are highly
327 reactive in the presence of water, such as smectite and montmorillonite. Their clogging
328 potential is prejudicial for water infiltration (Mays and Hunt, 2007).

329 The results are shown in Fig. 7. The sample contained several minerals including
330 quartz (50%), calcite (20%) and dolomite (10%). The remaining sample fraction was
331 attributed to the presence of various clays, namely vermiculite, an interstratified illite-
332 vermiculite and two kaolinite polytypes (halloysite 7Å and dickite). The halloysite:dickite
333 ratio was estimated using the RIR method at 15:2. It is noted that the results show the absence
334 of smectite and montmorillonite, two clay minerals that swell quickly in the presence of
335 water, leading to a rapid clogging of the pores.

336 **Fig.7**

337

338 **2.1.4. Particles size distribution of the deposited particles**

339 Fig. 8 shows the PSD of the retained particles in the surface (cake) and subsurface of
340 the columns. The distribution of the retained particles in the columns' subsurface were
341 measured evry 5 cm of depth (0–5 cm; 5–10 cm; 10–15 cm; 15–20 cm; 20–25cm and 25–30
342 cm). For clarity, only three PSD are presented in Fig. 8.

343 The PSD of the retained particles in columns show a very slight differences in the
344 particle size distribution as a function of the depth. However, there is a slight tendency
345 towards decreasing the size of the particles retained with the depth. 90% of particles that

infiltrated the sand-filled columns were less than 25 µm. An average median diameter around 6 µm was measured (Table 3).

The PSD of the particles constituting the cake (surface deposits) indicate a wider distribution up to 600 µm. The PSD presented in Fig. 8 is representative of all that measured for the different analysed samples. The average median diametre measured for the particles retained in surface was 25 µm. Also, as indicated in Table 3, more than 34% of the particles constituting the cake are greater than 63 µm. More than 50% of the particles deposited on MAR surface ranged between 30 and 400 µm. These results confirm what was expected, i.e. the largest particles are mainly retained at the columns' surfaces.

In this study, among the mechanism involved in the retention of the suspended particles in the subsurface, straining dominates; however, on the surface, straining and sedimentation are the two mechanisms that affect particle retention.

Straining of the particles in porous media depends on the ratio of d_{p50}/d_{g50}, where d_{p50} is the median diameter of the suspended particles and d_{g50} is the median diameter of the grains constituting the porous medium. As reported by Bradford et al. (2003), straining occurs when the d_{p50}/d_{g50} ratio is greater than approximately 0.005. The median grain diameter of the used sand in this study was d_{g50} = 520 µm, and the median diameter of suspended particles infiltrated in the sand filled columns was d_{p50} = 6 µm (Table 3). The ratio of d_{p50}/d_{g50} equals 0.011, which leads to significant particles retention by strainning in sand.

As discussed above, for surface deposition, larger particles were retained, and then the ratio of d_{p50}/d_{g50} equalled 0.048. Retention of larger particles by straining in the surface of the sand has actively participated in the filtration of particles of all sizes, including the finest, thus preventing their transport in deep, favouring surface clogging.

These results clearly show the extent of the low rainfall (during 91 days) to promote the mobilisation and transport of suspended particles carried by runoffs. They reveal that

371 despite the high grain size distribution of the sand used, unlike the natural soil of the recharge
372 sites, there is a significant clogging on the surface.
373
374 **Fig.8**
375 **Table 3**
376

377 ## 2.2. Assessment of sites clogging

378 ### 2.2.1. Distribution of surface clogging on the studied sites

379 To quantify the thickness of the deposited particles on natural soil of the wadi bed,
380 many pickets were placed at different positions of the recharge sites over a large area (~750
381 m²). As shown in Fig. 9, deposits accumulation varied significantly according to the distance
382 to the embankment. Investigations undertaken over 91 days indicate that, even with the low
383 rainfall, the thickness of the accumulated deposits is important and ranges between 0 and 12
384 cm, with an average of 2.5 cm. For site S1, the accumulated deposit reaches thicknesses
385 greater than 2 cm, at a distance of 40 metres from the embankment. However, this thickness is
386 reached in site S3 at a distance of 20 m from the embankment. This observation can be
387 justified by the position of the recharge sites; thus, site S1, which is upstream of sites S2 and
388 S3, retains more particles transported by the flows. Also, many factors can affect the cake
389 thickness such as wadi bed topography, presence of surface preferential flow and vegetation
390 density. In some picket positions, the cake thickness reached up to 6 cm (Fig. 9b), which is
391 owed to topographical depressions (bowl-shaped) where a significant volume of water
392 stagnates and favours more particles deposition. In contrast, suspended particles deposition
393 was distributed fairly evenly throughout site S1 (Fig. 9a), except on the right bank where
394 more deposits were observed. Among possible interpretation of the latter observation, the lack
395 of vegetation on the right bank favoured surface erosion from the bank during rainfall. As a

consequence, high accumulations were observed compared to the left bank which is covered with vegetation.

Note that it has been observed that some large cracks (aperture of 3 or 4 cm) do not close completely even if after several days of rain accompanying high water level (20 to 30 cm) in the recharge site. However, their depth has decreased, which is owed to the suspended particles deposition.

Fig. 9

2.2.2 Hydraulic conductivity

In this part, we discuss the hydraulic conductivity of the soil that controls the water infiltration from the recharge sites surface to the subsurface soil and therefore to the aquifer. For this purpose, as discussed above, *in situ* saturated hydraulic conductivity measurements at the surface and subsurface (around 100 cm depth) have been carried out using the double rings infiltrometer (Cf. section 1.3).

For all sites and for surface and subsurface measurements, saturated hydraulic conductivity varies from 8.33×10^{-5} to 1.67×10^{-6}, with an average value of 4.25×10^{-5} m/s. For example, in site S3, an average value of 3×10^{-5} ($\pm2\times10^{-6}$) m/s and 6×10^{-5} ($\pm3\times10^{-6}$) were obtained for k measurements in the surface and subsurface, respectively. These measured k values are low for silty-clayey soil but can be explained by the presence of micro cracks. As discussed above (section 1.3), cracks exist in the surface and the subsurface (Fig. 4) of the tested soils, and their presence increases water infiltration rate.

The measurement of the hydraulic conductivity of the cake represents a main element for assessing clogging. To evaluate the hydraulic conductivity of the formed cake without cracks, measurements were made on cake samples taken after the 91 days investigation, either on the columns surfaces or around the pickets. Hydraulic conductivity of the cake was determined by using a triaxial permeameter system. An example of measurements of the

hydraulic conductivity of the cake, under different confining pressure ranging from the greatest pressure (300 kPa) to the smallest (20 kPa), is presented in Fig. 10. The hydraulic conductivity of the cake under zero confining pressure is obtained by extrapolation of the curve (Fig. 10), and an average value of 4×10^{-8} m/s was retained.

Fig.10

Clayey soils tend to crack when drying (Morris et al., 1992). The resulting cracking causes crucial problems in geo-environmental engineering and dramatically affects hydraulic conductivity (Peron et al., 2009). Silty-clayey soil of El Himmer wadi bed has been submitted to several wetting and drying (W-D) cycles due to seasonal variations, including temperatures and rainfall. As a result of soil desiccation, cracks are created at the surface and in depth (Cf. Fig. 4). As mentioned above, the measured hydraulic conductivity in laboratory by triaxial permeameter is in the range of 10^{-8} m/s. However, measurements undertaken in the field using the double rings infiltrometer revealed a hydraulic conductivity that varies between 10^{-5} and 10^{-6} m/s. The ratio between the hydraulic conductivity measured in field and that obtained in laboratory (k_{field}/k_{lab}) can reach 10^{3}. Despite the difference between the two techniques of measurement and the difference in observation scale, the difference between the measured values in laboratory and in the field remains significant. It is very low for non-cracked samples and very high for cracked soils. Based on the experimental studies in laboratory, several studies have been conducted on the effect of a cracks network on hydraulic conductivity in clayey soil. Louati et al. (2018) showed that after three W-D cycles and for all tested samples with different initial densities, the hydraulic conductivity increased in the presence of cracks. Lu et al. (2015) also concluded that after a four W-D cycles; the conductivity increased from 8.3×10^{-9} to 1.5×10^{-7} m/s for compacted clay.

However, as reported by Rayhani et al. (2008), during the periods of rainfall (wetting cycles) that follow periods of evaporation (drying cycles), water fills cracked soil. The

hydrostatic forces increased, and the water is slowly absorbed by the clay. The effect of the absorption is to increase the unit weight of the clay as well as to reduce the unit weight of its shear strength. As a result of these processes, the driving forces (sliding) increase at the same time as the resistance forces (shear strength) decrease. During water filling, cracks tend to disappear and hydraulic conductivity decreases. This process can be carried out rapidly in clayey soil with high plasticity index (Rayhani et al., 2008). This phenomenon is known as the "self-healing".

In this study, before and after the studied period, the liquid limit w_L and plastic limit w_P of the soil covering the surface of the recharge sites were measured. The obtained results indicate that $w_L = 66\%$ and $w_P = 32\%$. Thus, the plasticity index I_p equals 34%.

After water infiltration in the studied sites, a slight reduction of the cracks opening in some locations was observed, which can be attributed to the self-healing due to the high plasticity index of the silty-clayey soil. In other locations, the cracks were filled entirely or partially by the particles transported by flows. Indeed, in the periods of high precipitations and, therefore, with a large contribution to the suspended particles deposition (sediment supply) in the recharge sites, deposits that form the cake could reduce the saturated hydraulic conductivity by 1,000 orders of magnitude in comparison to those measured during dry period. Thus, the hydraulic conductivity reduction generates less infiltration towards the subsurface, which is owed to evaporation.

3. Recommendations for monitoring clogging sites

Various factors can reduce infiltration rates in recharge sites. Physical clogging, predominantly related to a filter cake forming, is usually the most important factor. Management approaches were developed to reduce clogging effects and renovate recharge rates. To manage site clogging, recommendations exist such as deposits removal and scraping

(Mousavi and Rezai, 1999; Gale and Dillon, 2005), use of gravel filters (Hatt et al., 2007) and vegetation cultivation (Woo et al., 1997; Gonzalez-Merchan et al., 2014; Al-Maktoumi et al., 2017).

To extend bed life of recharge sites in wadi El Himmer, there are three recommendations: i) a regular scraping of clogged layers. Due to the cake thickness measured in this study, it is thought that at least one scraping per year is necessary for a depth of 10 to 20 cm. The scraping technique must be recurrent as long as these sites are exploitable. ii) The second recommendation, with lasting effects, is planting shrubs in the upstream of MAR sites and on the wadi banks, which could reduce fine particles transport and their deposition in MAR sites. Also, as discussed above, as infiltration is controlled by cracks (Römkens and Prasad, 2006; Dunkerley, 2008; Greve et al., 2010), the reduction of particles contribution towards these sites will make it possible to exploit the presence of theses cracks systems to maximise recharge. This last technique (vegetation) would reduce the number of scraping intervention on the sites. Thus, it is thought that the cultivation of the *Stipa tenacissima* upstream of the MAR sits can be a good solution. As reported by Eldridge et al. (2010), the shrub *Stipa tenacissima* can enhance the sorptivity and infiltration 2–3 times higher than in intact on soil crusts. In addition, this shrub is adapted to the silty soil and to arid and semi-arid climates (Ghiloufi et al., 2015), which makes it suitable for cultivation in an environment characterised by increasing degradation of water resources (Ramı´rez et al., 2007). Cultivation of the shrub *Stipa tenacissima* in wadi El Himmer represents a hydro-ecological solution; it is clean, less expensive and more efficient for limiting particles transfer and renovating infiltration through the wadi bed. iii) The third recommendation consists of the construction of a settling basin upstream of the recharge sites, supplied by rainwater during floods and dam releases; this may be useful for reducing flow rates and the sedimentation rate of downstream recharge sites.

Therefore, an experimental model should be developed even before the construction of the recharge facilities, in order to predict or estimate the impact of clogging in MAR sites. Moreover, the data generated by the model can be easily integrated into the cost–benefit ratio of the models, making it possible to predict the most cost-effective cleaning strategies (Phipps et al., 2006), in order to improve the percolation efficiency of the MAR and minimise the operating costs.

Conclusions

This study was undertaken to investigate the extent of clogging in Managed Aquifer Recharge (MAR) sites in wadi El Himmer (Berrechid, Morocco) over 91 days. To evaluate the *in situ* clogging, sand-filled columns and pickets were implanted in the wadi bed. Results indicate that, although the low rainfall during the studied period, clogging that occurred in wadi bed is significant. The thickness of the deposited particles forming a cake (surface clogging) is important and drastically reduces the hydraulic conductivity of the wadi bed soil. A 1,000 order of magnitude can be reached during the wetting cycles when the cake formed is cracks free. The obtained results from the columns show damage to the sand medium that is owed to surface and subsurface clogging. The main mechanism involved in the sand clogging, either in the surface or subsurface, is straining. Because of the large particle size distribution of the particles carried by the flow, more than 50% of the particles deposited on MAR surface ranged between 30 and 400 µm. Hydraulic conductivities measured *in situ* during the drying period are in the order of 10^{-5} m/s and are affected by the presence of cracks that promote infiltration. However, due to the high plasticity index of the MAR soil, a slight reduction of the cracks opening during wetting cycles is observed. In addition, contribution of fine particles deposited in these cracks would participate actively in the reduction of hydraulic conductivity.

Despite the low rainfall (an average of 1.34 mm/day) and the short period (91 days) of this investigation, MAR sites clogging is effective; the thickness of the deposits exceeds 3 cm in a large part of the MAR. However, a long-term study is necessary to more precisely evaluate the role of cracks under cyclic drying and wetting.

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FIGURES

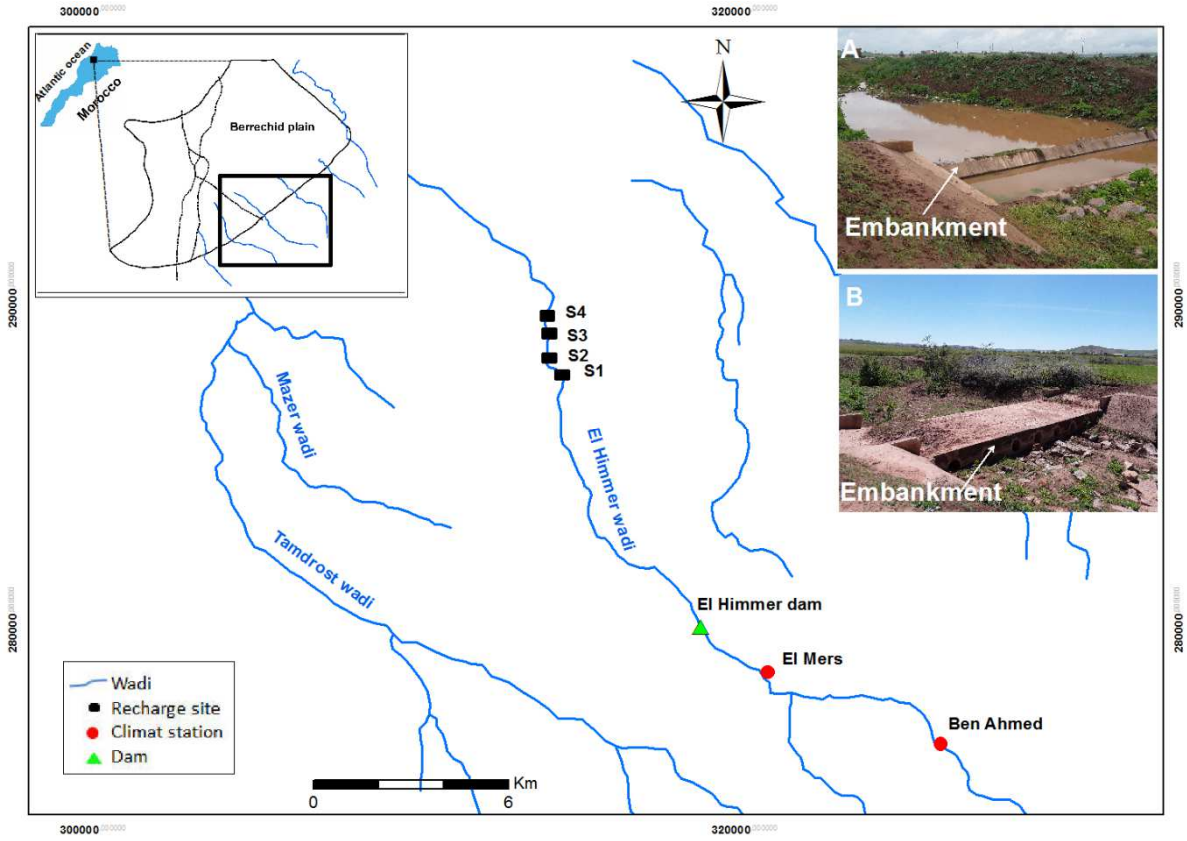


Fig.1. The study sites (S1, S2, S3, and S4) are located along the El Himmer Wadi. Inset photos indicate a (A) Percolation Tank and (B) a Recharge releases located at the studied sites (S1 and S2)

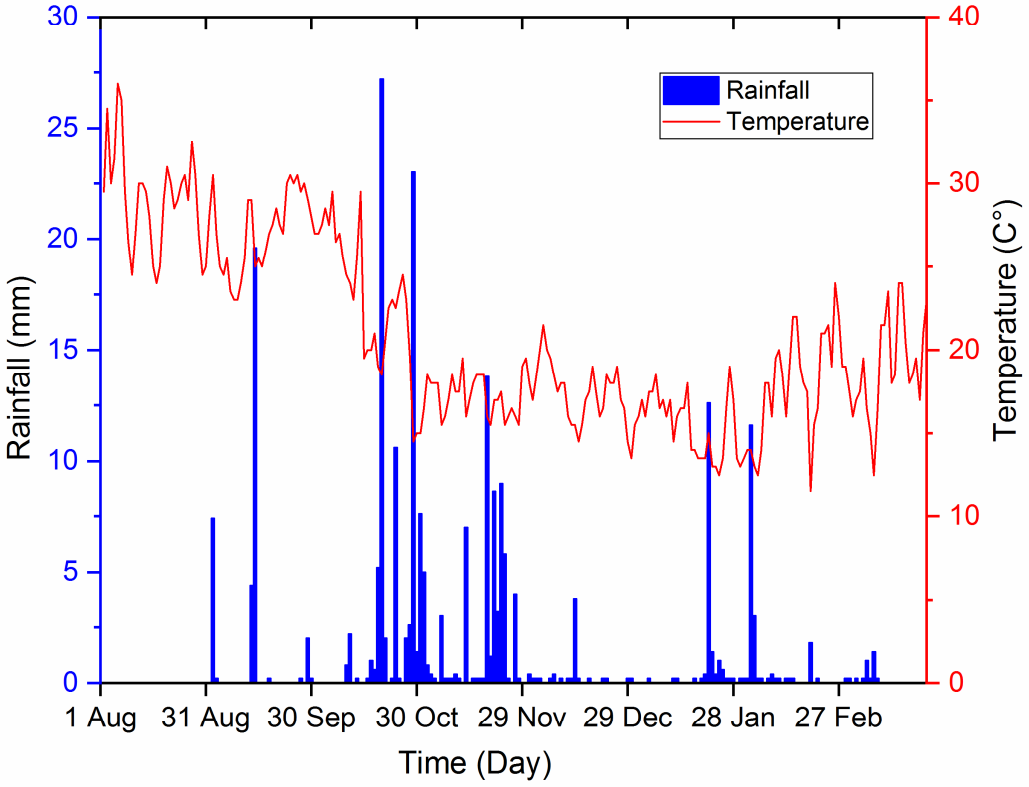


Fig.2. Daily rainfall and temperature at El Mers climate station in El Himmer wadi from 01/08/2018 to 24/03/2019

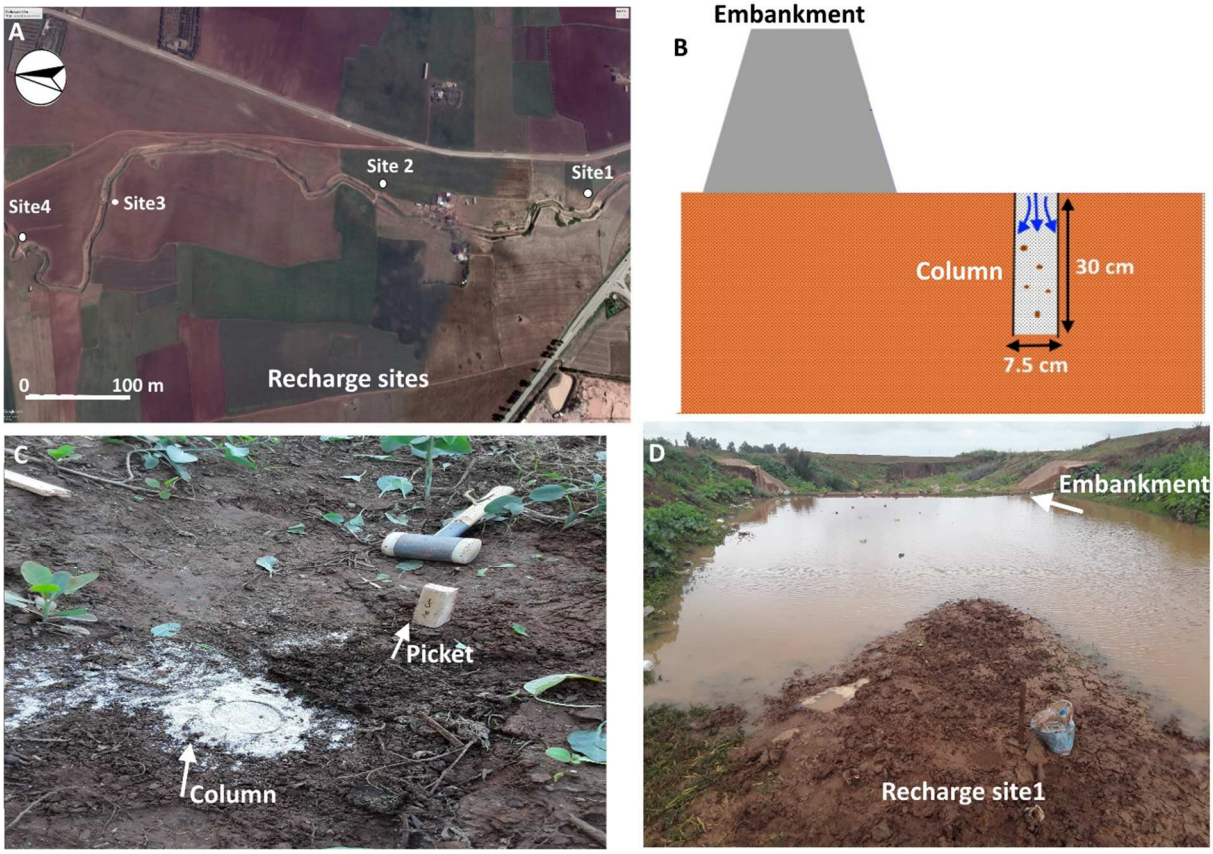


Fig.3. Layout at the field site. The upper panels show recharge sites positions in El Himmer wadi (A) and not scaled schematic profile of the columns implanting on the wadi bed (B). The lower panels show photo of filling column and picket installed before runoff (C) and recharge site during high-flow (D)

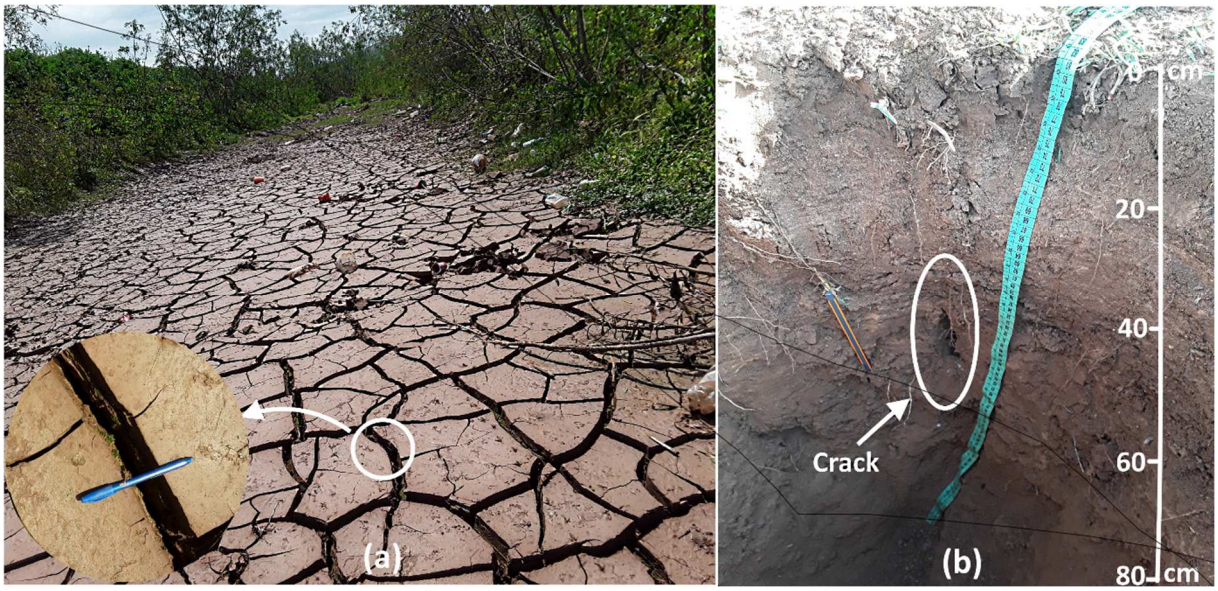


Fig.4. Photo of the surface (a) and (b) subsurface cracks in the field study in dry period

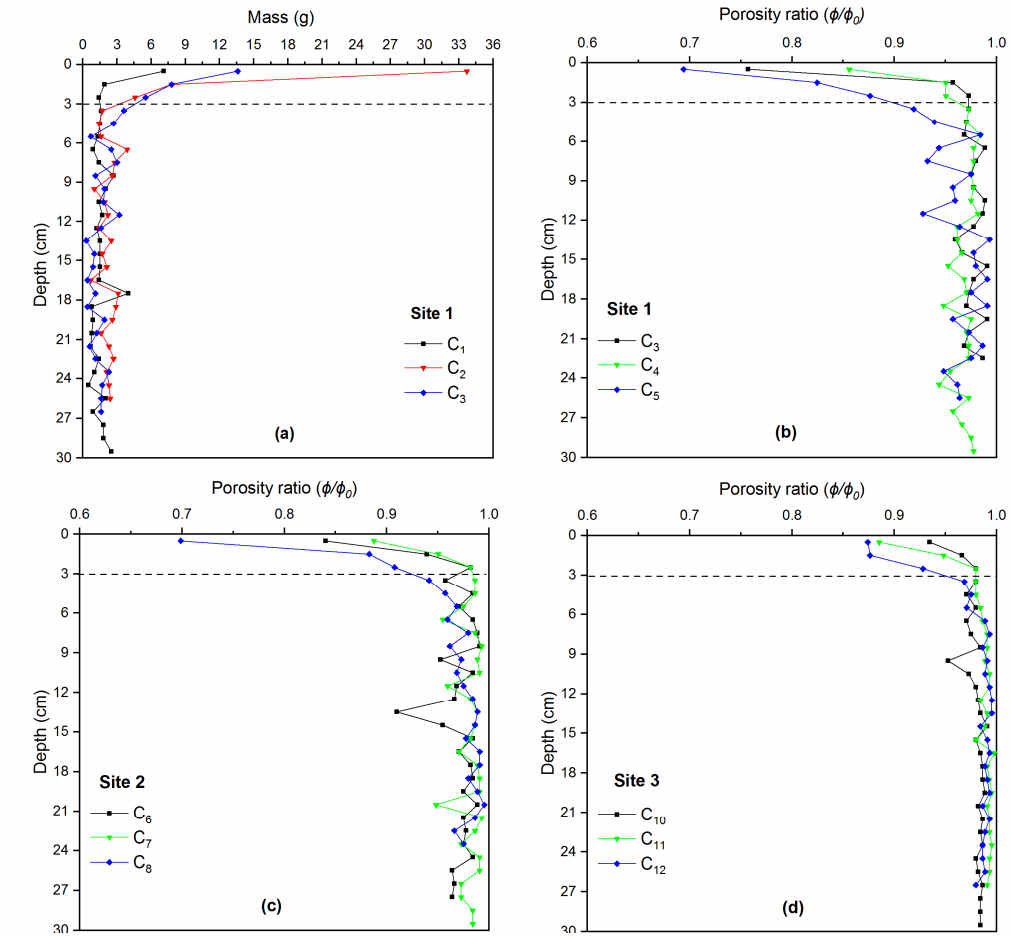


Fig.5. (a) Mass of the retained particles in the sand filled columns C1, C2, and C5 implanted in site S1. Profiles of porosity decline of the clogged sand filled columns implanted in sites (b) S1, (c) S2, and (d) S3

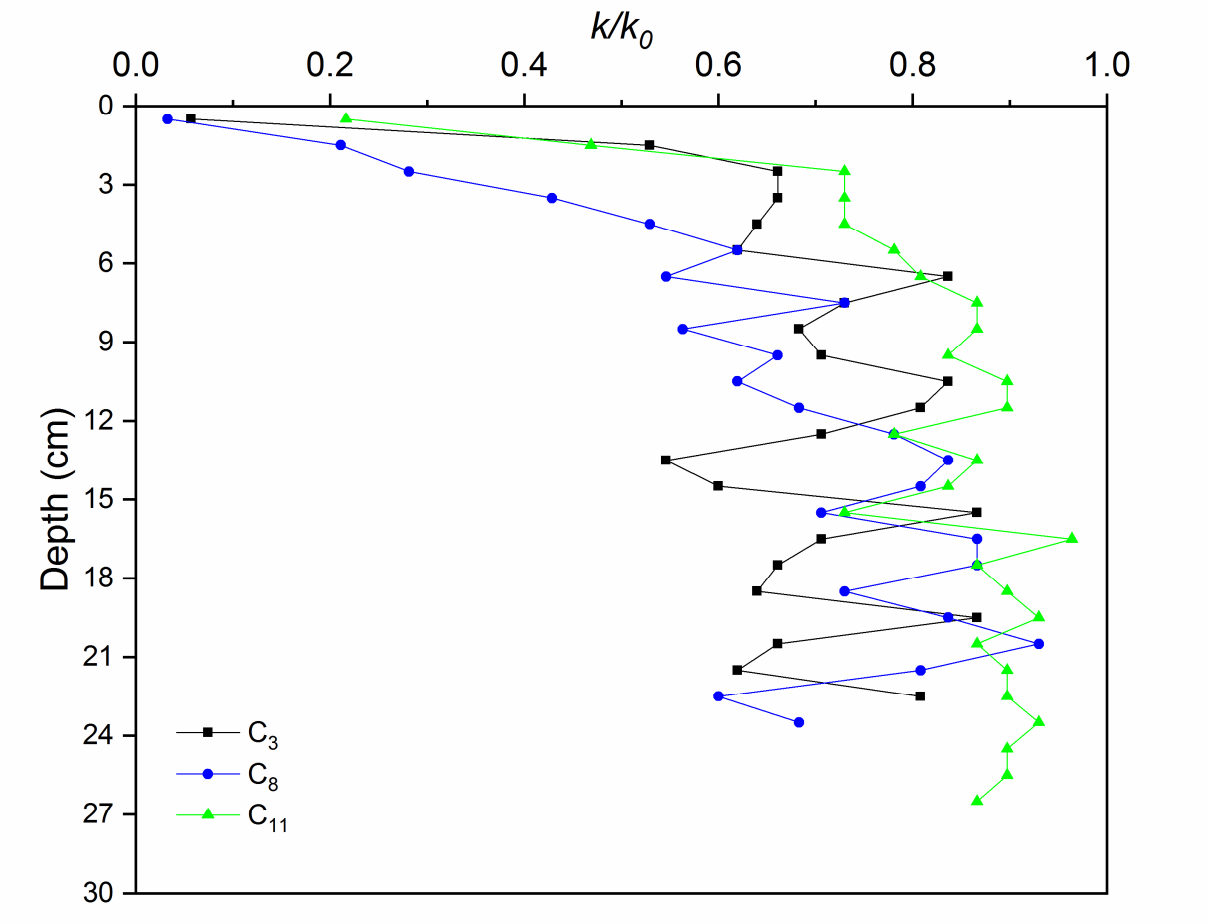


Fig.6. Hydraulic conductivity ratio of the sand filled columns C3, C8 and C11 from sites S1, S2 and S3 respectively

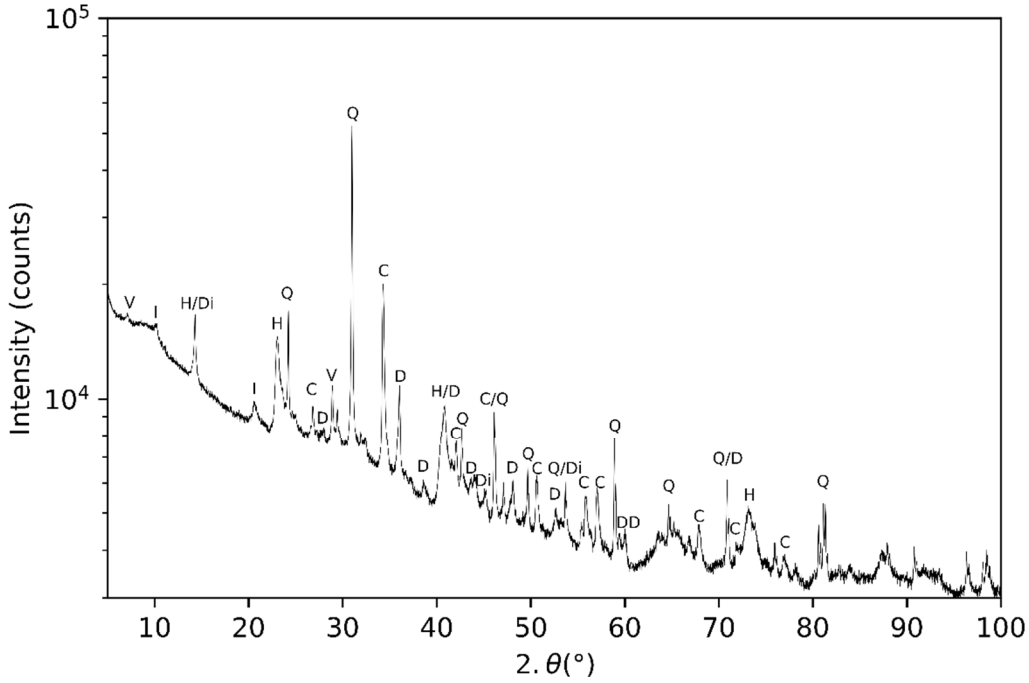


Fig.7. Powder diffraction of the mineral indicating the presence of vermiculite (V), interstratified illite-vermiculite (I), halloysite (H), dickite (Di), dolomite (D), quartz (Q) and calcite (C). Some peaks were not indexed in order to avoid redundancy

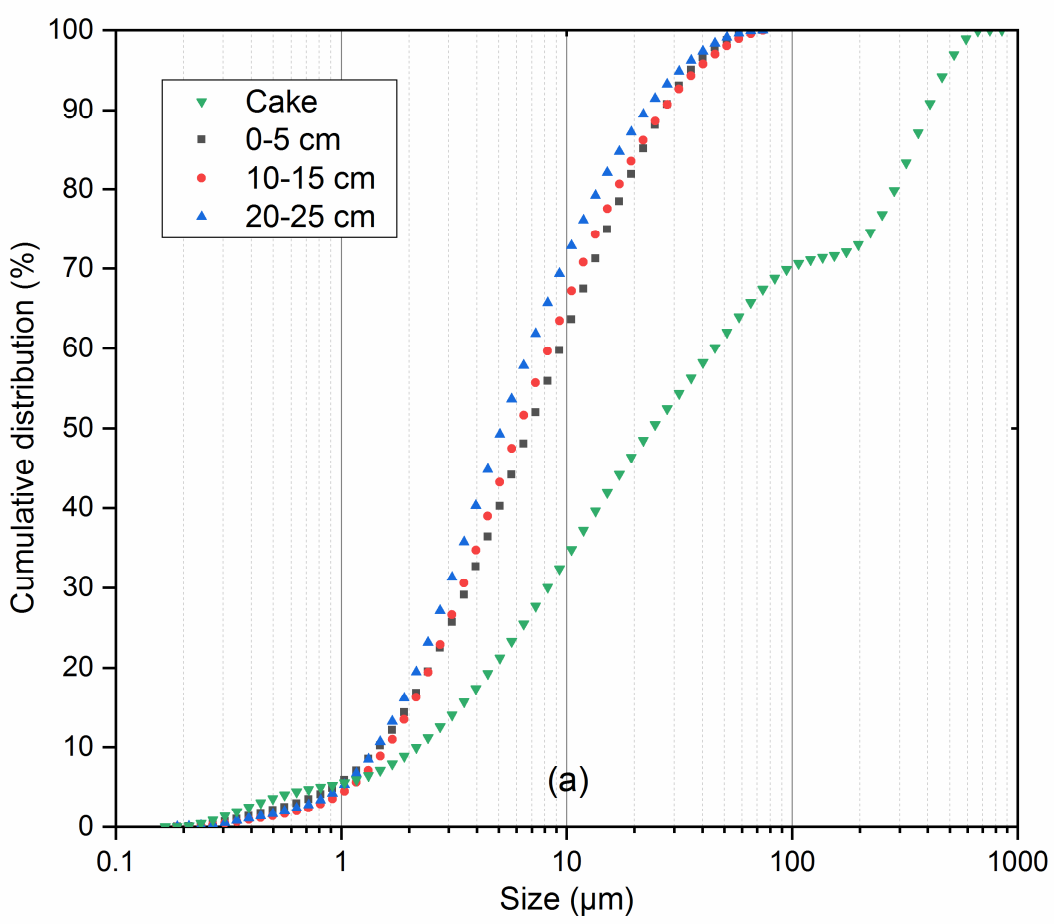


Fig.8. Particle size distribution of the particles retained in surface (cake) and subsurface (internal deposition) of the columns implanted in wadi bed

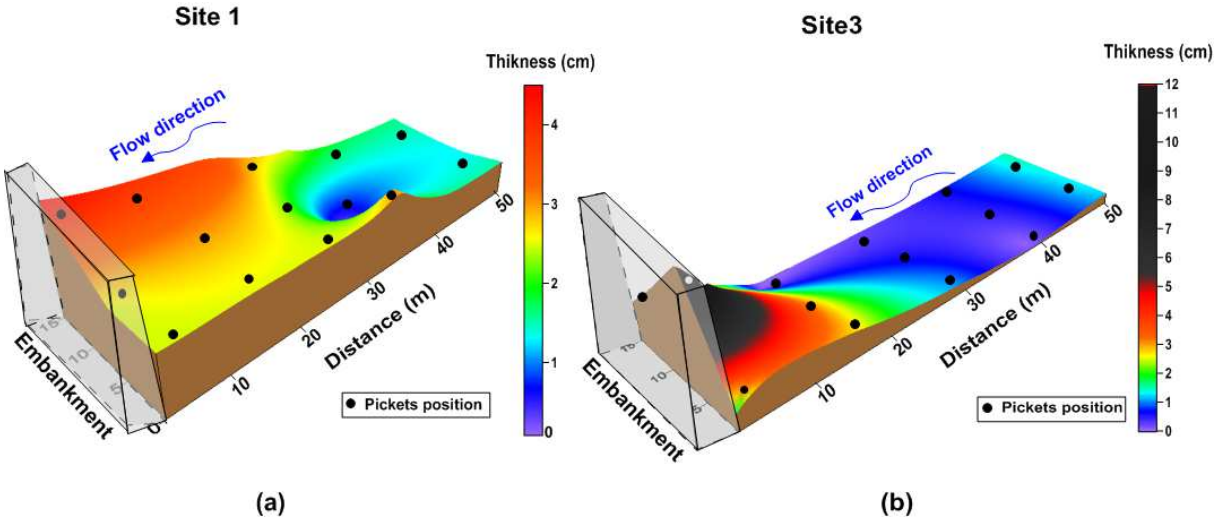


Fig.9. Thickness of surface deposits in the recharge a) site S1, and b) site S3

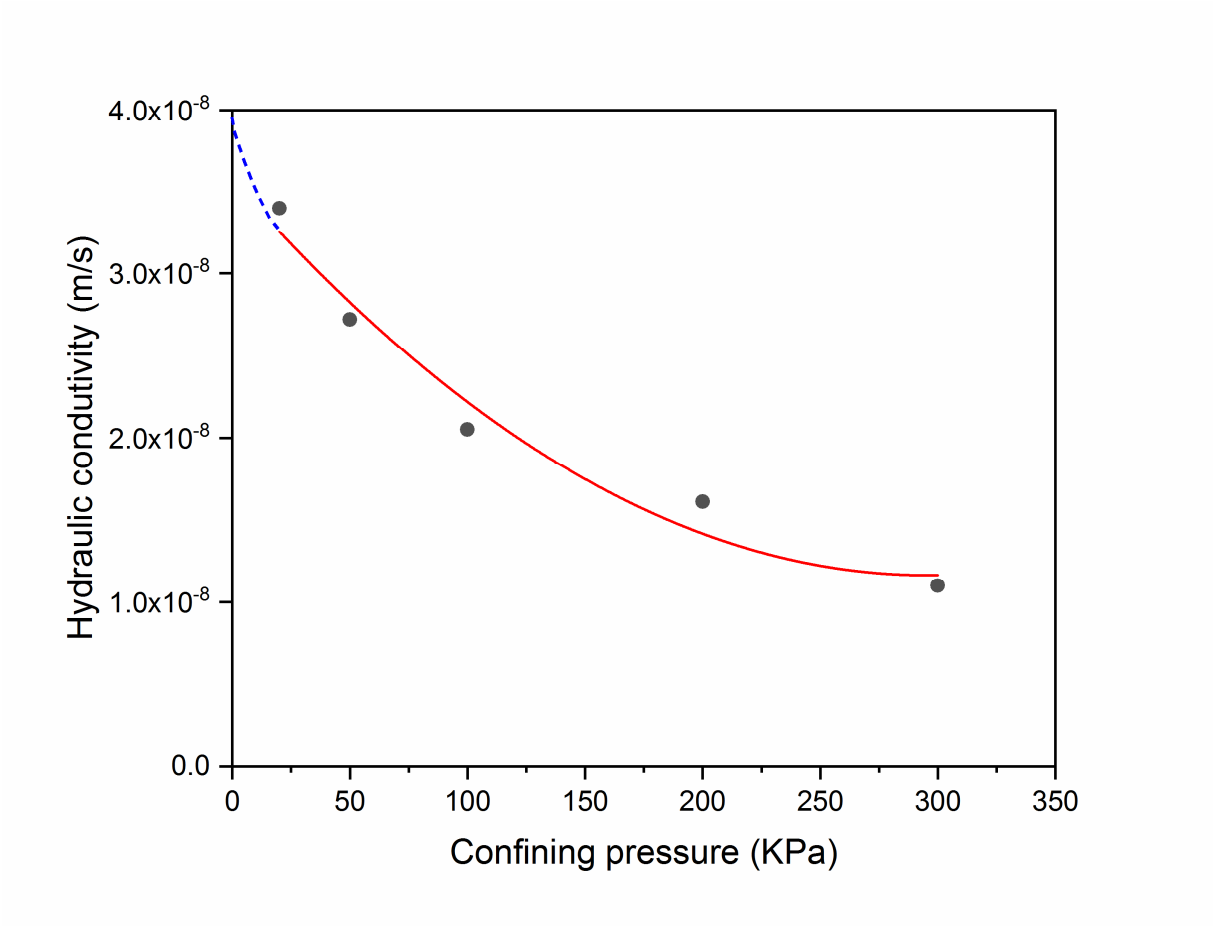


Fig.10. Example of measurement of the hydraulic conductivity for a formed cake (3.5 cm diameter and 3 cm high) at different confining pressures

Tables

Table 1. Mass of deposits in sand filled columns in the first 3 cm and between 3 and 30 cm depth

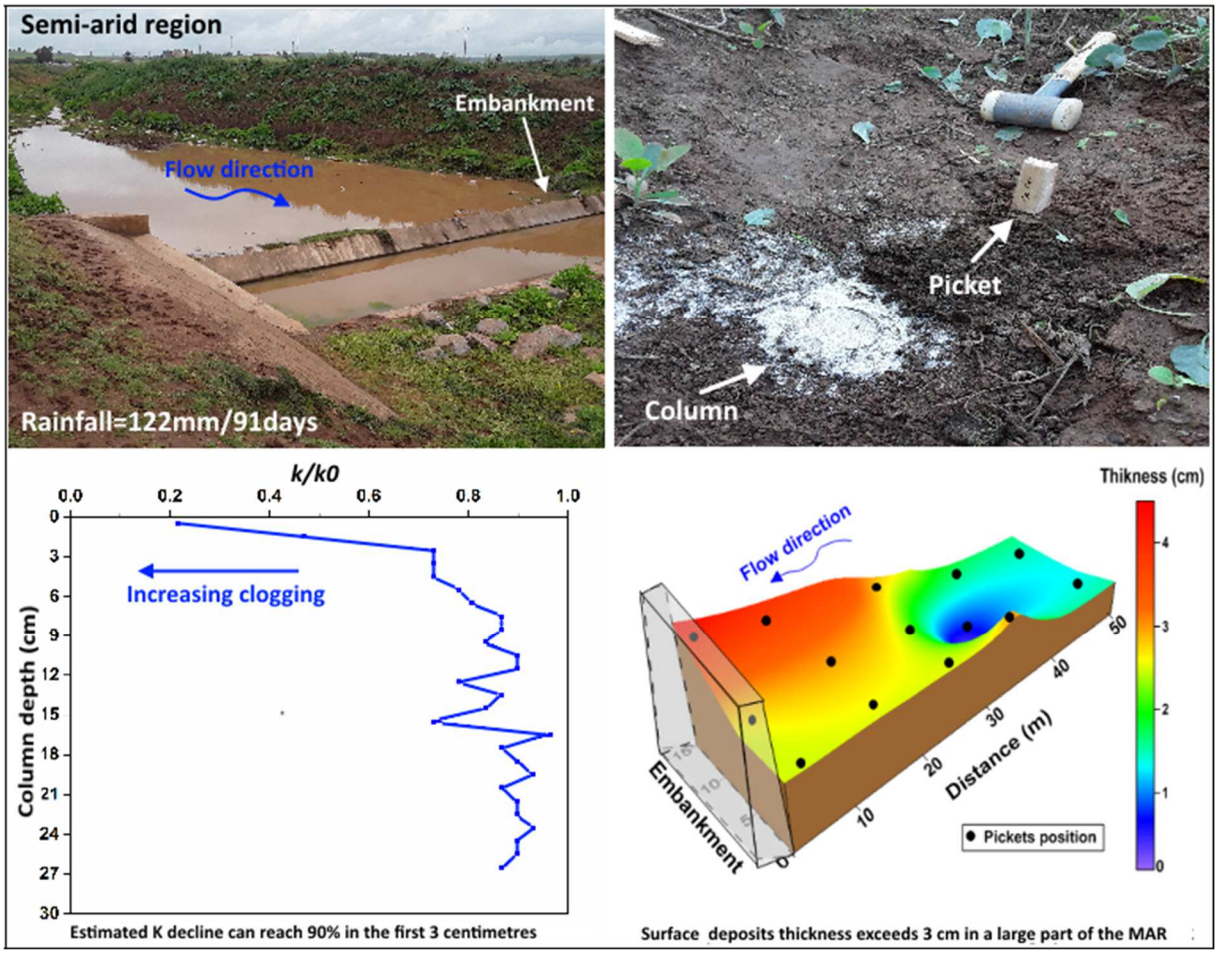
		Site S1					**Site S2**				**Site S3**		
Column number		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
Deposit Mass (g)	**0 - 3 cm**	10.4	46.1	13.9	10.8	26.9	10.6	8.0	22.7	18.3	5.3	8.3	14.3
	3 - 30 cm	51.1	95.6	34.2	48.0	65.1	41.5	30.2	45.1	65.3	28.0	19.0	27.7

Table2. Thickness of the deposited particles (cake) on columns surfaces

	S1					S2				S3		
Column	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
Cake thickness (cm)	4.0	2.5	0.7	0.5	2.0	3.0	3.0	0.5	0.5	7.0	2.8	0.0

Table 3. Size of the particles retained in depth and in surface (cake)

	(≤ 63 µm) (%)	(> 63 µm)(%)	d_{P10} (µm)	d_{P50} (µm)	d_{P90} (µm)
Particles retained in surface	66.0	34.0	2.1	24.7	409.0
Particles retained in depth	100.0	0.0	1.5	6.0	25.0


Semi-arid region
Embankment
Flow direction
Rainfall=122mm/91days
Picket
Column
k/k0
0.0
0.2
0.4
0.6
0.8
1.0
Column depth (cm)
0
3
6
9
12
15
18
21
24
27
30
Increasing clogging
Estimated K decline can reach 90% in the first 3 centimetres
Thikness (cm)
Flow direction
Embankment
Distance (m)
0
10
20
30
40
50
Pickets position
Surface deposits thickness exceeds 3 cm in a large part of the MAR