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Effects of long-term irrigation with treated wastewater. Part 1: evolution of soil physico-chemical properties.

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Abstract

The long-term impact of irrigation on a Mediterranean sandy soil irrigated with TWW (Treated Waste Water) since 1980 was evaluated. The main soil properties (CEC, pH, size distribution, exchangeable cations and chloride, hydraulic conductivity) as well as the organic matter and Cu, Cr and Pb speciation in an irrigated soil and a non-irrigated control soil at various soil depths were monitored and compared during a 2-a experiment. In this first part, the evolution of the physico-chemical soil properties are described. The irrigation with TWW was beneficial with regard to water and nutrient supplying. All the exchangeable cations other than K⁺ were higher in the irrigated soil than in the reference one. A part of the exchangeable cations was not fixed on the exchange complex but stored as labile salts or in concentrated soil solution. Despite the very sandy soil texture, both saturated and unsaturated hydraulic conductivity exhibited a significant diminution in the irrigated soil, but remained high enough to allow water percolation during rainy periods and subsequent leaching of accumulated salts, preventing soil salinization. In the irrigated soil, ESP (Exchangeable Sodium Percentage) exhibited high values (20% on average) and the soil organic C was lower than in the reference. No significant effect was noticed on soil mineralogical composition due to irrigation.

1. Introduction

Reclaimed water originating from wastewater treatment plants (treated wastewater, TWW) is becoming increasingly used for agricultural purpose such as irrigation, especially in arid and semi-arid regions and in highly populated areas. The TWW constitutes a reliable water and nutrients source for crops (Jiménez-Cisneros, 1995) and its use for irrigation reduces the amount of nutrient-rich waters returned to rivers or the sea. If irrigation with TWW offers many advantages, its use can however affect the physicochemical properties of the soils and consequently crop production (Feign et al., 1991; Chen et al., 2004). These effects depend not only on the quality of the irrigation waters but also on the soil type, the amounts of TWW used, the duration of irrigation and the local climate.

Salinity plays an important role in relation to organic as well as inorganic compound dynamics. Because of their high ionic strength, the TWW can carry significant amounts of potentially toxic metals usually found at trace concentrations, which can slowly accumulate up to critical levels (Yadav et al., 2002) causing crop contamination (Gupta et al., 2008). On the other hand, increasing salinity reduces organic complexation for most metals, due to increased competition for available sites (Mantoura et al., 1978), and thus induces metal displacement from the solid phase to the soil solution, allowing leaching to the aquifer (Lamy et al., 2006). Sodicity can affect the soil structure stability, reducing hydraulic conductivity and resulting in poor drainage (Gonçalves et al., 2007; Mandal et al., 2008), and can also affect the plant nutrition balance (Richards, 1954) as well as soil microbiological parameters (Ndiaye et al., 2006). Most of the papers dealing with the impact of irrigation with TWW on soil properties and metal mobility are based on a detailed, but incomplete set of data. In this study it was proposed to evaluate the long-term impact of irrigation on a Mediterranean sandy soil irrigated with TWW since 1980 from a comprehensive set of data. The main soil properties (CEC, pH, size distribution, pH, exchangeable cations and Cl⁻, hydraulic conductivity) as well as the organic matter and Cu, Cr and Pb speciation were monitored and compared in an irrigated soil and a non-irrigated control soil at various soil depths over a 2-a experiment. In this first part, the evolution of the physico-chemical soil properties are described, while the evolution of potentially toxic metals (PTM) and organic matter in soil are addressed in a second part.

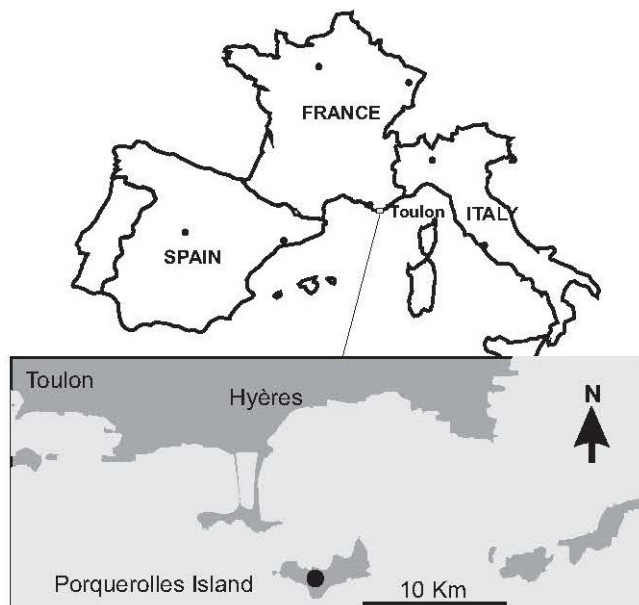


Figure 1 – Location of the experiment site

2. Materials and methods

2.1. Study area and collection of samples

The study area is located in the Porquerolles Island, south of France (Lat. 42°59'43"N and 6°12'09"S) (Fig. 1). The region has a Mediterranean climate, with a mean monthly air temperature ranging from 7.3 to 35.2°C, a monthly rainfall ranging from 1.1 to 174.1mm (Fig. 2), long periods of dryness that can extend to 5-6 months and frequent strong winds inducing high evaporation rates.

The studied irrigated soil is currently a peach trees orchard (*Prunus persica*). It is irrigated with a TWW originating from an activated sludge water treatment plant, followed by 3 successive polishing lagoons. The first is a 4000m², 1m depth microphytes lagoon; the second is a mixed lagoon which has a 1300m², 1m depth microphytes area and a 700m², 0.3m depth macrophytes area; the third one consists of a 4000m², 0.3m depth macrophytes lagoon. The TWW used for irrigation was pumped out at the exit of the third lagoon (L₃). As the Porquerolles Island population increases by a factor of 100 or more every summer, the primary wastewater volume and, consequently, the TWW composition change through the year. Depending on the population demand, the groundwater pumping induced an uplift of seawater which mixed with fresh groundwater, resulting in abnormally saline water in the distribution network and thus a more saline TWW.

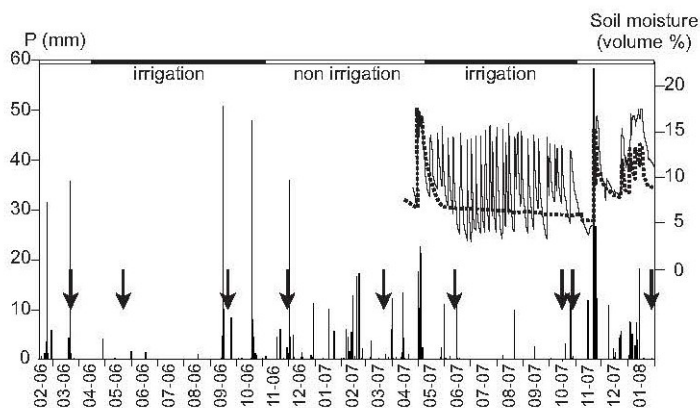


Figure 2 – Rainfall and soil moisture. Vertical lines give every daily rain. Vertical arrows indicate the sampling days. Dotted line gives the soil moisture at 20 cm in soil P_{ref}, continuous line the soil moisture at 20 cm in soil P.

A drip irrigation system was used, with lines running along the peach tree rows and two drippers situated 50cm on both side of each tree; flux per dipper was around 8.4 L.h⁻¹. The applied volume of TWW was dependent on the aridity of the climate: the irrigation system was stopped during winter and in summer after rainy periods; during arid periods, irrigation was applied for 8 to 10 h/day once a week, sometimes twice a week during the driest periods (August 2007 for example), depending on the opinion of the crop technical staff. Rainfall and irrigation frequency can be directly deduced

from the humidity monitored at 20cm depth at each station, the irrigated and the reference one (Fig. 2). No fertilizers were applied to either soil during the experiment.

Soil samples were collected at 3 depths (0-20, 20-40 and 40-60 cm) at two sites, P and P_{ref}. The point P was located under irrigated peach trees and within the wetting area of the drippers. The point P_{ref} was located in a non-irrigated area, 4 m away from point P, covered with natural grassland. Despite the differences in vegetation cover, P_{ref} is considered hereafter as a reference, as no better sampling point was available within the area. The sampling dates (22/03/06; 22/05/06; 21/09/06; 29/11/06; 22/03/07; 12/06/07; 16/10/07; 28/10/07, 28/01/08) were chosen to be roughly every 3 months. The second sampling in October, 2007 was performed to evaluate the effect of a short but intense rainfall event after 4 months of dryness.

2.2. Chemical analysis of the TWW

The TWW was analysed in situ for pH and electrical conductivity (EC), then filtered and poisoned with NaN₃ immediately after sampling to avoid microbial development. The filtrate was analysed for Cu, Cr, Pb and Cd using graphite furnace atomic absorption spectrometry (GF-AAS, Thermo Electron FS95). A Shimadzu TOC-5000A analyzer was used for DOC (dissolved organic C) analysis. Exchangeable cations (K⁺, Na⁺, Ca²⁺, NH₄⁺ and Mg²⁺) and anions (Cl⁻, NO₃⁻, HPO₄⁻ and SO₄²⁻) were determined by ion chromatography (Dionex DX-120 and DX 500). Detection limits were 0.5 mg L⁻¹ for K⁺, Na⁺, Ca²⁺, Mg²⁺ and HPO₄⁻ and 0.07 ppm for NH₄⁺, NO₃⁻ and Cl⁻.

2.3. Physico-chemical analysis of soil

The air-dried soil was passed through a 2 mm sieve prior to analysis. Soil pH was determined both in water and KCl 0.1 M, in suspensions consisting of a 1:5 soil:solution ratio according to the NF ISO 10390 method. Particle size distribution was determined by laser granulometry (Mastersizer Malvern 2-18) after destruction of the organic matter with 30% H₂O₂. Exchangeable cations K⁺, Na⁺, Ca²⁺, NH₄⁺ and Mg²⁺ were extracted according to a standard method with Co hexamine chloride (Orsini and Remy, 1976). 2.5 g of soil were extracted with 50 mL of [Co(NH₃)₆]³⁺ solution at 5 meq/L and shaken for 2 h at room temperature. The supernatant was analyzed by ion chromatography. The CEC was given by difference between the initial amount of Co and that remaining in solution after ion exchange with the sample, using an UV spectrophotometry at 473 nm. Chloride was extracted from 2.5 g of soil with 50 mL of ammonium acetate 1 mol.L⁻¹, and quantified by ion chromatography. The sodium absorption ratio (SAR) (Richards, 1954) and the exchangeable sodium percentage (ESP) were calculated using the following formulae:

$$S = \frac{R \left[\frac{[N]}{[C^{2+}] + [M^{2+}]} \right]^a}{\sqrt{[C^{2+}] + [M^{2+}]}} \quad \text{and} \quad ESP = 100 \frac{[Na]}{CEC}$$

where cation concentrations are expressed in mmol.L⁻¹. Soil organic C (SOC) was measured with a Shimadzu TOC-5000A analyzer. Mineralogical identification was done by X-ray diffraction (XRD) spectroscopy with Cu-K α radiation (PHILIPS PW1200) on powder samples finely crushed in a tungsten carbide mill.

2.4 Soil moisture monitoring

Soil moisture and soil water potential were monitored from April 2007 to November 2008 by in-situ instrumentation. Moisture capacitive sensors (SDEC HMS 9000) and tensiometers (SDEC SMS 2500S) were installed at 20, 40 and 60 cm depth, with 3 sensors at each depth for both P and P_{ref} soils. Data were stored in an OTT Logosens2 station-manager and sent to the laboratory by GSM-Data. They allowed the calculation of the soil hydraulic balance over 6 months, from May to October, 2006.

2.5 Soil hydraulic conductivity

The soil hydrodynamic properties were measured on undisturbed samples taken on 1237cm³ steel cylinders (H=7cm, R=7,5cm). The saturated hydraulic conductivity (K_s) was determined by using 3 different hydraulic head gradients, the volume of water passed throughout the sample being measured after 2 h at every head gradient applied. The unsaturated hydraulic was determined by the Wind evaporation method (Wind, 1968; Tamari et al., 1993) using a SDEC apparatus equipped with SDEC220 ceramics, a Campbell CR10X logger and the ESPAS software (Mohrath et al., 1997).

2.6. Statistical analysis

In order to evaluate the correlations between the parameters on the whole data set obtained over the 2 a-long monitoring, a Principal Component Analysis (PCA) was performed using MATLAB.

3. Results and discussion

3.1. Chemical properties of the TWW

The TWW used to irrigate the peach trees was of domestic origin. The chemical characteristics of the TWW at different periods of the years are given on Table 1. The TWW pH ranged from 7.1 to 8.6 and the median was 8.2. It was within the acceptable interval for irrigation, which ranges from 6.0 to 9.0. Some near-the-limit values (8.6 in March 2006) confirm the necessity of monitoring because of possible nutritional imbalance (Ayers and Westcot, 1985). The average value of the EC (Electric Conductivity) of the TWW was 1458 μ S.cm⁻¹, a high value which is higher than the limit

recommended by the European Commission for water effluent used for irrigation ($300 \mu\text{S}\cdot\text{cm}^{-1}$). The average Na^+ and Cl^- values were 114 and $343 \text{ mg}\cdot\text{L}^{-1}$, respectively, while the maximum Na^+ and Cl^- values were 163 and $564 \text{ mg}\cdot\text{L}^{-1}$, respectively. According to Ayers and Westcot (1985), these values result in restrictions for agricultural use, most of the time slight to moderate with regard to Na^+ but high with regard to Cl^- . With regard to the levels considered as critical for irrigation water by the European Union, most of the time, the Na^+ concentration remained below the $150 \text{ mg}\cdot\text{L}^{-1}$ limit whereas the Cl^- concentration was over the $200 \text{ mg}\cdot\text{L}^{-1}$ limit. It must be noted, however, that peach trees are Na-sensitive (FAO, 1973).

Table 1. Chemical characteristics of treated wastewater (TWW). n.d., not determined; n.f. not found. *Limit concentrations tolerated by the European Commission for irrigation water (Catchment Management Agencies, recommendation 91-692)

measured parameter	March 06	June 06	Sept. 06	Nov. 06	Jan. 07	March 07	CMA*
pH (± 0.2)	8,6	8,3	7,1	8,1	7,3	8,2	6.5-8.4
EC (± 20)($\mu\text{S}\cdot\text{cm}^{-1}$)	n.d.	1478	1319	1652	1306	1536	$300 \mu\text{S}\cdot\text{cm}^{-1}$
DOC (± 0.01)($\text{mg}\cdot\text{L}^{-1}$)	28,08	11,91	11,37	2,66	7,58	9,05	n.f
Na^+ (± 0.01)($\text{mg}\cdot\text{L}^{-1}$)	98,56	89,56	121,7	163,05	111,59	99,84	$150 \text{ mg}\cdot\text{L}^{-1}$
NH_4^+ (± 0.02)($\text{mg}\cdot\text{L}^{-1}$)	40,58	55,67	38,56	72,63	66,67	41,54	$5 \text{ mg}\cdot\text{L}^{-1}$
K^+ (± 0.03)($\text{mg}\cdot\text{L}^{-1}$)	17,84	15,97	27,48	61,45	20,59	18,22	$12 \text{ mg}\cdot\text{L}^{-1}$
Mg^{2+} (± 0.03)($\text{mg}\cdot\text{L}^{-1}$)	24,43	9,32	15,45	75,81	13,42	11,3	$50 \text{ mg}\cdot\text{L}^{-1}$
Ca^{2+} (± 0.03)($\text{mg}\cdot\text{L}^{-1}$)	59,11	27,62	45,53	5,53	36,46	35,6	$50 \text{ mg}\cdot\text{L}^{-1}$
SAR (± 0.02)	2,72	3,76	3,98	3,93	4,02	3,70	6.00-12.00
Cl^- (± 0.02)($\text{mg}\cdot\text{L}^{-1}$)	392	424,8	263,4	340,93	274,54	564,41	$200 \text{ mg}\cdot\text{L}^{-1}$
NO_3^- (± 0.02)($\text{mg}\cdot\text{L}^{-1}$)	33,4	37,8	11,6	3,6	6,31	4,66	$50 \text{ mg}\cdot\text{L}^{-1}$
HPO_4^- (± 0.005)($\text{mg}\cdot\text{L}^{-1}$)	0,84	1,201	2,601	0,031	0,041	0,04	$5 \text{ mg}\cdot\text{L}^{-1}$
SO_4^{2-} (± 0.05)($\text{mg}\cdot\text{L}^{-1}$)	358,9	221,8	58,8	198,43	194,25	242,83	$250 \text{ mg}\cdot\text{L}^{-1}$
Cr (± 0.05)($\mu\text{g}\cdot\text{L}^{-1}$)	0,15	0,17	n.d	n.d	n.d	n.d	$50 \mu\text{g}\cdot\text{L}^{-1}$
Cd (± 0.05)($\mu\text{g}\cdot\text{L}^{-1}$)	0,022	0,23	0,13	0,53	n.d	0,22	$5 \mu\text{g}\cdot\text{L}^{-1}$
Cu (± 0.05)($\mu\text{g}\cdot\text{L}^{-1}$)	6,2	7,67	3,88	8,84	3,23	5,76	$50 \mu\text{g}\cdot\text{L}^{-1}$
Pb (± 0.05)($\mu\text{g}\cdot\text{L}^{-1}$)	5,28	0,25	n.d	n.d	0,33	0,57	$50 \mu\text{g}\cdot\text{L}^{-1}$

Regarding major nutrients, average values were 27, 25 and $35 \text{ mg}\cdot\text{L}^{-1}$ for K^+ , Mg^{2+} and Ca^{2+} , respectively, 212 and $0.8 \text{ mg}\cdot\text{L}^{-1}$ for SO_4^{2-} and HPO_4^{2-} , respectively, and 16 and $53 \text{ mg}\cdot\text{L}^{-1}$ for NO_3^- and NH_4^+ , respectively. Intervals of variation within the 2-a measurements were higher by a factor of 3 for all of these ions except NH_4^+ which varied within a factor of 1.9. The SO_4^{2-} , NO_3^- and NH_4^+ values were high when compared to other studies (Vazquez-Montiel et al., 1996). The Na^+ , K^+ and

Mg²⁺ concentrations were well correlated ($R^2 > 0.8$). The Cl⁻ concentration exhibited a high range of variation, from 263.4 to 564.4 mg.L⁻¹, and was uncorrelated with alkaline cations, which the authors are unable to explain. The SAR varied from 2.7 to 4.1, which is under the limit recommended by the European Commission for irrigation water (6.0 to 12.0). When compared to EC and according to NRCS (2008) these values indicate, however, slight to moderate restriction for use.

The DOC values varied from 3 to 28 mg.L⁻¹, with an average of 12 mg.L⁻¹, indicating that the TWW was a source of organic matter for the irrigated soil. The PTM concentrations were far below the limits established by the European Commission for water effluent continuously used for irrigation. These low concentrations were expected because of the domestic origin of the wastewater.

In conclusion, the effluent showed a high temporal variability but represented a source of major nutrients, except P. Its Na⁺ and Cl⁻ contents indicate a possible risk of soil salinization. The PTM contents are lower than the recommended values, but do not exclude a risk of accumulation over time in soils, which justifies monitoring of soil metal content.

3.2. Effects of long-term use of TWW on soil properties

The main chemical and physical properties of the soils and their evolution with time are given in Table 2. Sulphate, PO₄³⁻ and NO₃⁻ ions were under the limit of detection for all samples and thus will not be discussed further.

Table 2. Physico-chemical properties of both soils P and Pref as affected by duration of treated wastewater application and soil depth. FSil: fine silt, CSil: coarse silt, FSa: fine sand, CSa: coarse sand

Depth	Particle-size distribution					pH		SOC	Exchangeable Cations					ESP	CEC
	Clay	Fsil	Csil	Fsa	Csa	pH _w	pH _{KCl}		Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	NH ₄ ⁺		
	% ± 0.1					± 0.2		% ± 0.02	meq.kg ⁻¹ ± 0.1					± 0.3	meq.kg ⁻¹ ± 0.1
<i>March 2006</i>															
P 0-20	1.0	2.4	4.7	31.3	60.6	7.7	6.1	0.42	5.1	2.9	9.5	16.3	13.9	40	12.6
P 20-40	1.2	3.7	3.3	29.4	62.3	7.8	6.3	0.38	3.7	2.1	7.0	17.3	13.7	44	8.4
P 40-60	1.1	3.5	4.0	24.4	67.0	7.7	6.4	0.38	3.6	2.0	7.1	15.4	16.4	42	8.4
Pref 0-20	1.2	2.3	6.0	26.8	63.4	6.9	6.0	0.68	2.0	5.4	6.0	14.3	5.6	31	6.6
Pref 20-40	1.8	4.0	5.1	27.7	60.0	6.9	5.7	0.31	1.8	4.6	5.8	12.5	5.2	22	8.4
Pref 40-60	2.8	7.4	3.2	25.1	61.6	6.9	5.6	0.29	2.1	5.0	4.9	14.8	5.7	28	7.2
<i>May 2006</i>															
P 0-20	0.6	1.6	1.3	30.8	65.7	6.9	6.1	0.44	3.9	3.1	9.7	21.5	13.6	27	14.4
P 20-40	0.5	2.5	1.4	26.6	69.1	6.9	6.0	0.39	4.6	2.0	7.6	20.0	13.0	31	15.0
P 40-60	0.6	2.9	1.4	28.4	66.7	7.0	6.0	0.35	2.9	1.0	8.1	16.8	11.7	22	13.2
Pref 0-20	1.4	5.8	2.9	27.0	70.0	6.8	5.9	0.83	2.0	4.0	7.5	17.7	5.5	16	12.0
Pref 20-40	2.6	4.9	3.4	24.4	64.6	6.9	5.8	0.65	1.6	3.9	7.5	14.9	1.9	10	16.8
Pref 40-60	2.9	6.5	4.4	24.6	61.6	6.9	5.8	0.62	1.8	3.0	7.5	16.4	1.4	17	10.8
<i>September 2006</i>															
P 0-20	2.1	2.7	3.0	33.2	52.8	8.4	7.1	0.52	2.5	1.6	7.5	10.1	1.4	26	9.6
P 20-40	1.8	3.6	3.7	34.0	57.0	7.7	6.5	0.53	2.2	1.6	7.7	9.8	1.9	20	10.8
P 40-60	1.2	3.8	3.3	32.3	58.5	7.6	6.1	0.27	3.0	2.2	5.6	9.4	0.8	28	10.8
Pref 0-20	2.9	3.4	3.7	33.8	57.3	6.7	5.7	0.58	1.0	4.6	6.5	5.5	4.2	13	7.8
Pref 20-40	2.4	4.2	4.0	39.6	49.8	6.8	5.5	0.37	0.6	4.0	4.4	5.6	4.2	5	12.0
Pref 40-60	2.7	4.7	5.0	41.9	45.7	6.8	5.7	0.46	0.9	3.6	4.6	5.5	4.2	8	11.4
<i>November 2006</i>															
P 0-20	1.1	3.0	2.5	35.7	57.7	7.6	6.3	0.49	3.2	3.5	8.8	18.8	5.2	7	42.6
P 20-40	1.7	2.97	2.3	40.3	52.7	7.7	6.3	0.43	3.2	3.5	8.4	15.7	5.1	10	31.8
P 40-60	1.3	3.0	2.5	40.4	52.8	7.5	6.1	0.31	2.9	3.4	7.4	13.4	5.0	12	24.6

Pref 0-20	1.9	3.5	3.4	34.6	56.6	6.6	5.5	0.77	2.8	3.4	7.1	9.1	5.0	8	34.2	
Pref 20-40	2.6	4.7	4.4	37.0	51.2	6.6	5.2	0.49	2.7	3.3	7.6	8.7	4.9	8	35.4	
Pref 40-60	3.5	4.6	4.3	37.8	49.8	6.7	5.1	0.44	2.8	3.2	7.2	8.4	6.1	9	30.0	
<i>May 2007</i>																
P 0-20	1.9	3.5	3.9	38.0	56.6	7.2	6.3	0.51	4.6	2.5	7.2	16.6	9.1	16	28.2	
P 20-40	2.0	3.8	3.8	38.1	56.1	7.4	6.1	0.32	3.6	1.0	4.3	10.9	3.5	8	46.8	
P 40-60	2.6	3.6	3.7	32.8	63.5	7.1	6.4	0.19	3.9	2.2	5.7	12.1	6.3	16	24.6	
Pref 0-20	2.1	4.1	4.4	36.0	43.4	6.8	5.5	0.62	2.5	4.0	7.8	15.1	5.9	10	24.6	
Pref 20-40	2.2	4.6	6.0	32.8	55.2	6.8	5.2	0.41	2.4	4.4	5.0	10.9	4.3	7	37.2	
Pref 40-60	3.3	8.2	5.9	37.3	54.2	6.5	5.5	0.44	2.4	4.3	6.3	16.5	5.9	8	28.2	
<i>June 2007</i>																
P 0-20	1.3	2.1	3.2	38.2	55.2	7.8	6.6	0.42	4.4	5.9	13.4	14.6	9.4	41	10.8	
P 20-40	1.4	2.2	3.2	34.9	61.6	7.4	6.8	0.35	3.7	5.6	13.0	22.7	11.4	36	10.2	
P 40-60	2.4	2.9	3.8	33.5	63.4	7.0	6.9	0.28	5.2	6.5	12.5	14.4	7.0	51	10.2	
Pref 0-20	2.2	4.7	4.3	38.6	47.3	6.3	5.6	0.92	2.7	3.6	8.9	18.7	6.5	22	12.0	
Pref 20-40	3.0	4.1	5.7	34.7	56.5	5.9	5.4	0.51	2.3	2.5	7.3	16.0	6.2	25	9.0	
Pref 40-60	3.5	5.4	5.6	32.4	53.1	5.8	5.1	0.36	3.0	3.8	8.1	17.9	5.2	38	7.8	
<i>October 16 - 2007</i>																
P 0-20	1.6	3.4	3.2	33.4	58.4	7.8	6.3	0.44	1.1	3.0	8.8	19.7	8.1	10	11.4	
P 20-40	2.6	4.7	3.5	34.0	55.1	7.4	5.9	0.39	1.0	4.0	7.2	16.7	7.6	10	9.6	
P 40-60	2.2	4.1	3.3	32.8	57.7	7.0	5.8	0.29	1.6	2.4	6.7	13.6	5.9	19	8.4	
Pref 0-20	2.1	4.2	3.5	34.8	55.3	6.6	5.2	1.11	1.2	4.6	5.0	13.2	6.0	7	18.0	
Pref 20-40	2.3	4.4	3.8	38.3	51.2	6.8	5.0	0.49	1.5	4.6	5.0	13.1	5.7	12	12.6	
Pref 40-60	1.5	3.5	4.1	37.5	53.2	6.9	5.5	0.40	1.1	4.9	4.0	13.6	7.5	10	10.8	
<i>October 28 - 2007</i>																
P 0-20	1.2	2.3	3.9	35.9	56.8	7.2	6.6	0.63	2.0	4.2	6.7	16.1	4.6	3	66.0	
P 20-40	1.6	3.3	4.0	35.6	56.5	7.3	5.8	0.34	1.2	2.7	5.1	14.0	3.4	2	54.0	
P 40-60	2.6	4.6	4.3	32.5	56.0	7.7	5.6	0.28	1.6	2.5	6.1	13.4	1.7	3	58.2	
Pref 0-20	3.8	3.6	5.6	35.9	54.2	6.7	5.3	0.91	1.2	5.9	5.7	12.1	4.3	2	60.6	
Pref 20-40	4.0	5.3	6.1	30.5	52.1	6.4	4.9	0.48	1.2	4.5	4.4	9.4	3.4	2	61.2	
Pref 40-60	2.7	4.5	3.9	34.4	54.6	7.0	5.0	0.24	0.9	3.0	3.4	7.4	2.6	1	61.8	
<i>January 2008</i>																
P 0-20	1.14	2.34	1.73	28.68	66.09	6.8	5.8	0.4	4.1	5.4	9.8	21.9	8.0	6	69.6	
P 20-40	1.09	2.25	1.9	37.92	56.05	6.8	6.0	0.35	2.3	2.7	7.8	23.6	5.2	4	51.6	
P 40-60	0.77	1.55	1.44	32.7	63.5	6.0	5.4	0.27	2.0	2.4	5.2	18.0	4.6	4	48.6	
Pref 0-20	1	1.91	1.66	36.95	58.84	6.0	5.5	0.71	1.3	4.8	4.5	19.1	4.6	2	54.6	
Pref 20-40	1.66	2.62	1.65	40.16	55.45	5.8	5.4	0.51	0.6	4.8	7.8	16.4	4.5	1	52.2	
Pref 40-60	1.71	2.54	1.57	35.54	58.74	5.8	5.1	0.24	1.0	3.3	6.2	11.4	2.7	3	33.6	

3.2.1. Soil texture and hydraulic conductivity

Both soils have a coarse sandy texture, without noticeable variations with depth. The average of the sum of clay and silt fractions within the top 60 cm of soil is 8.1% for P and 11.8% for P_{ref}. Despite the very sandy soil texture, the hydraulic conductivity exhibited great differences between the two studied soils. The saturated hydraulic conductivity (K_{sat}) at 30 cm in depth was 6.4 and 38.2 mm.h⁻¹ for the P and P_{ref} soils, respectively. The unsaturated hydraulic conductivity ($K(h)$) expressed in mm.h⁻¹ was properly described for values of h comprised between -0.15 and -5 mH₂O by the following linear regressions, where h is the head pressure expressed in water column metre [mH₂O]:

$$\text{Log}(K(h)) = -2.26 \text{Log}(-h) - 3.52 \quad \text{for the P soil } (R^2=0.98)$$

$$\text{Log}(K(h)) = -2.26 \text{Log}(-h) - 1.44 \quad \text{for the P}_{ref} \text{ soil } (R^2=0.99)$$

These results indicate a significant difference between the P and P_{ref} soils over the whole range of measured head pressure, in spite of their close granulometry. Such a decrease in hydraulic conductivity after irrigation has been found by numerous authors (Vinten et al., 1983; Vandevivere and Baveye, 1992; Tarchitzly et al., 1999; Gonçalves et al., 2007), but was unexpected with soil having a very sandy texture. This can be related to aggregate breakdown, dispersion of the finer

fraction and collapse of the porosity due Na^+ accumulation in the soil exchange complex. The hydraulic conductivity, however, remains high in the irrigated soil and the risk of soil waterlogging can be discarded. During rainy periods, the high hydraulic conductivity favours the leaching of accumulated salts, preventing excessive salinization. On the other hand, the risk of salinization of the aquifer has to be considered with regard to the total amount of water percolating in depth.

The lower content of clay and silt fractions in the P soil could indicate an impoverishment of the fine fractions in the irrigated soil, which could be due to washing out of the fine particles released by dispersion. This process is likely favoured in soil P with regard to soil P_{ref} , because the total amount of water input in soil P is the sum of irrigation and rainfall, while soil P_{ref} is only subjected to rainfall. This likely only occurs after the heaviest rains, because the hydric balance (Table 3) indicates that, from May to October 2006 the cumulative infiltration in the P soil was negligible. Any conclusion, however, has to be considered with caution because of the lack of geostatistical data on soil texture variability. It must also be noted that the whole experiment and especially the hydric balance was performed during an exceptionally dry period with 603 mm of cumulative rainfall over 2 a, from February 2006 to January 2008, while the average annual rainfall over the last 20 a was around 450 mm.

Table 3. Soil hydric balance from May to October, 2006. Values in mm H_2O .

	Soil P	Soil P_{ref}
Irrigation	450	0
Rainfall	138	138
Cumulative infiltration (-) or capillary rise (+)	-4	+38
Soil moisture variation	-4.3	-4.3
Evapotranspiration	-580	-173

3.2.2. Soil mineralogy

XRD analyses were conducted for both soils on samples taken from 0-20, 20-40 and 40-60 cm. No significant differences were found between P and P_{ref} . The diffractograms indicated the dominance of quartz, in agreement with the sandy texture of the soil, and the presence of illite, smectite, hematite, vermiculite and MnO_2 , especially in the deeper layer (60cm). The proportion of illite was slightly higher at depth (3 % at 0-20 cm and 20-40 cm versus 6 % at 40-60 cm, for both soils).

3.2.3. Soil pH

The soil pH measured in water (pH_w) was systematically more acidic in P_{ref} than in P. As no basic amendment input was added to the P soil, it can be concluded that irrigation with TWW raised the soil pH by approximately 0.8 units. Variations of pH_w with time affected P soil (from 6.85 to 8.35)

to a larger extent than for P_{ref} soil (from 6.74 to 6.94). Increases of soil pH under irrigation with TWW have been previously reported by Mancino and Pepper (1992), who found that irrigation with TWW raised the soil pH by 0.1 to 0.2 units when compared with irrigation with drinking water. These authors attributed such a pH rise to (i) the high content of basic cations such as Na⁺, Ca²⁺ and Mg²⁺ of the TWW, which raised the alkaline reserve of the soil, and (ii) an enhanced rate of denitrification that produced hydroxyl ions. These two processes are likely to have occurred in the present case.

The difference between pH_w and the pH measured in KCl solution (pH_{KCl}) indicates the presence of an acidity reserve. For most cases this reserve increased with depth, despite a decrease of organic matter content (for example, ΔpH=1.27, 1.22 and 1.52 for 0-20, 20-40 and 40-60cm, respectively, for the P soil in September 2006). A closer look at the pH_{KCl} values shows a strong drop with depth following rain after a long dry period (September 2006 and October 28th 2007), especially for the irrigated soil. This could be related to the leaching of basic cations, which would indicate efficient desalinization by heavy rain.

3.2.4. Soil organic matter

Individual values of soil organic C (SOC) for each of the sampling periods are given in Table 2 and average, maximum and minimum values are given in Table 4. The SOC was lower in the irrigated soil than in the reference one (average of all samples 0.38% for P_{ref} versus 0.55% for P). Such a diminution, despite the organic C supplied by the TWW, has been observed elsewhere (Polglase et al., 1995; Gloaguen et al., 2007) and is likely related to an intensification of microbial activity due to labile C and N supplied by the TWW.

Table 4. Soil organic C values expressed in %

Depth	Average	Max	Min
P 0-20	0.47	0.63	0.40
P 20-40	0.39	0.53	0.32
P 40-60	0.29	0.38	0.19
Pref 0-20	0.79	1.11	0.58
Pref 20-40	0.47	0.65	0.31
Pref 40-60	0.39	0.62	0.24

3.2.5. Exchangeable ions and CEC

Variations of the exchangeable cations with time are explained by the combined effects of supply from irrigation, aerosols, rains or fertilizers, supply by capillary transfers, leaching after heavy rains and root uptake. Input of nutrient cations from weathering of minerals is unlikely because of the very low content of Na⁺, K⁺, Ca²⁺ or Mg²⁺ bearing minerals in the soils.

Table 5. Average values for exchangeable cations and CEC expressed in meq.kg⁻¹

Depth	Na ⁺	K ⁺	Mg ⁺⁺	Ca ⁺⁺	NH ₄ ⁺	CEC
P 0-20	3,4	3,5	9,0	17,3	8,1	29
P 20-40	2,8	2,8	7,6	16,7	7,2	26
P 40-60	2,9	2,7	7,2	14,0	6,6	23
Pref 0-20	2,0	4,5	6,6	13,9	5,2	26
Pref 20-40	1,6	4,1	6,1	11,9	4,5	27
Pref 40-60	1,8	3,8	5,8	12,4	4,6	22

The average values for exchangeable Na⁺, Mg²⁺, Ca²⁺ and NH₄⁺ (given in Table 5) and most of the individual values for each sampling period (Table 2) were higher for soil P compared to soil P_{ref}, indicating that the TWW input for these species was higher than the plant uptake. In contrast, the K⁺ concentrations were lower in soil P when compared to soil P_{ref}, indicating that high Ca²⁺ and Mg²⁺ concentrations in the TWW likely enhanced K⁺ uptake by the peach trees or favoured K⁺ leaching by competing for adsorption on soil surfaces.

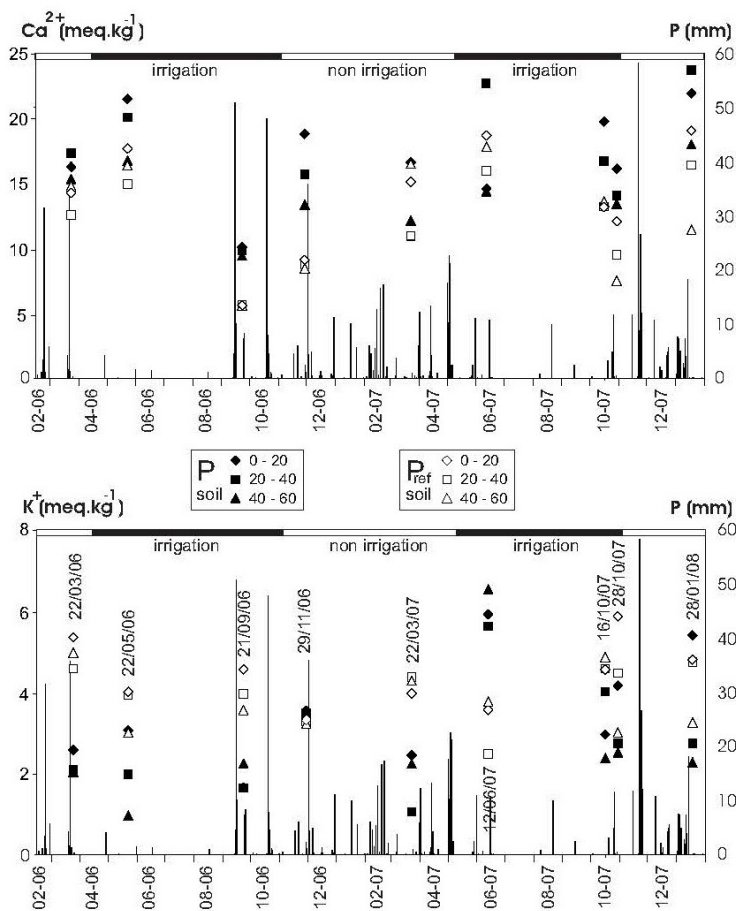


Figure 3 – Exchangeable K⁺ and Ca²⁺ for soil P and soil P_{ref}. Vertical lines indicate every daily rain.

Figure 3 gives shows variations with time for the exchangeable cations Ca^{2+} and K^+ . Looking at the differences between the 23/03/06 and the 22/05/06 sampling times, it has to be noted that the period between those dates was dry, that irrigation begun at the beginning of April and that the vegetation was in phenological growth stage resulting in high root uptake. The exchangeable Ca^{2+} increased between the two sampling periods in both P and P_{ref} soils, due to TWW input for the P soil and to capillary transfer for the P_{ref} soil. The exchangeable K^+ decreased, likely mainly due to root uptake. The heavy rain (more than 50mm) just before the 21/09/06 sampling resulted in both soils being leached of exchangeable Ca^{2+} and other exchangeable cations except K^+ , as observed in other studies (Nielsen and Stevenson, 1983). Such leaching, but to a lower extent, was also observed between the 16/10/07 and the 28/10/07 samples, a 12mm rain event having occurred between these two dates. The rainy periods without irrigation before the 22/03/07 sampling resulted in similar exchangeable Ca^{2+} values in both soils, while the exchangeable K^+ diminished more in the P soil than in the P_{ref} soil, indicating a greater leaching during this period of low growth rate. Calcium and K^+ behaviour at the beginning of the 2007 irrigation period was similar to that observed in 2006.

It must be noted that the study soils, because of their low clay content, have a low buffering capacity with regard to adsorbed species. This helps to explain the higher values for exchangeable Ca^{2+} and Mg^{2+} with regard to Na^+ , despite the higher TWW supply for this latter cation. During evaporation, the more soluble Na^+ cations can remain in solution when Ca^{2+} and Mg^{2+} precipitate as labile minerals such as calcite, magnesite or mixed carbonates or even magnesium chloride (Laribi and Alzubaidi, 2007). Sodium is then able to be more easily leached in depth during short draining events.

The average exchangeable Cl^- was 149, 141 and 161 meq.kg^{-1} for the 0-20, 20-40, 40-60 cm horizons of soil P, respectively, and 123, 114 and 119 meq.kg^{-1} for the corresponding horizons of soil P_{ref} . As these values were high compared to the other ions, they were checked and confirmed by the Mohr method. Despite these high values, a good correlation was found ($R^2 > 0.96$) for each horizon between Cl^- and Na^+ . Chloride is usually not adsorbed or held back by soils, it moves easily with soil water, is taken up by roots and accumulates in leaves. If the Cl^- concentration in the leaves exceeds the tolerance of the crop, injury symptoms develop such as leaf burn or drying of leaf tissue (Eaton, 1942). During arid periods, however, it can precipitate as magnesium chloride in a first step, then as halite (Laribi and Alzubaidi, 2007). As for Na^+ , the highest exchangeable Cl^- values were found in the third layer of the irrigated soil and, as for most cations, a diminution of exchangeable Cl^- was observed immediately after heavt rain events, indicating efficient leaching.

The CEC values of both soils were quite low, but in the higher range as calculated for the clay, organic matter and coarse silt fraction content (Turpault et al., 1996). No clear correlations, however, were found between the CEC and the organic matter or the clay content. Average values given in

Table 4 show no significant differences between P and P_{ref} soils. Most of the time, the CEC values were lower than the sum of average exchangeable Na⁺, K⁺, Mg²⁺ and Ca²⁺, especially for soil P, indicating that part of the exchangeable cations was not fixed on the exchange complex but stored as labile salts or in concentrated soil solution, as is usual for saline soils.

Sodium levels in soils are often reported as exchangeable sodium percentage (ESP) while in irrigation or soil waters they are reported as the sodium adsorption ratio (SAR). ESP for the P soil ranged from 2 to 51% (20% on average) while for the P_{ref} soil it ranged from 1 to 38% (12% on average). These are high values, considering that soils that have more than 6% ESP are considered to have structural stability problems related to potential clay dispersion (van de Graaff and Patterson, 2001), which is in accordance with the results concerning hydraulic properties explained previously. However, the high exchangeable Ca²⁺ and Mg²⁺ and the fact that the CEC values were lower than the sum of average exchangeable cations likely lower the Na⁺ dispersion capacity.

3.3. Statistical analysis

The PCA analysis achieved from the results of all the samples showed a clear distinction between soils P and P_{ref} (Fig. 4a). 42% of the variance is explained by the first two factorial axes. This relatively low percentage is due to distinctive behaviour between samples from the P and P_{ref} soils. The discriminating parameters between the two classes of samples can be evaluated by the relative position of the gravity centre of each parameter with regard to the position of the gravity centres of the classes P and P_{ref} (Fig. 4b). The construction of the P_{ref} class is mainly determined by textural parameters, confirming that the textural differences between the two soils are significant, and by K⁺, confirming the different behaviour of this cation compared to the others. The construction of the P class is mainly determined by the higher values for Cl⁻, pH_w, pH_{KCl}, Na⁺.

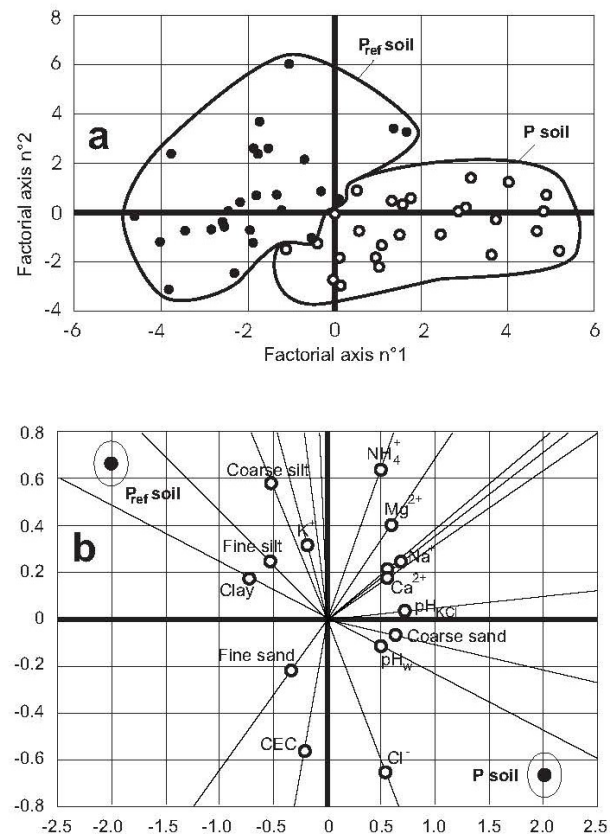


Figure 4 – Statistical results from all samples: a – Projection of data on the 1st and 2nd factorial axis diagram; b – Relative positions of gravity centers

4. Conclusions

Irrigation of a very sandy Mediterranean soil with TWW was beneficial with regard to water and nutrient supplies; all the exchangeable cations other than K^+ were higher in the irrigated soil than in the reference one. A part of the exchangeable cations was not fixed on the exchange complex but stored as labile salts or in concentrated soil solution, which is common under arid conditions.

Despite the very sandy texture of the irrigated soil studied, both saturated and unsaturated hydraulic conductivity exhibited a significant diminution in the irrigated soil compared to the reference one. The conductivity values remained, however, high enough to allow water percolation during rainy periods and the subsequent leaching of accumulated salts, preventing excessive soil salinization. On the other hand, this would allow salt or other solute transfer down to the water table at depth.

The decrease of the hydraulic conductivity can be related to high ESP values, 20% on average for the irrigated soil. However, the fact that the exchangeable Ca^{2+} and Mg^{2+} remained high and that the CEC values were lower than the sum of average exchangeable cations likely lower the Na^+ dispersion capacity. The soil organic C values were also lower in the irrigated soil than in the reference one, which is likely related to an intensification of microbial activity due to labile C and N supply by the TWW. Such a decrease of SOC is also able to favour the changes.

No significant effect on soil mineralogical composition due to irrigation was noted.

The results presented in this first part, focused on the physicochemical soil properties, will be used in a second part for a better understanding of PTM and organic matter dynamics under long-term irrigation with TWW.

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