Generalization and formalization of the US EPA procedure for design of treated wastewater aquifer recharge basins: II. Retrofit of Souhil Wadi (Nabeul, Tunisia) pilot plant

Hamadi Kallali, Mitsuo Yoshida, Jamila Tarhouni and Naceur Jedidi

ABSTRACT

The 'Cap Bon' peninsula in Tunisia suffers from intensive tourist activities, high demographic increase and industrial development. As groundwater had been for a long time the main water source, aquifers had been subject to a severe depletion and seawater intrusion. Despite the measures taken prohibiting new drillings and water carrying by the construction of a waterway linking the region to the north-west region of Tunisia, the problem of water shortage persists. Artificial recharge of groundwater with treated wastewater has been decided as a technique to replenish the region aquifers. A pilot plant was constructed in the early 1980s in Souhil Wadi (Nabeul) area. Many experiments have been carried out on this plant and have led to controversial opinions about its performance and its impact on groundwater contamination. This contribution concerns the application of the procedure that we developed from the generalization and the formalization of the United States Environmental Protection Agency (US EPA) methodology for the design of treated wastewater aquifer recharge basins. This upgrading procedure implemented in a spreadsheet, has been used to retrofit the Souhil Wadi facility in order to improve its performance. This method highlighted the importance of the safety factor to estimate wastewater infiltration rate from clean water permeability measurements. It has, also, demonstrated the discordance between the initial design parameters of Souhil Wadi facility and their current status as they have changed with time and the infiltration capacity of the basins has been affected by clogging. Indeed, it has been demonstrated that with the current state of clogging of the basins, the design infiltration rate limited by the most restrictive layer (6.1 cm/hr) corresponds to 22% of the surface infiltration rate reached after a drying period of 10 d, which means that we need more basins to absorb the daily loading rate. The design method leads to the construct ion of five basins of 961 m^2 (31×31 m) each, with one basin being flooded for 3 d with 27 cm of water daily and rested for 10 d. The current status is completely different as only four basins are constructed with 324 m^2 each. Many actions in the short, medium and long term have been advised in order to improve the system performance.

Key words | aquifer recharge, clogging, hydraulic loading rate, retrofit, safe factor, treated wastewater, wet/dry cycle

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INTRODUCTION

The 'Cap Bon' peninsula (Tunisia) suffers from intensive tourist activities, high demographic increase and industrial development. These factors provoked an over-exploitation of coastal aquifers inducing a pronounced saline intrusion (Kallali *et al.* 2007; Trabelsi *et al.* 2011). Despite the measures taken prohibiting new drillings and water carrying by the construction of a waterway linking the region to the north-west region of Tunisia, the problem of water shortage persists. An integrated water management including wastewater reuse became a necessity to ensure a sustainable development. After successful applications around the world (Murray 2009), treated wastewater reuse in agriculture and in artificial recharge of groundwater has been decided as techniques for water resources shortage attenuation and for replenishing

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the region's aquifers. The main challenge is to reach a zero discharge of treated wastewater in order to provide the farmers with sufficient water and avoid coastal waters pollution. A pilot plant was constructed in the early 1980s in Souhil Wadi (Nabeul) area (Rekaya 1986). Many experiments have been carried out on this plant and have led to controversial opinions about its performance and its impact on groundwater contamination (Mahjoub *et al.* 2009). In this work, we applied the generalized and formalized procedure of the US EPA design methodology (US EPA 2006) developed by Kallali *et al.* (2013). This method, implemented in a spreadsheet, has been used to retrofit the Souhil Wadi facility in order to improve its performance.

MATERIAL AND METHODS

Description of the facility

The Souhil Wadi facility for treated wastewater aquifer recharge is located in the area of Nabeul (north-east Tunisia). The site is composed of four infiltration basins constructed on an area of approximately 2,000 m^2. The basins are marked as B1, B2, B3 and B4 (Figure 1). The geometry of the basins is almost square with approximately 324 m^2 (18×18 m) of infiltrative area. The walls have a slope of 45 degrees and are covered with a geotextile sheet (bidim) to avoid the crumblings. The average depth of these basins is about 1.5 m. Each basin is equipped with a supply flow meter and a limnimetric ladder for the follow-up of water ponding. The groundwater pollution is monitored with several piezometers around and far downstream of the facility.

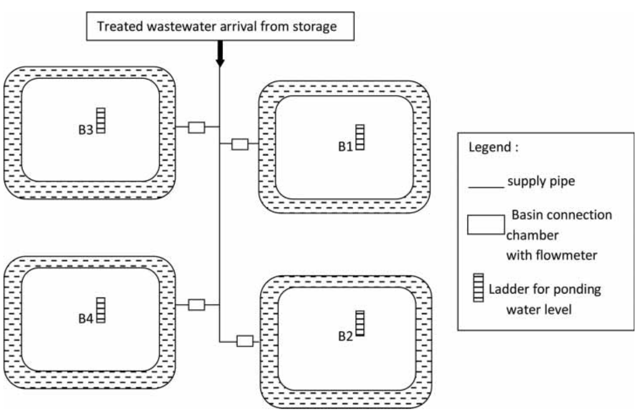

Figure 1 | Layout of the recharge basins in Souhil Wadi Facility.

Site geologic description

The borehole is located at the centre of the pilot plant. The exact position is identified by global positioning system (GPS) as 36°27′22″N, 10°42′02″E. It consists of a 30 m deep borehole (φ10 cm) penetrated using a rotary drilling machine. According to the observations, the subsurface strata can be divided into two geologic units; the upper unconsolidated sand-gravel layers ('Upper Unit') correlated to Late Quaternary are composed of unconsolidated coarse sediments such as sand, coarse sand, and gravel layers, and the lower consolidated silt-clay beds ('Lower Unit') correlated to Tertiary marine strata (Bensalem & Taamallah 1995; Elmejdoub & Jedoui 2009) are constituted by well-consolidated silt to clay sediments. The water table was measured around 10 m in depth. Unconsolidated sand and gravel layers in the Upper Unit are the porous media for groundwater circulation, and consolidated silt and clay beds in the Lower Unit play a role of hydrogeological basement (Kallali & Yoshida 2002).

Permeability measurement method

In order to measure the permeability of subsurface sediments, we collected eight non-disturbed samples (labelled from P1 to P8) from the borehole cores.

We employed two different methods for laboratory permeability tests: the Constant Head Test (CHT) for coarse grained samples and the Falling Head Test (FHT) for fine grained samples (ASTM Standard D2434-68 2006; ASTM Standard D5084-03 2003).

Infiltration rate recovery

We performed a field measurement of the infiltration rate with clear water inside a basin. We employed the double ring method with FHT. The method is described in the US Environmental Protection Agency (1981) Process Design manual. The measurements are made daily after 3 d of basin submersion with treated wastewater.

RESULTS AND DISCUSSION

The experimental results were used to apply the formalized and generalized form of the US EPA design methodology (US EPA 2006) developed by Kallali *et al.* (2013) in order to retrofit the facility design and optimize its operation.

Permeability measurement results and determination of the annual hydraulic loading rate

The results of laboratory permeability tests are summarized in Table 1. The permeability varies from 10^{-4} to 10^{-5} m/sec for silty sand and gravel in the Upper Unit while less than 10^{-9} m/sec for silt and clay in the Lower Unit.

The results are in concordance with further investigations on the region; indeed, Rekaya (1986) estimated that the vadose zone thickness varies from 10 to 13 m, the aquifer thickness from 2 to 3 m and the aquifer permeability estimation based on granulometry 10^{-4} to 10^{-5} m/sec.

US EPA calculation method

The lowest value for the saturated permeability (K_s) measured on borehole core samples taken in the lithologic layers is 1.7×10^{-5} m/sec, which corresponds to a 5 m deep layer.

The clean water infiltration rate, K_v, in cm/hr, calculated from the literal transformation of K_s reaches 6.1 cm/hr. We calculate the clean water annual loading rate (L_{cw}) as:

$$L_{cw}\ (\text{m/yr}) = K_v\ (\text{cm/hr})\ (24\ \text{hr/d})\ (365\ \text{d/yr})\ (1\ \text{m}/100\ \text{cm}) = 534\ \text{m/yr}$$

The adjustment or safety factor recommended for laboratory permeability measurements ranges from 4 to 10%. As the restrictive layer is located at 5 m depth, wastewater quality will be improved and we can assume a safety factor of 10% is adequate. We can, thus, calculate the wastewater annual loading rate (L_{ww}) by:

$$L_{ww}\ (\text{m/yr}) = (0.10) \times 534 = 53.4\ \text{m/yr}$$

The designed 6-month loading rate will be set to:

$$L_{ww}\ (\text{m/yr}) = (6/12)\ (53.4) = 27\ \text{m/6 months.}$$

Generalized calculation method

In order to take into account seasonal variation of K_v, we applied the water temperature effect calculation given by Lin et al. (2003). K_v is measured in autumn and the average water temperature is as follows: winter 15 °C, spring 25 °C, summer 35 °C and autumn 20 °C. If we attribute to winter, spring, summer and autumn the indices 1, 2, 3 and 4 respectively, we have for our case:

$(K_v)_1 = 5.6$, $(K_v)_2 = 6.9$, $(K_v)_3 = 8.7$ and $(K_v)_4 = 6.1$ cm/hr

The operation fractions of day for all seasons are: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 10/24 = 0.42$.

The operation fractions of seasons are: $\alpha_1 = 1$ (winter), $\alpha_2 = 0.66$, $\alpha_3 = 0$ and $\alpha_4 = 0.33$.

The number of days by season are: $D_{WI} = 90$, $D_{SP} = D_{SU} = 92$ and $D_{AU} = 91$ d/yr.

The treated wastewater aquifer recharge facility of Souhil Wadi is operated only in the rainy period (November–April) when there is no need for irrigation. As the facility is not equipped with automated operation devices, manual operation concerns only 10 hr per day.

The numbers of operation days by season are:

$$D_1 = \alpha_1 D_{WI} = 1 \times 90 = 90\ \text{d}$$
$$D_2 = \alpha_2 D_{SP} = 0.66 \times 92 = 61\ \text{d}$$
$$D_3 = \alpha_3\ D_{SU} = 0 \times 92 = 0\ \text{d}$$
$$D_4 = \alpha_4 D_{AU} = 0.33 \times 91 = 30\ \text{d.}$$

The period of application is: $D_A = D_1 + D_2 + D_3 + D_4 = 181$ d/yr.

Table 1 | Results of permeability measurements and their correspondent clear water infiltration rates for the lithologic layers

Sample Reference	Depth, m	Measurement method	Temperature, °C	$K_{20\,°C}$*, m/s	K_v, cm/hr
P1	2.5	CHT	27	1.36×10^{-4}	49.03
P2	4.0	CHT	27	2.04×10^{-4}	73.55
P3	5.0	CHT	26	1.70×10^{-5}	6.10
P4	6.5	CHT	26	2.16×10^{-5}	7.80
P5	10.5	CHT	26	5.22×10^{-5}	18.80
P6	13.0	CHT	26	6.13×10^{-5}	22.06
P7	17.0	FHT	26	1.59×10^{-9}	Impermeable
P8	18.5	FHT	26	2.84×10^{-9}	Impermeable

*Indoor measured permeability at 20 °C.

$(L_{cw})_1 = 0.24\ \beta_1 D_1\ (K_v)_1 = 0.24 \times 0.42 \times 90 \times 5.6 = 50.8$ m
$(L_{cw})_2 = 0.24\ \beta_2 D_2\ (K_v)_2 = 0.24 \times 0.42 \times 61 \times 6.9 = 42.4$ m
$(L_{cw})_4 = 0.24\ \beta_4 D_4\ (K_v)_4 = 0.24 \times 0.42 \times 30 \times 6.1 = 18.4$ m
$L_{cw} = 50.8 + 42.4 + 18.4 = 112$ m/6 months.

If we consider that the same method is used in permeability measurement, the safety factors are: $\sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 = \sigma = 0.1$ and the seasonal application rates are: $(L_{ww})_1 = 0.10 \times 50.8 = 5$ m, $(L_{ww})_2 = 0.10 \times 42.4 = 4$ m, $(L_{cw})_4 = 0.10 \times 18.4 = 2$ m.

The total rate for the 6-month operation is: $L_{ww} = (0.10)$ (112 m/yr) = 11 m/6 months.

Infiltration rate recovery results and determination of the wet/dry cycles

Figure 2 shows the measured *in situ* saturated permeability evolution versus the number of days of resting after 3 d of wetting.

Figure 3 shows the percentage of recovery of the initial permeability measured before the basin operation of 3 d.

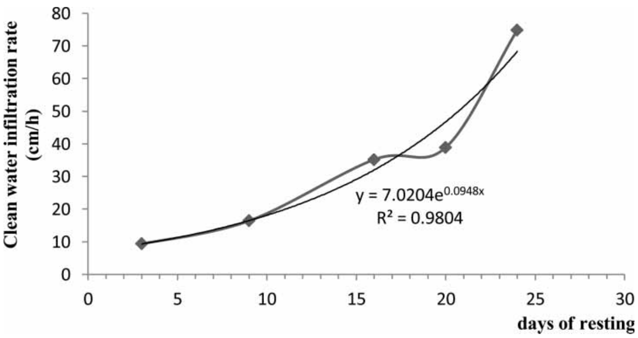

Figure 2 | Increase of the clean water infiltration rate with resting days.

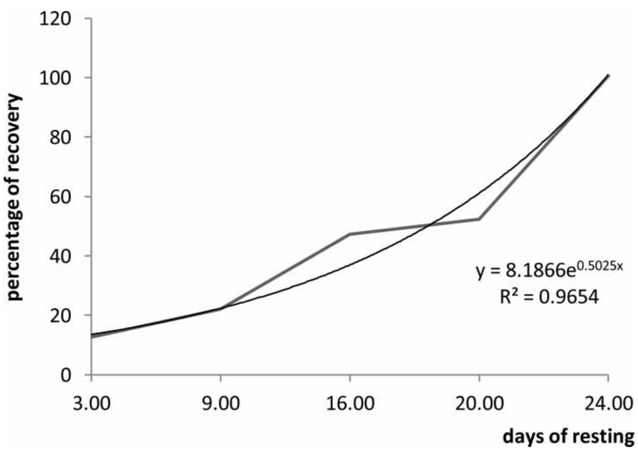

Figure 3 | Percentage of recovery of the clean water infiltration rate with resting days.

We notice that the full recovery of the initial permeability is obtained only after 24 d of resting.

Based on US EPA recommendations

In order to maximize the infiltration, the US EPA procedure (US EPA 1981) recommends a cycle of 3 d of dosing for 10 d of resting in winter and only 5 d of resting for 3 d of flooding in summer.

Based on experimental results

The basin experiment has shown that 24 d are necessary to recover the initial clean water infiltration rate after 3 flooding days (Figure 3). According to this first interpretation, the wet/dry cycle has to be 3/24 and the ratio (τ) of wetting days (D_w) to drying days (D_d) is equal to 0.125. But we notice a big difference between the permeability results for those obtained by the rings' method operated *in situ* at the bottom of the basin and for those obtained by indoor measurement for the most restrictive layer. Indeed, the former gives a clean water infiltration rate of 70 cm/hr, which gives an estimated wastewater infiltration rate of 2.8 cm/hr (with a safety factor of 4%), and the latter gives a clean water infiltration rate equal to 6.1 cm/hr and its corresponding wastewater infiltration rate of 0.61 cm/hr (with a safety factor of 10%). As the latter has to be considered for design, this means that we need a resting time just to recover only 22% of the initial infiltration rate. Referring to Figure 3, 22% of recovery corresponds to 10 d of rest. Therefore, the wet/dry cycle will be 3/10 as recommended by the US EPA for winter and $\tau = 0.3$. However, the experiment has been performed in March (spring); so for winter we have to slightly extend the resting period to 12 d and maintain the same cycle in autumn.

For our case, the cycle number of days (D_C) for a given season is:

$(D_C)_1 = (D_w)_1 + (D_d)_1 = 3 + 12 = 15$ and $\tau_1 = 0.25$
$(D_C)_2 = (D_w)_2 + (D_d)_2 = 3 + 10 = 13$ and $\tau_2 = 0.3$
$(D_C)_4 = (D_w)_4 + (D_d)_4 = 3 + 10 = 13$ and $\tau_4 = 0.3$

Evaluation of the seasonal number of cycles

US EPA calculation method

We have:

- Summer period (April, 30 d): 3 d wet for 5 d dry for a cycle of 8 d.

- Winter period (November–March, 151 d): 3 d wet for 10 d dry for a cycle of 13 d.

The number of cycles in summer: 30/8 = 3.75 rounded up to 4 cycles.

The number of cycles in winter: 151/13 = 11.6 rounded up to 12 cycles.

The total cycles per 6 months: 4 + 12 = 16.

Generalized calculation method

The number of cycles in winter: $(N_C)_1 = \text{ROUND}\ [\alpha_1\ D_1/(D_C)_1] = \text{ROUND}\ [1\times 90/15] = 6$ cycles.

The number of cycles in spring: $(N_C)_2 = \text{ROUND}\ [\alpha_2\ D_2/\ (D_C)_2] = \text{ROUND}\ [0.66\times 92/13] = 5$ cycles (4.7 rounded up to 5).

The number of cycles in autumn: $(N_C)_4 = \text{ROUND}\ [\alpha_4\ D_4/(D_C)_4] = \text{ROUND}\ [0.33\times 91/13] = 2$ cycles (2.3 rounded down to 2).

The total cycles per 6 months: $N_C = 6 + 5 + 2 = 13$.

First reiteration of the calculated parameters

After the rounding of the number of cycles by season, the further calculated parameters have to be recalculated accordingly.

Recalculation of the operating days

The operating days by season become:

$D_1^* = (N_C)_1\ (D_C)_1 = 6\times 15 = 90$ d
$D_2^* = (N_C)_2\ (D_C)_2 = 5\times 13 = 65$ d
$D_4^* = (N_C)_4\ (D_C)_4 = 2\times 13 = 26$ d
$\alpha_1^* = 1$ (winter), $\alpha_2^* = 0.71$ and $\alpha_4^* = 0.29$

The total period of application:

$$D_A^* = \alpha_1^*\ D_1^* + \alpha_2^*\ D_2^* + \alpha_4^*\ D_4^* = 1\times 90 + 0.71\times 92 + 0.29\times 91 = 181\ \text{d/yr}$$

Recalculation of the seasonal and annual hydraulic loading rates

$(L_{cw})_1^* = 0.24\ \beta_1 D_1^*\ (K_v)_1 = 0.24\times 0.42\times 90\times 5.6 = 50.8$ m
$(L_{cw})_2^* = 0.24\ \beta_2 D_2^*\ (K_v)_2 = 0.24\times 0.42\times 65\times 6.9 = 45.2$ m
$(L_{cw})_4^* = 0.24\ \beta_4 D_4^*\ (K_v)_4 = 0.24\times 0.42\times 26\times 6.1 = 16$ m
$L_{cw}^* = 50.8 + 45.2 + 16.0 = 112$ m/6 months

and

$(L_{ww})_1^* = 0.10\times 50.8 = 5.1$ m, $(L_{ww})_2^* = 0.10\times 45.2 = 4.5$ m,
$(L_{cw})_4^* = 0.10\times 16.0 = 1.6$ m
$L_{ww}^* = (0.10)\ (112\ \text{m/yr}) = 11$ m/6 months.

The seasonal hydraulic loading rates by cycle

The loading rate, by cycle, is given by:

$(L_C)_1 = (L_{ww})_1^*\ /\ (N_C)_1 = 5/6 = 0.85$ m
$(L_C)_2 = (L_{ww})_2^*\ /\ (N_C)_2 = 4.5/5 = 0.9$ m
$(L_C)_4 = (L_{ww})_4^*\ /\ (N_C)_4 = 1.6/2 = 0.8$ m.

The seasonal daily hydraulic loading rates

As the flooding days are the same for all seasons and equal to 3, the seasonal daily loading rates are given by:

$(L_D)_1 = (L_C)_1/3 = 0.85/3 = 0.28$ m/d
$(L_D)_2 = (L_C)_2/3 = 0.9/3 = 0.3$ m/d
$(L_D)_4 = (L_C)_4/3 = 0.8/3 = 0.27$ m/d.

Determination of the seasonal daily application area

The seasonal daily application area ($(A_D)_i$) is given by:

$$(A_D)_i = (Q_D)_i/(L_D)_i$$

where $(Q_D)_i$ is the daily flow rate for a season i.

In our case, the flow rate is constant at 260 m^3/d for all seasons; the daily application area is therefore given by:

$(A_D)_1 = 260/0.28 = 929\ m^2$
$(A_D)_2 = 260/0.3 = 867\ m^2$
$(A_D)_4 = 260/0.27 = 975\ m^2$

Second reiteration of the calculated parameters

As the autumn required area of 975 m^2 is the biggest, it will be retained in the basins' construction and the further calculated parameters have to be reevaluated accordingly.

Recalculation of the daily hydraulic loading rates

The seasonal daily loading rates are given by:

$$(L_D)_1^* = (L_D)_2^* = (L_D)_4^* = Q_D/(A_D)_4 = 260/975 = 0.27\ \text{m/d}$$

Recalculation of the hydraulic loading rates by cycle

The seasonal loading rates by cycle are given by:

$(L_C)_1^* = (L_C)_2^* = (L_C)_4^* = 3\times (L_D)_4^* = 3\times 0.27$ m/d $= 0.8$ m/cycle.

Recalculation of the seasonal and annual hydraulic loading rates

The seasonal loading rates are given by:

$(L_{ww})_1^{**} = (L_C)_1^*(N_C)_1 = 0.8 \times 6 = 4.8$ m
$(L_{ww})_2^{**} = (L_C)_2^*(N_C)_2 = 0.8 \times 5 = 4.0$ m
$(L_{ww})_1^{**} = (L_C)_4^*(N_C)_4 = 0.8 \times 2 = 1.6$ m

The annual loading rate becomes:

$L_{ww}^{**} = 4.8 + 4 + 1.6 = 10.4$ m

Determination of the number of basin sets and total application area

US EPA calculation method

The recommended cycles are:

- Summer period (April, 30 d): 3 d wet for 5 d dry for a cycle of 8 d.
- Winter period (November–March, 151 d): 3 d wet for 10 d dry for a cycle of 13 d.

The recommended minimum number of basins corresponding to summer period is three and for winter the adopted cycle is five. The total number to be constructed will be five.

Formalized calculation method

The total number of basins by season is given by: $(N_T)_i = 1 + \tau_i/n_i(D_d)_i$

$(N_T)_1 = ((1 + \tau_1)/n_1)\ (D_d)_1 = ((1 + 0.25)/3) \times 12 = 5$
$(N_T)_2 = ((1 + \tau_2)/n_2)\ (D_d)_2 = ((1 + 0.3)/1) \times 10 = 13$
$(N_T)_4 = ((1 + \tau_2)/n_4)\ (D_d)_4 = ((1 + 0.3)/1) \times 10 = 13$

The total number to be constructed will be 13. But as $1/\tau = 3.33$ is not entire, the total number of basins will not be a multiple of the operating basins set in order to assure the rotation in the cycle. As we have no storage basin available, we will adopt the winter cycle for all the periods (3:12) and the number of required basins will be five.

The numbers of operating and resting basins by day for all seasons are:

$N_{OB} = D_w/n = 3/3 = 1$ and $N_{RB} = D_d/n = 12/3 = 4$.

The infiltrative area of a basin is given by: $975/1 = 975$ m^2 and the total infiltrative area is: $975 \times 5 = 4{,}875$ m^2, but in order to have square basins, the basin side is taken as the entire value of the square root of the area: $l_S = 31$ m, and the basin area becomes 961 m^2 and the total infiltrative area becomes $961 \times 5 = 4{,}805$ m^2.

Third reiteration of the calculated parameters

Number of cycles recalculation

As the days of a cycle are fixed for all seasons to 15 (3 flooding days and 12 resting days), the number of cycles will be:

in winter: $(N_C)_1^* = \text{ROUND}\ [\alpha_1\ D_1/(D_C)_1] = \text{ROUND}\ [1 \times 90/15] = 6$ cycles.
in spring: $(N_C)_2^* = \text{ROUND}\ [\alpha_2\ D_2/(D_C)_2] = \text{ROUND}\ [0.66 \times 92/15] = 4$ cycles.
in autumn: $(N_C)_4^* = \text{ROUND}\ [\alpha_4\ D_4/(D_C)_4] = \text{ROUND}\ [0.33 \times 91/15] = 2$ cycles.

The total cycles per 6 months: $N_C^* = 6 + 4 + 2 = 12$.

Number of operating days recalculation

$D_1^{**} = 6 \times 15 = 90$ d and $\alpha_1^{**} = 1$, $D_2^{**} = 4 \times 15 = 60$ and $\alpha_2^{**} = 0.65$, $D_4^{**} = 2 \times 15 = 30$ and $\alpha_4^{**} = 0.33$.

The period of application: $D_A^{**} = D_1^{**} + D_2^{**} + D_4^{**} = 180$ d/yr.

Recalculation of the daily hydraulic loading rates

The seasonal daily loading rates are given by:

$(L_D)_1^{**} = (L_D)_2^{**} = (L_D)_4^{**} = Q_D/\ (A_D)_4 = 260/961 = 0.27$ m/d

Recalculation of the hydraulic loading rates by cycle

The seasonal loading rates by cycle are given by:

$(L_C)_1^{**} = (L_C)_2^{**} = (L_C)_4^{**} = 3 \times (L_D)_4^{**} = 3 \times 0.27$ m/d $= 0.8$ m/cycle.

Recalculation of the seasonal and annual hydraulic loading rates

The seasonal loading rates are given by:

$(L_{ww})_1^{***} = (L_C)_1^{**}(N_C)_1^* = 0.8 \times 6 = 4.8$ m
$(L_{ww})_2^{***} = (L_C)_2^{**}(N_C)_2^* = 0.8 \times 4 = 3.2$ m
$(L_{ww})_1^{***} = (L_C)_4^{**}(N_C)_4^* = 0.8 \times 2 = 1.6$ m

The annual loading rate becomes:

$L_{ww}^{***} = 4.8 + 4 + 1.6 = 10.4$ m/6 months

Table 2 | Wastewater characteristics and treatment efficiency of Dar Chaâbane and Béni Khiar (SE4) WWTPs

Year	Sample	Statistics	pH	Electric conductivity (mS/cm)	Chloride (mg/l)	SS (mg/l)	COD (mg/l)	BOD_5 (mg/l)	TKN (mg/l)
1988 (Amami 1988)	Influent	Average	7.3	2.87	633	736	1472	536	77
		Min	7.0	2.60	554	240	752	332	70
		Max	7.7	3.23	738	1317	2329	624	80
	Effluent	Average	7.8	3.12	773	21	93	14	77
		Min	7.6	2.78	625	6	59	9	75
		Max	8.0	3.58	1184	40	126	19	84
	Mean efficiency rate (%)		–	–	–	97	93	97	0
2001 (Kallali 2001)	Influent	Average	7.9	2.94	386	345	597	448	86
		Min	7.8	2.64	304	82	372	160	57
		Max	8.0	3.23	446	692	779	740	111
	Effluent	Average	7.7	3.09	438	71	114	67	66
		Min	7.6	2.64	394	7	27	5	27
		Max	8.1	3.39	479	380	569	175	84
	Mean efficiency rate (%)		–	–	–	65	75	88	18

SS: suspended solids; COD: chemical oxygen demand; BOD: biochemical oxygen demand; TKN: total Kjeldhal nitrogen.

Wastewater characteristics and determination of BOD and SS loading rates

Table 2 gives the wastewater characteristics at the inlet and outlet of the WWTP for different years of the plant operation. We noticed that the plant performance worsens with time due to plant overloading.

The average BOD loading rate is: $260 \times 10^3 \times 67 \times 10^{-3} = 17{,}420$ g/d which corresponds to about 18 g(m^2·d) or 180 kg(ha·d). As the flooding days are: $3 \times 12 = 36$ d, the 6-month BOD loading is about 627 kg or 16,100 kg/ha.

The average SS loading rate is: $260 \times 10^3 \times 71 \times 10^{-3} =$ 18,460 g/d which corresponds to about 19 g/((m^2·d) or 190 kg/(ha·d). As the flooding days are: $3 \times 12 = 36$ d, the 6-month SS loading is about 682 kg or 17,061 kg/ha.

As typical loading rates vary from 6,000 to 46,000 kg (ha·yr) (US EPA 1981), we consider that the BOD and SS loadings are not limiting factors.

CONCLUSION AND PERSPECTIVES

The iterative method of calculation, achieved by formalizing the expert knowledge acquired by many years of installations operation in the United States, has been implemented in the case of the Souhil Wadi (Nabeul, Tunisia) treated wastewater aquifer recharge facility in order to retrofit its design and improve its operation.

Concerning field experiments, it has been demonstrated that with the current state of clogging of the basins, the design infiltration rate limited by the most restrictive layer (6.1 cm/hr) corresponds to 22% of the surface infiltration rate reached after a drying period of 10 d, which means that we need more basins to absorb the daily loading rate.

The design method leads to the construction of five basins of 961 m^2 (31×31 m) each, with one basin flooded for 3 d with 27 cm of water daily and rested for 10 d. The current status is completely different as only four basins are constructed with 324 m^2 each. The following steps should be implemented in order to optimize the facility operation:

- Automate the feeding system of the facility in order to allow a 24 hr operating of the basins and reach the 27 m/6 months of rate calculated by the US EPA method.
- Scarify the basins' bottoms in order to shorten the needed days of rest by increasing the infiltration rate.
- Reconsider the safety factor for the determination of design wastewater infiltration rate from the most restrictive layer permeability as the water attaining this layer is largely devoid of suspended solids after going through 5 m depth of vadose zone.

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