Removal improvement of bacteria (*Escherichia coli* and enterococci) in maturation ponds using baffles

A. Ouali, H. Jupsin, J. L. Vasel, L. Marouani and A. Ghrabi

ABSTRACT

Korba wastewater treatment plant is a conventional activated sludge followed by three maturation ponds (MP1, MP2, MP3) in series acting as a tertiary treatment. The first study of wastewater treatment plants showed that the effluent concentration of *Escherichia coli* and enterococci at the outlet of the (MP3) varies between 10^3 and 10^4 CFU/100 ml. After the hydrodynamic study conducted by Rhodamine WT which showed short-circuiting in the MP1, two baffles were introduced in the first maturation pond (MP1) to improve the hydrodynamic and the sanitary performances. The second hydraulic study showed that the dispersion number '*d*' was reduced from 1.45 to 0.43 by this engineering intervention and the Peclet number was raised from 0.69 to 2.32. The hydraulic retention time was increased by 14 h. Because of well-designed baffles, the removal efficiency of *E. coli* and enterococci was raised between 0.2 and 0.7 log units for the first maturation pond.

Key words | baffles, *Escherichia coli*, enterococci, hydraulic residence time, maturation pond

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INTRODUCTION

In Tunisia, wastewater stabilization ponds (WSPs) are commonly used as an efficient method of wastewater treatment; given their unsophisticated technology, low operating and maintenance costs and their ability to handle fluctuating organic and hydraulic loads. Hence, the development of this type of treatment process for water reuse will depend on its efficiency to comply with health regulations (Brissaud *et al.* 2000). However, one of the constraints of the development of this system is the complexity of their design, which takes into account all the relevant physical, chemical and biological processes governing the purification kinetics of the system (Nameche & Vasel 1998). It is therefore necessary to provide precise predictions of the performance of lagoons designed for tertiary treatment (Brissaud *et al.* 2000). Most research on the hydraulic flow pattern and thus on each wastewater plant performance require the need to undertake tracer experiments (Nameche & Vasel 1998). Indeed, improved hydraulic design can reduce the concentration of pollutants that escape treatment and therefore improve the water quality of the receiving environment (Shilton & Harrison 2003).

The design of maturation ponds is based on pathogen removal; usually bacterial decay (Pearson *et al.* 1995; Bracho *et al.* 2006). Whatever the mechanism of bacterial inactivation, the kinetic disinfection follows first-order kinetics (Marais 1974; Bastos *et al.* 2011).

$$N_t = N_0 e^{-Kt} \tag{1}$$

where N_0 and N_t: number of bacteria at the inlet and outlet of the pond; K: kinetic coefficient (h^{-1}).

Many studies have been conducted to identify the main factors involved in bacterial reduction, including the exposure to sunlight or ultraviolet (UV) irradiation (Andrianarison *et al.* 2010; Ouali *et al.* 2011), temperature (Marais 1974; Nameche & Vasel 1998), hydraulic retention time, pond depth, number of ponds (n) and the length/breadth ratio (L/B) (Lloyd *et al.* 2003; Bracho *et al.* 2006; Von Sperling 2007).

The retention time is considered to be the main factor in the removal of pathogens and parasites (Frederick & Lloyd 1996). Marais (1974) mentioned that the minimum value for the retention time is close to 3 days because low retention times can lead to a short circuit. As hydraulic efficiency and hydraulic retention time are fundamental factors controlling the performance of WSPs and many other water treatment processes, there is a strong case for critically reviewing the design principles used for FC removal in WSPs. Juanico (1991) showed that bacteria removal

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efficiency was associated with the hydraulic model. He showed that plug flow reduces pathogens at a rate more than four orders of magnitude higher than perfectly mixed ponds. According to Marais (1974), a series of equally sized ponds would probably produce the effluent quality required by the design engineers recommended in design manuals. The highest removal rates of organic material, ammonia and faecal coliform found in three pond series (da Silva *et al.* 2011). Muttamara & Puetpaiboon (1997) demonstrated that subdividing the pond with simple baffles produces a significant improvement in treatment without other additional investments. Inadequate number of treatment stages and individual ponds has frequently been found to undermine the performance, and the principal reason for this finding has been generally identified as hydraulic short circuiting (Frederick & Lloyd 1996). It follows that the reason so many WSP systems fail to meet the guideline values is that even with three to five ponds in series, significant hydraulic short circuiting in only one pond stage of a series, or a few percentage points in several stages, is sufficient to reduce overall performance by greater than half a $\log_{10}$ (Lloyd *et al.* 2003). If 1% of the volume of the effluent is entering and exiting the pond in less than 24 h, the performance of pathogen removal in the pond rarely exceeds 99%. Similarly, if 10% of the effluent stagnates and leaves the pond in less than 24 h, performance of the pond does not exceed 90% (Frederick & Lloyd 1996). Thus, it would be very useful to assess the level of short circuit in the pond. Within these ponds the water flow is affected by other physical parameters, the most important being the pond design, dead zones, position of the inlet and outlet of the water pond and the position of the baffles (Shilton & Harrison 2003; Fyfe *et al.* 2007).

The setting-up of the baffles is generally regarded as a simple method to improve the hydraulic and treatment efficiency. The calculation of fluid dynamics suggests that the setting-up of the baffles should significantly improve the removal of bacteria (Shilton & Harrison 2003). Nonetheless research by Lloyd *et al.* (2003) has concluded that baffles do not necessarily improve performance; their design requires care and further evaluation. It was also demonstrated that wind speed and direction have a great influence on the mixing and the flow model in the ponds (Badrot-Nico *et al.* 2010).

Frederick & Lloyd (1996) have asserted that short circuiting was attributed mainly to the prevailing wind direction and the orientation of the lagoons including inlet–outlet arrangements. The reduction of wind effects reduces mixing and hence dispersion, and significantly increases the average hydraulic retention time, thus contributing to improving FC removal (Lloyd *et al.* 2003). These findings indicate that dispersion number '*d*' is not the static variable traditionally suggested, but rather a dynamic variable which varies depending on pond flows, environmental conditions as well as pond design. The dispersion number '*d*' is used as a descriptor of the magnitude of longitudinal dispersion within the pond, on a scale ranging from 0 (plug flow) to ∞ (completely mixed condition). Dispersion number analysis of WSPs was developed from retrospective analysis of pond hydraulic performance (Sweeney *et al.* 2003). A number of expressions have been empirically developed to predict dispersion number based on pond parameters such as length, width, depth, and flow rate (Polpresert & Bhattarai 1985). Lloyd *et al.* (2003) showed that faecal coliform removal was inversely proportional to the dispersion number, likewise retention time is very closely linked with flow dispersion number: the lower the dispersion number, the greater the hydraulic residence time is.

The aim of this study is to improve the maturation pond removal efficiency of *Escherichia coli* and enterococci of Korba wastewater treatment plant by the introduction of baffles designed to reduce the short circuiting flow and the dead zones.

METHODS

Korba's wastewater treatment plant (Figure 1) is a conventional activated sludge, followed by three maturation ponds in series acting as a tertiary treatment (MP1, MP2, and MP3). Treated effluent is essentially used for artificial recharge of Korba aquifer; the rest is discharged into the Korba lagoon to maintain its ecological equilibrium.

After a first hydrodynamic study that demonstrated the existence of short circuits and dead zones, two baffles were introduced to improve the removal efficiency of the first maturation pond. The first one 12.97 m long and the other 30.03 m long were installed toward the outlet of the first maturation pond (Figure 1(b)). The overall height of the baffles was 1.15 m. To determine the hydraulic retention time and the dispersion number before and after the introduction of the baffles, two tracer tests were performed.

All the samples were collected between September 2008 and April 2010. These samples were collected at the wastewater treatment plant inlet, at the first lagoon (MP1) inlet and at the MP2 and MP3 outlet. The evaluation of treatment performance was judged by the removal of faecal indicators (*E. coli* and intestinal enterococci). The collected samples

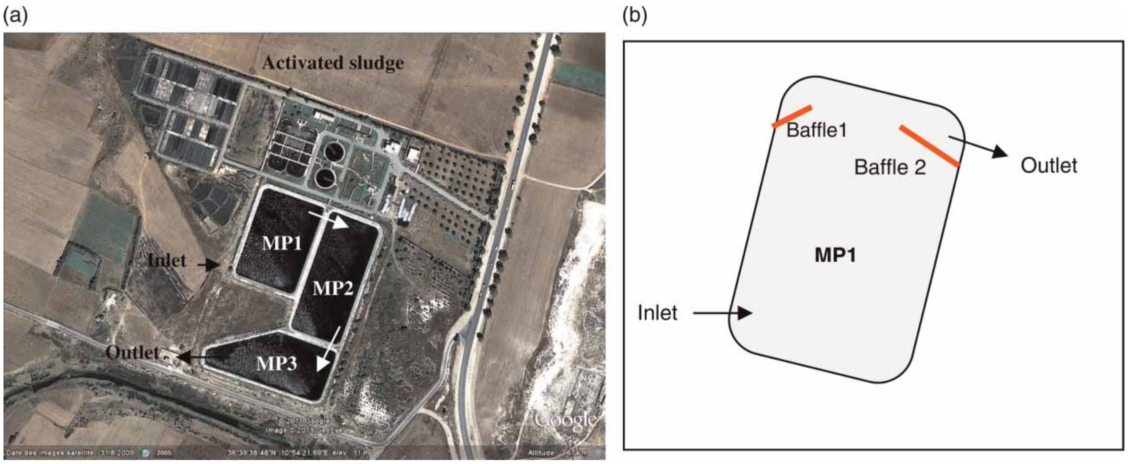

Figure 1 | (a) Overview of Korba's wastewater treatment (36°39′38.48″ N, 10°54′21.69″ E; Google photo); (b) position of the baffles inside MP1.

were analyzed immediately. The technique used to quantify *E. coli* and enterococci in the laboratory was the membrane filtration method using Chromocult Coliform-Agar (Merck, Germany) and Chromocult Entecocci-Agar (Merck) as culture medium.

The evaluation methodology used included physico-chemical logging (YSI-6920), simultaneous tracer studies to define hydraulic retention time and the dispersion number. The tracer Rhodamine WT was selected, because it is non-toxic, cost effective, easily measured at low concentrations, and stable during the study (Bracho *et al*. 2006). The dye concentration was logged with fluorometric probe (YSI-6920) at the lagoons outlet. Additional grab samples were collected using an automatic sampler (ISCO 6712).

The study was developed in two steps:

- Performance evaluation of Korba wastewater treatment and maturation ponds followed by a tracer study with Rhodamine in the first maturation pond (MP1).
- Installation of two baffles in the first maturation (Figure 1(b)) pond followed by a second tracer study which allowed a bacteriological and hydraulic evaluation.

RESULTS AND DISCUSSION

Bacteriological evaluation before setting-up the baffles

The bacterial performance obtained during a preliminary diagnostic WWTP before the setting-up of the baffles is presented in Table 1. The overall performance of the treatment plant does not comply with permissible levels for the WHO (1989) reuse guideline (<1,000 FC/100 ml).

Table 1 | *E.* coli and enterococci removal by Korba WWTP during preliminary evaluation before the installation of the baffles

	Raw sewage	Inlet MP1	Outlet MP1	Outlet MP2	Outlet MP3
E. coli (CFU/100 ml) ($n = 3$)	5.17×10^5	1.38×10^5	4.23×10^4	2×10^4	9×10^3
log (CFU *E. coli*/100 ml)	5.71	5.13	4.62	4.3	3.95
E. coli removal in each unit (log unit)		0.58	0.51	0.32	0.35
E. coli removal by the maturation ponds (log unit)		1.18			
E. coli removal at WWTP (activated sludge + 3 MPs) (log unit)	1.76				
Enterococci (CFU/100 ml) ($n = 3$)	1.50×10^6	6×10^5	1.63×10^5	6×10^4	2×10^4
log (CFU Ent./100 ml)	6.54	5.77	5.21	4.77	4.3
Enterococci removal in each unit (log unit)		0.77	0.56	0.44	0.47
Enterococci removal by the maturation ponds (log unit)		1.47			
Enterococci removal at WWTP (activated sludge + 3 MPs) (log unit)	2.24				

Bacteriological and hydraulic performance after the setting-up of the baffles

To improve hydraulic and bacteriological performance of the first maturation pond and the entire tertiary treatment unit, two baffles were installed at the corners at the outlet side of the MP1 (Figure 1(b)).

Hydraulic performance

The evolution of Rhodamine WT concentration before and after installation of the two baffles in pond 1 is presented in Figure 2. The evaluation of hydraulic and biological performance of the first pond and the three maturation ponds in series before the geometry of the first maturation pond was modified, showed a large dead volume in the first pond which affects the treatment efficiency of the pond and the tertiary treatment unit (Figure 2).

The evolution of Rhodamine concentration at the pond outlet can be written as a function of time *t*.

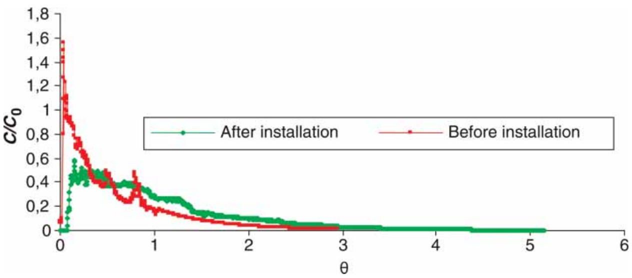

Figure 2 | The evolution of Rhodamine WT concentration before and after installation of baffles. C_0: the average Rhodamine concentration in the pond ($C_0 = M/V$). *M*: Rhodamine mass injected at the MP1 inlet. *C*: Rhodamine concentration at the MP1 outlet. $\theta = t/\tau$ (with τ: theoretical retention time ($\tau = V/Q$); *Q*: low rate.

The first appearance of the tracer at the pond 1 outlet (Figure 2) was delayed by 14 h for a flow of 139.15 m^3 and 62.14% recoveries of dye tracer. This outcome had a positive effect on the average hydraulic retention time, producing a 14 h increase. The hydraulic retention time was increased from 2.41 days to 3 days, and the dispersion number was reduced from 1.45 to 0.43. The Peclet number was increased from 0.69 to 2.32. The short circuit and the dead zones in the first maturation pond significantly decreased from 39.55 to 7.05% after the setting up of the baffles.

Bacteriological evaluation

After the introduction of the baffles at the outlet of the first maturation pond the hydraulic behavior of the pond was changed. This situation is fundamental in achieving the objective of this work and approaching the WHO (1989) reuse guidelines. The geometric average effluent concentration was reduced from 9×10^3 CFU/100 ml to 3×10^3 CFU/100 ml for *E. coli* and from 2×10^4 CFU/100 ml to 7×10^3 CFU/100 ml for enterococci (Table 1 and Table 2).

After the introduction of the baffles, we improved the flow rate and reduced the dead zones and short circuit so the hydraulic retention time was increased and the dispersion number was decreased for better performance of the maturation ponds. These results match those founded by Shilton & Harrison (2003), Lloyd *et al.* (2003) and Aldana *et al.* (2009). In reality, retention time does not act alone; many researchers have highlighted the importance of other factors controlling FC removal mechanisms. These include sunlight disinfection (Nelson *et al.* 2009; Bolton *et al.* 2010). The retention time is very closely linked with flow dispersion number (Bracho *et al.* 2006). Values

Table 2 | *E. coli* and enterococci removal by Korba sewage treatment plant after upgrading

	Raw sewage	Inlet MP1	Outlet MP1	Outlet MP2	Outlet MP3
E. coli (CFU/100 ml) ($n = 3$)	1.3×10^6	3.5×10^5	6×10^4	1×10^4	3×10^3
log (CFU *E. coli*/100 ml)	6.11	5.5	4.74	4.05	3.5
E. coli removal in each unit (log unit)		0.61	0.76	0.69	0.55
E. coli removal by maturation ponds (log unit)		2			
E. coli removal at WWTP (activated sludge + 3 MPs) (log unit)	2.61				
Enterococci (CFU/100 ml) ($n = 3$)	3.50×10^6	9.75×10^5	1.63×10^5	4.23×10^4	7×10^3
log (CFU Ent./100 ml)	6.54	5.98	5.21	4.62	3.84
Enterococci removal in each unit (log unit)		0.56	0.77	0.59	0.78
Enterococci removal by maturation ponds (log unit)		2.14			
Enterococci removal at WWTP (activated sludge + 3 BM) (log unit)	2.24				

for the dimensionless dispersion number (d), describing the hydraulic behavior of ponds, theoretically range from 0 for perfect plug flow to infinity for a completely mixed pond. However, the values of dispersion in the ponds of Brazil vary between 0.8 and 3.0 and between 0.5 and 3.0 in those of Portugal (Marecos do Monte & Mara 1987).

The results of this study are summarized in Table 3 which shows the reduction of dispersion of 1.45 at 0.43, hence approaching the plug flow conditions. In this study was calculated before and after the introduction of the baffles. Ponds approach plug flow conditions (low 'd' values) obviously have less short-circuiting and provide more time for the reactions to take place, resulting in better treatment efficiency (Polpresert & Bhattarai 1985). Treatment efficiency is much better when dispersion number (d) is low (Juanico 1991; Lloyd *et al.* 2003). The changes in the hydraulic behavior of the first maturation pond were fundamental in achieving the main objective of this research as it influences significantly the bacteriological performance. In general, existing maturation ponds require engineering interventions to improve their hydraulics and change them from dispersed flow to plug flow (Lloyd *et al.* 2003). This situation would guarantee that all the elements in water have a defined minimum retention time and the same exposure to sunlight for their natural disinfection.

The results obtained in the first maturation pond show that such simple installation of two well designed baffles can increase the bacteriological pond performances. The geometric average effluent concentration for this period reduced from 1.3×10^6 CFU/100 ml to 3×10^3 CFU/100 ml for *E. coli* and from 3.5×10^6 CFU/100 ml to 7×10^3 CFU/100 ml for enterococci (Table 2). The comparison of the geometric average of *E. coli* and enterococci effluent concentration shows that we can achieve the guidelines for irrigation reuse. The changes in the hydraulic behaviour of the first maturation pond influence its bacteriological performance. The *E. coli* removal by the first maturation pond increased from 0.51 log units to 0.76 log units after upgrading (Table 2). The elimination rate calculated with experimental average retention time increased from 0.013 to 0.03 h^{-1} before and after transformation, respectively. The removal of enterococci was also influenced by the introduction of the baffles. The enterococci removal increased from 0.56-log unit before upgrading to 0.77 log unit after (Table 2). The elimination rate calculated with experimental average retention time increased from 0.015 h^{-1} to 0.03 l h^{-1}.

Table 3 | Impact of the baffles installed in pond 1 on the hydraulic residence time

Parameters	Before baffles installation	After baffles installation
Nominal residence time (d)	3.53	2.43
Hydraulic residence time (d)	2.45	3.03
Dispersion number	1.45	0.43
Peclet number	0.69	2.32

The results of the study are in agreement with those of Shilton & Mara (2005). They found that the incorporation of two baffles equally spaced along the longitudinal axis of the pond indicated a potential improvement in the removal of *E. coli* in 4 days in the primary maturation pond from 5×10^6 per 100 ml to 340 per 100 ml. The reduction in an un-baffled series was two orders of magnitude less effective. They finally concluded that well designed baffles have considerable potential for reducing pond area requirements and hence costs.

The bacteriological performance of the ponds was consequently influenced by the introduction of the baffles in the first pond. The removal efficiency of *E. coli* by the three maturation ponds increased from 1.18 log units to 2 log units after the upgrading. Similarly, the removal efficiency of enterococci increased from 1.47 log unit to 2.14 log unit after the introduction of baffles.

The results of this study are evidence that when the dispersion number decreases, the bacterial removal increases, which is in agreement with the results of Lloyd *et al.* (2003). These findings are also in accordance with those of (Bracho *et al.* 2006), which can be evidence that dispersion number decreases and bacterial removal increases when the L/W ratio in stabilization ponds is increased. The results of the study are also in agreement with those of Muttamara & Puetpaiboon (1997). They installed in a pilot scale zero, two, four, six baffles in a maturation pond and managed to increase faecal coliform removal from 87.2 to 99.2%, retention time also increased from 4.7 to 5.79 days as dispersion number d decreases from 0.159 to 0.102. Indeed, the results are consistent with those of Shilton & Harrison (2003). Furthermore, they are consistent with studies carried by Pearson *et al.* (1995) on a pilot scale. According to (Badrot-Nico *et al.* 2010) the addition of baffles had a positive impact on the bacterial removal and on the sensitivity to wind direction. Before the introduction of the baffles, the outlet was already reached 1 h 40 after the injection. The addition of L-shaped baffles added to diminish hydraulic short-circuiting, reduced dead zones and increased the hydraulic retention time (12 h after the injection). The bacterial removal was also influenced by the introduction of the baffles. It increased from 1.03 log unit before upgrading to 1.24-log unit after. Similarly, the coliform die off coefficient increased from 0.6 to 1.2 d^{-1} for a wind speed of 2 m/s.

All these studies confirm that the introduction of the baffles in the maturation ponds improve their hydraulics characteristics and bacteriological performances. The knowledge of the hydraulic behaviour of the ponds requires the undertaking of tracer tests, which can take, both in terms of the injection procedure and in terms of the used tracer, many different forms. In all cases, these tests remain extremely long, costly and tedious operations to perform. The settling up of the baffles in the maturation pond is very complicated and requires intervention after a good tracer study. Despite the encountered difficulties, it is still required to undertake tracer tests in order to accurately model the physical, chemical and biological parameters involved in the disinfection process.

CONCLUSION

In the present case, it has been noted that if a hydrodynamic study shows that a given pond suffers from short circuits, simple well designed baffles can considerably improve the hydrodynamic and consequently the removal efficiency. This work shows that the hydraulic behaviour affects considerably the kinetic coefficient of *E. coli* and enterococci. Their die-off coefficient increases with the introduction of baffles.

Maturation ponds installed at the end of an activated sludge wastewater treatment plant, need better hydraulic design to improve bacteriological removal and to reach the guidelines of wastewater reuse. With limited means, satisfactory results can be achieved. The use of the baffles in existing maturation ponds or wastewater stabilization ponds to increase bacterial removal reduces investment and maintenance coasts, because no additional land is required. An appropriate engineering intervention reduces dead zone and dispersion, optimizes the hydraulic retention time; and consequently improves the bacterial removal.

In perspectives of this work, it would be interesting to undertake tracer tests in the second and the third maturation pond to determine the total real hydraulic retention time, to improve the sanitary quality of the treated wastewater and to reach the guideline of wastewater reuse without restriction. According to the results published in the literature, the feasibility of the tracing method and the difficulties that accompany the tracer tests, need more investigations. The design, the form, the wind and the position of communication between the maturation ponds are also very important and need some modelling and simulation studies.

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