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Mixing and its impact on faecal coliform removal in a stabilisation pond

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Abstract
Faecal coliform removal in stabilisation ponds is highly dependent on shortest water retention times. Tracer tests have been performed in a 3,300 m^2 and 1.0 m deep pond, located in Southern France, to measure the retention times and bring light on the main influencing factors and mechanisms. Tracer concentrations were monitored at the outlet and 60 locations within the pond - at the surface, mid depth and the bottom of the water column. Pond water temperatures were measured at different depths and locations, together with pH, DO and red-ox potential. Wind velocity and rainfall were recorded. Water quality was monitored at the inlet, outlet and within the pond. Water retention times were shown to be strongly affected by weather conditions. Windy periods appeared to favour mixing regardless of the season. In sunny periods of spring and summer, a clear stratification was observed during daytime and vanished gradually during the night, suggesting alternation of mixed and stratified hydrodynamic patterns. This alternation was shown to influence microorganism contents within and at the outlet of the pond. Accurate prediction of shortest water retention times and disinfection performance requires 3D unsteady state fluid dynamic models that are able to take the influence of wind and water temperature distribution into account.

Keywords
Waste stabilisation pond, detention time, weather, feacal coliform removal,

INTRODUCTION

Water retention time is, together with solar radiation and temperature, one of the most important factors which influence pathogenic micro-organism removal in stabilisation ponds. This is the reason why a number of tracer tests have been performed during the eighties and in recent years (Racault *et al*., 1984, Marecos do Monte and Mara, 1987, Nameche and Vasel, 1998, Shilton *et al*., 2000, Brissaud *et al*., 2000, ….). Many results confirm that the old Marais's assumption, which states that ponds behave as perfectly mixed reactors, is fairly valid for medium and long term water transfer. But, as they play a key role in micro-organism removal performances, a particular attention has to be paid to shortest retention times (Brissaud *et al*., 2000). Looking at the first hours or the first days after the tracer injection, it appears that shortest retention times hardly abide by dispersed plug flow or completely mixed reactor models. Short-circuits are often put forward (Frederick and Lloyd, 1996) but, on the other hand, mixing is never immediate. Moreover, as reported by Shilton *et al*. (2000) and found in author's experiments, successive tests performed in the same lagoon have shown that shortest detention times may be highly variable from one run to another, which leads to uncertainty in disinfection predictions.

These observations suggest that pond hydrodynamics depend not only on pond design but also on climatic conditions. Tracer tests and other related observations should be analysed from this particular point of view so as to determine the relevant mechanisms to be taken into account by computational fluid dynamic models.

MATERIALS AND METHODS

Two tracer tests were performed in pond n°2 of the wastewater treatment plant of Murviel les Montpellier, Southern France, in summer and winter of the year 1998. The pond had a surface area of 3,300 m^2 and a mean depth of 1 m (Figure 1). The flow rate was assessed to be less than 40 m^3/d in summer and around 70 m^3/d in winter, which means that, outside rainy periods, mean residence times were higher than 7 weeks.

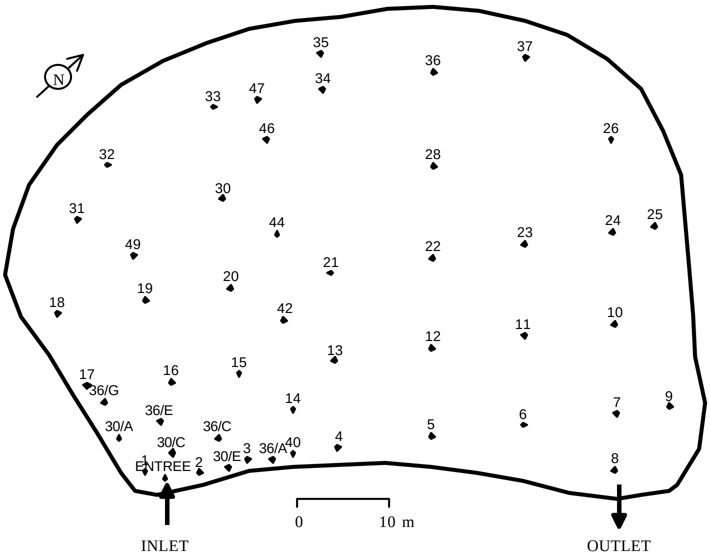

Figure 1 Pond layout with the sampling locations

The tracer, $NaI.2H_2O$, was injected in pond inlet, near the bottom of the pond. Iodine concentrations were monitored at the outlet and within the pond, at the surface, mid depth and the bottom for the summer test and at the surface, mid depth, 10 cm above the bottom and the bottom for the winter test. During the winter test, water temperature was measured together with sampling for iodine analysis. Wind speed and direction were recorded for the test periods. More details on the experimental setting are available in Brissaud *et al.* (2000).

Temperature vertical profiles were recorded in the middle of the pond for 7 weeks, from April to June 2000. By that time, the height of the water column had been increased up to 1.3 m in order to store water for summer irrigation. DO, pH and red-ox potential profiles were monitored every week in the afternoon. Rainfall was measured two kilometres away and wind, air temperature and sunlight duration were recorded at Montpellier airport, 30 km from the plant.

In summer 2000, samples were taken weekly for 5 weeks at 4 points, W, X, Y and Z, located in the middle of each quarter of the pond. Samples were analysed for faecal coliforms; pH, DO and temperature were measured. Outlet water was continuously sampled for 24 h and faecal coliform content analysed in every 4 hours sample.

RESULTS

In the winter run, water temperatures were remarkably homogeneous, with the exception of the neighbourhood of the inlet and the Southern bank which were sheltered from the wind. Temperature gaps between the surface and the bottom did not exceed 0.2 °C. As a consequence and as the flow-rate through the pond was low, wind was the main factor driving fluid dynamic into the pond. The result was that, though the wind velocity was only between 2 and 3 m/s, the tracer reached the outlet in less than 7 hours after injection (Figure 2). In the afternoon of the injection day, iodine concentrations showed horizontal and vertical heterogeneity even far from the inlet, with values up to 15 mg/L at half distance between inlet and outlet. The iodine breakthrough was the result of preferential pathways. The next day, the heterogeneity was smoothly diminishing as shown in Figure 3, with concentrations ranging from 0.11 to 0.45 mg/L with the exception of one very high value of 18 mg/L at the surface. However, iodine concentration at the outlet was the double of the one *at complete mixing*, demonstrating the influence of preferential pathways activated by wind stresses which varied in intensity and direction.

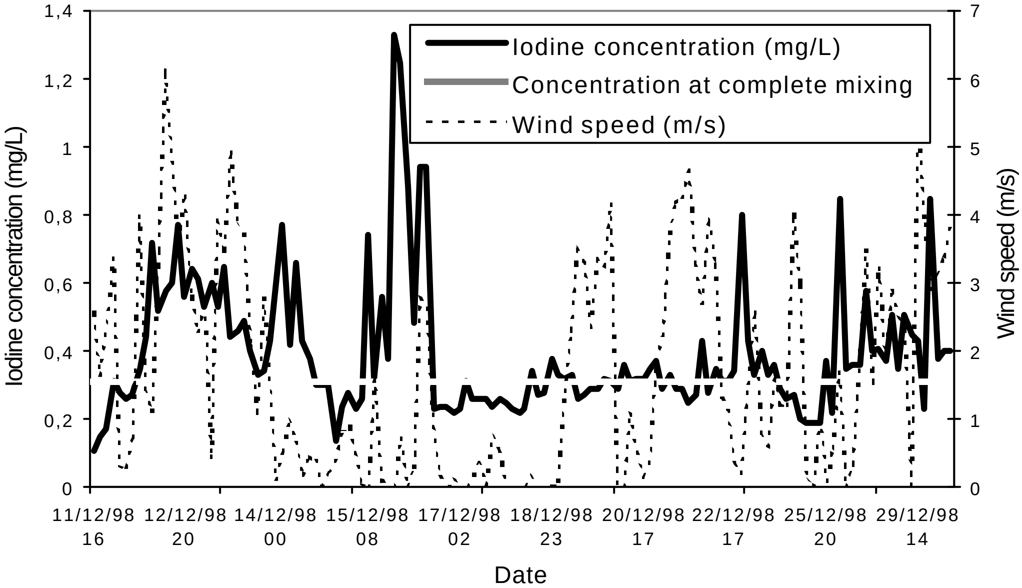

Figure 2 Winter test - tracer concentration at the outlet of the pond and wind speed (the tracer was injected at 10 a.m. on Dec 11)

In the following days, the concentrations became more homogeneous, with mean values increasing slowly towards the concentration at complete mixing, while concentration peaks still appeared at the outlet, manifesting the existence of remnant poorly mixed layers.

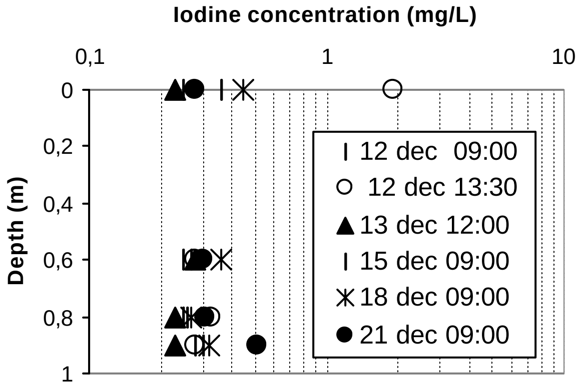

Figure 3 Winter test – mean tracer content profiles

In the summer test, already reported in Brissaud *et al*. (2000), the water body was observed to be strongly stratified during the day and a mixing occurred during the first night following the tracer injection - the wind velocity being negligible -, allowing the tracer to reach the outlet at the end of the night (Figure 4). Then, the outlet concentration increased rapidly up to the concentration at complete mixing. The day following the injection, iodine concentrations measured into the pond confirmed the mixing of the tracer in the whole water body, despite several high concentrations observed at the bottom of the pond. The following days, concentrations were more homogeneous but some high values were still observed at the bottom, explaining concentration peaks observed at the outlet.

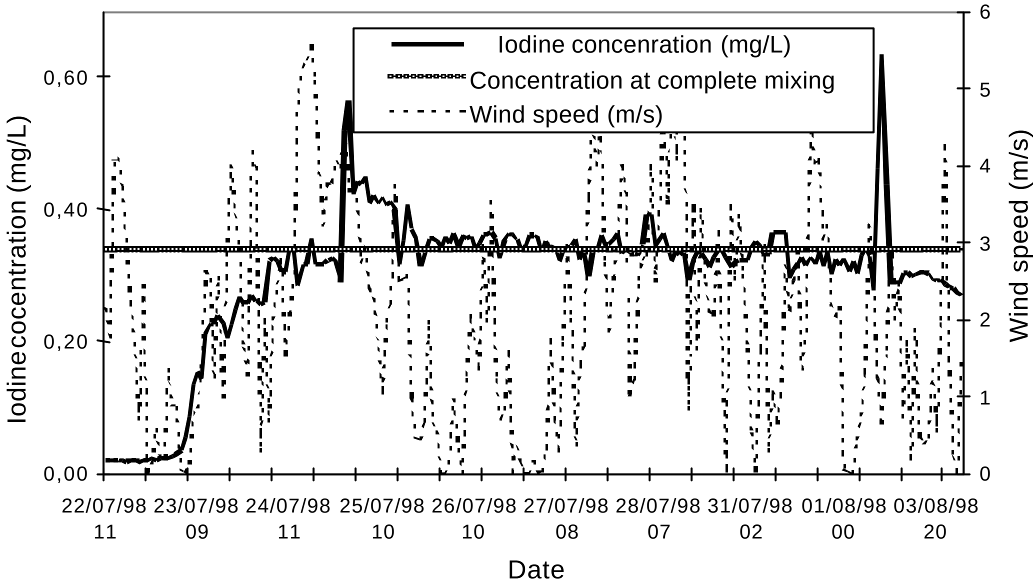

Figure 4 Summer test – tracer concentration at the outlet and wind speed

Though in both cases the *concentration at complete mixing* was reached within a few days, breakthrough curves were notably different. The hydrodynamic behaviour of the pond was mainly driven by the wind in winter while, in summer, thermal stratification overshadowed the influence of the wind. Thermal stratification had to be closely monitored in order to understand how the mixing occurs when stratification is observed during the day.

Temperatures recorded during the spring of the year 2000 showed two different behaviours (Figure 5).

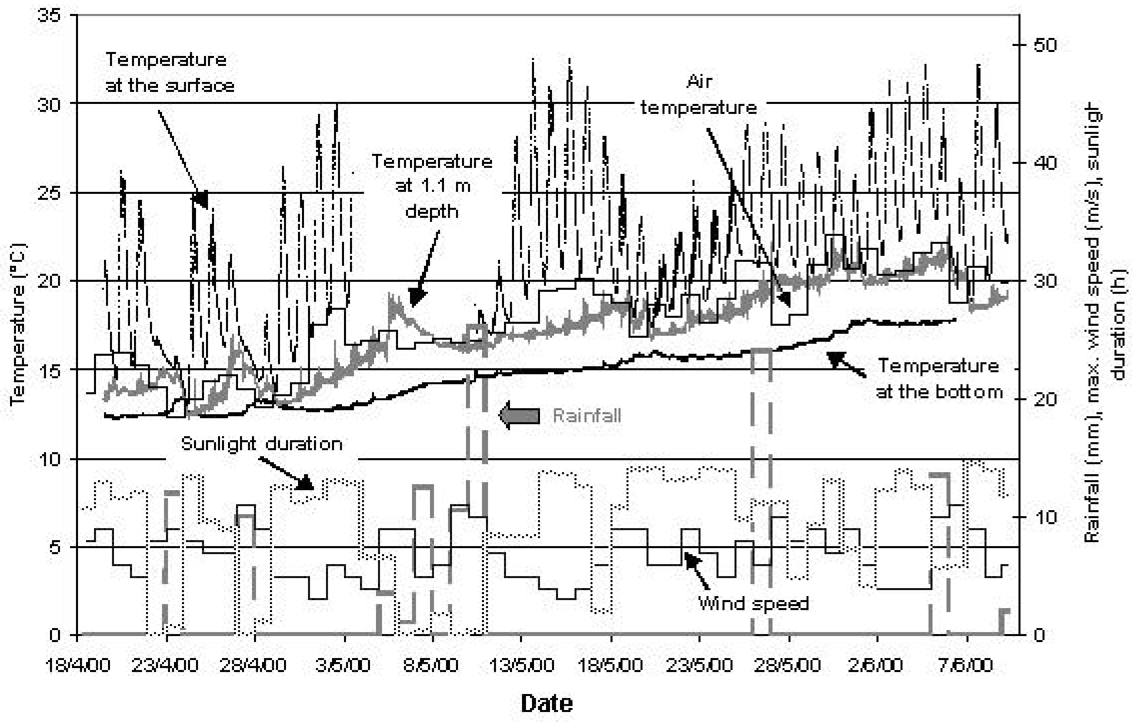

Figure 5 Pond water temperature and climatic variables

In sunny and low wind periods, a clear stratification was observed during the day, with high temperature, DO, pH and red-ox potential in the epilimnion. Temperature varied rapidly at the surface with maximum differences of more than 15°C between night and day. Deeper in the pond, the range of the temperature variation diminished. Daily variations were less than 3°C at 1.1 m below the surface and negligible at the bottom. During daytime, temperature decreased from the surface to the bottom, together with DO, pH and red-ox potential, but the stratification vanished gradually during the night. For several periods, temperature at the surface and 0.15 m depth fell below the temperature at 0.65 m depth and sometimes reached the temperature at 1.1 m, suggesting a nocturnal mixing over the main part of the water column. At the bottom of the pond, a thin layer of colder water hardly mixed with the rest of the water body. This behaviour explains the patterns of tracer concentrations observed in the summer tracer test. The mixing resulting from the inversion of vertical temperature gradients during the first night led to the spreading of the tracer in the whole pond and its breakthrough at the outlet. High concentrations noticed in the bottom layer are the consequence of its difficulty to mix with the upper layers.

During cloudy, rainy and/or windy periods, temperature variations within the water column and from day to night are significantly lowered. It happened that temperatures were uniform over the main part of the water column whatever the hour of the day, demonstrating the importance of the mixing into the pond (Figure 6). For some short periods, the bottom layer appeared to be involved in the mixing process.

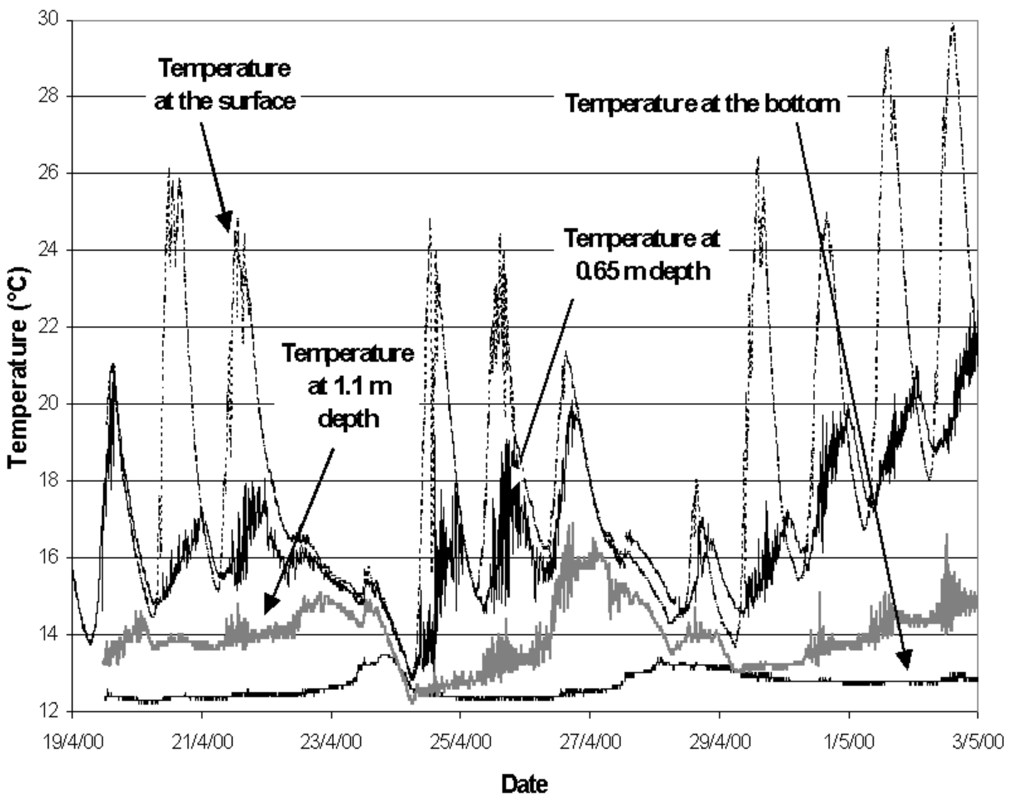

Figure 6 Pond water temperature profiles

In sunny and low wind periods of spring and summer, the water body was highly stratified during the day; the upper layers, involving more than half of the water column, mixed during the night. In cloudy and windy periods and in winter, vertical temperature gradients were less important. It can be concluded that mixing is effective all along the year, but that the processes leading to water mixing are different. In sunny and low wind periods, the main factor is the daily inversions of temperature and water density gradients; in other periods, the wind drives the mixing. Both mechanisms lead to different water velocity fields and different patterns of short detention times, which affect disinfection performances.

Faecal coliform contents in water sampled weekly during 5 weeks at 4 different locations into the pond, at the surface, mid depth and the bottom, illustrated the influence of the summer hydrodynamic regime on micro-organism removal (Table 1). All samples were taken during daytime. Faecal coliform content was increasing from the surface to the bottom, with few exceptions. This is due to ultra-violet radiation attenuation but may also be attributed to the effect of water stratification. On 24 July, samples were taken early in the morning; pH, temperature and DO values showed that the stratification was not yet established in the half upper part of the pond. The result was that coliform contents were not so different at the surface and mid depth. The effect of the change from cloudy to sunny weather could be observed on 19 August.

Table 1 Faecal coliform contents and physico-chemical parameters at 4 locations

Parameter	Wsurf	Wmd	Wbot	Xsurf	Xmd	Xbot	Ysurf	Ymd	Ybot	Zsurf	Zmd	Zbot
20 July, 3 to 4 p.m., sunshine, low wind												
E. Coli. / 100 mL	8.2 E2	3.6 E3	5.3 E3	6.5 E2	2.4 E3	1.2 E4	8.3 E2	1.6 E3	5 E3			
pH	9.7	9.2	9.1	9.8	9.8	9.1	9.9	9.5	9.2			
Temperat. (°C)	30.0	27.9	27.0	29.0	29.0	26.0	29.3	28.7	27.0			
D O (mg/L)	27	13.1	9.5	23.6	29	9.7	25	21	12.4			
24 July, 8 to 9 a.m., sunshine, low wind												
F. Coli. / 100 mL	2.2 E4	3.6 E4	6.8 E4	2.2 E4	2.2 E4	5.8 E4	3.1 E4	2.0 E4	4.7 E4	1.6 E4	2.6 E4	8.8 E4
PH	9.2	9.1	9.1	9.2	9.1	8.7	9.1	9.1	8.6	9.1	9.1	8.2
Temperat. (°C)	25.7	25.8	25.3	25.4	25.1	25.1	25.3	25.1	24.9	25.6	25.5	25
D O (mg/L)	5.7	6.5	4.1	4.5	4	0.8	4.5	4	0.8	4.3	4.5	0.8
30 July, 1 30 to 2 45 p.m., sunshine,												
F. Coli. / 100 mL	3.2 E3	6..2 E3	7.7 E3	5.5 E3	1.1 E4	1.1 E4	3.0 E3	3.6 E3	9.3 E3	5.8 E3	1.1 E4	1.3 E4
PH	9.4	8.9	8.8	9.0	8.9	8.75	9.3	8.9	8.8	9.2	8.9	8.8
Temperat. (°C)	29.1	25.3	24.7	26.1	24.6	24.3	27.6	24.6	23.9	27.8	24.6	24.2
D O (mg/L)	21.6	5.1	3.2	6.6	3.1	2.1	15.9	5	3.9	13.5	2.7	2.4
5 August, 12 30 to 2 p.m., sunshine												
F. Coli. / 100 mL	4.7 E4	6.2 E4	9.2 E4	5.4 E4	6.5 E4	1.3 E5	3.2 E4	1.2 E5	1.3 E5	6.2 E4	6.5 E4	8.8 E4
PH	9.3	8.8	8.2	9.3	9.1	8.2	9.4	8.7	8.3	9.2	9.0	8.2
Temperat. (°C)	25.7	22.8	21.1	25.6	24.2	21.6	27	22.6	21.4	26	24.5	21.6
D O (mg/L)	20.2	6.1	1.2	19.9	14	1.5	24.9	3.2	1.5	17.5	11.9	1.5
19 August, 8 a.m. (W), noon (X), 4 p.m. (Y), 8 p.m. (Z), sun and clouds, wind												
F. Coli. / 100 mL	7.6 E4	1.4 E5	1. 4 E5	6.8 E4	9.2 E4	5.4 E4	1.2 E4	3.6 E4	1.0 E5	1.2 E4		
PH	8.0	8.0	8.0	8.2	8.0	7.94	8.8	8.1	8.0	8.7	8.0	7.95
Temperat. (°C)	22.	22.6	22.6	25.3	24	23.9	29.9	25.1	24	27.5	24.6	23.5
D O (mg/L)	0.9	0.7	1.0	3.3	1.9	1.9	18.4	1.9	1.9	11.9	1.4	1.7

Mean faecal coliform contents vary from one day to another. The increase observed between 20 and 24 July is the result of the accidental unloading of 500 m^3 water from pond n°1 into pond n°2. The same amount of water from pond n°1 was transferred to pond n°2 in the night of 3 to 4 August due to rainfall. The recovering of water quality after these events involved the whole water body, thus demonstrating that, despite the stratification observed during the day, there was an effective mixing of the pond. Otherwise, coliform content would have been higher in the bottom. The influence of diurnal hydrodynamic regime was also shown in the outflow. Contents in micro-organisms of faecal origin appeared to depend on the hour of the day (Figure 7). Peak concentrations were observed in the second half of the night and in the morning, when water of the lower part of the pond, bearing the highest concentrations, has merged with the rest of the water body.

CONCLUSION

Mixing appears to be a main feature of pond dynamics. The mechanisms by which it is driven are (i) daily variations of water temperature and density fields and (ii) wind friction at the surface of the pond. Both mechanisms are directly ruled by climatic conditions. The structure of mixing and, therefore, shortest retention times depends on the dominant mechanism. Both mechanisms may be combined. Thus, significant differences in disinfection performances may be expected from one day to another and even during the same day. But, as shown in Table 1, greater variations may result from temporary increase of inlet flow, as often happens during rain events.

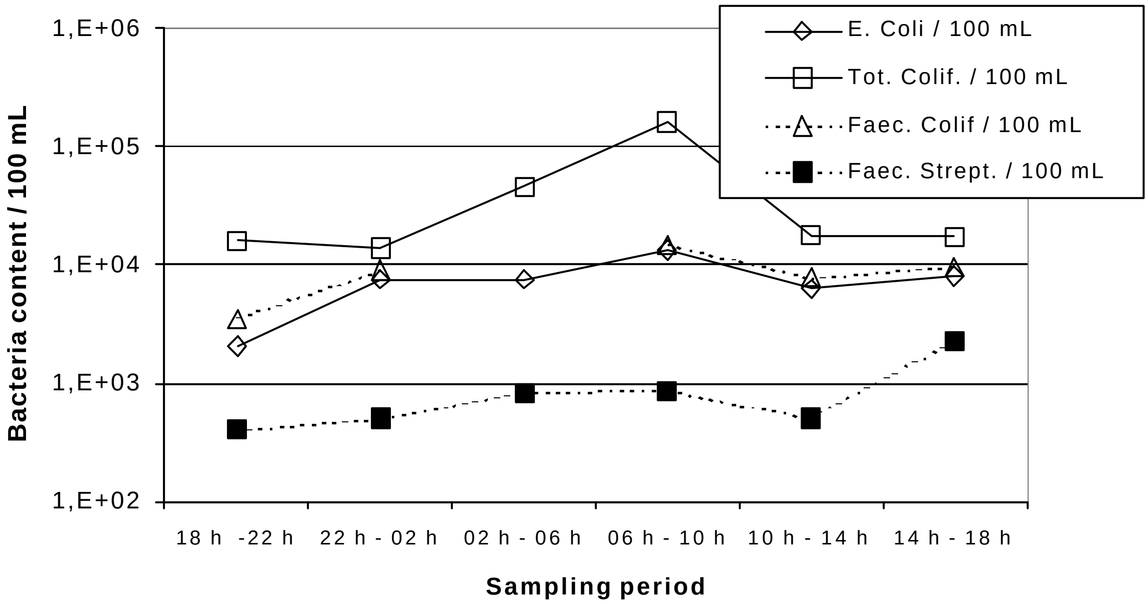

Figure 7 Round the clock monitoring of bacteria content at the pond outlet

Accurate prediction of shortest retention times requires unsteady state computational 3D fluid dynamic models able to (i) take into account the influence of wind and (ii) to simulate and take into account water temperature fields on flow pattern. Then, thanks to local meteorological records and assuming that inlet flow rate and coliform die-off kinetics are well known, it will be possible to provide disinfection performances forecasts as function of the season and in probabilistic terms. The prediction of disinfection performances of polishing lagoons and associated uncertainties is necessary for planning projects of agricultural wastewater reuse.

On the other hand, a better knowledge of fluid dynamics may help to understand and better predict bacterial die-off kinetics and improve the quality of disinfection prediction (Xu *et al.*, in press).

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