Taking wind into account in the design of waste stabilisation ponds

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ABSTRACT

Up to now, most investigations on the dependency of the fluid flow patterns and performance of waste stabilisation ponds (WSPs) on wind speed and direction and pond layout have been performed using 2D and 3D CFD steady state isothermal models. 3D non steady state models integrating thermal processes and boundary conditions taking into account the full influence of meteorological factors are likely to provide more realistic predictions of WSP performance. Such modelling was undertaken for 4 pond layouts, 2 without baffles and 2 with baffles. Wind speed and direction were kept constant throughout each simulation while other meteorological forcings were derived from field measurements. Twelve wind directions and 2, 4 and 6 $\mathrm{m\,s^{-1}}$ wind speeds were considered for each WSP layout. Simulations allowed verifying that the pond performance is dependent on the wind direction and velocity, that baffles may improve WSP performance and that the addition of well-designed baffles has the advantage of reducing its sensitivity to the wind.

Key words | CFD model, design, fluid flow pattern, waste stabilisation ponds, wind

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INTRODUCTION

Fluid flow patterns in waste stabilisation ponds (WSPs), water residence time's distributions (RTDs) and microbial performance depend on the pond design and on the meteorological conditions and particularly wind velocity and direction. RTD and WSP performance are better evaluated through hydrodynamic numerical models – instead of conceptual models – that compute water temperature and velocity as well as solute or microorganism concentrations, from the equations describing the involved physical and biological processes and non steady-state boundary conditions.

Two-dimensional (2D) hydrodynamic models were initially used to investigate the influence of pond design, considering a steady state regime and no meteorological influence (Wood *et al.* 1995; Persson 2000; Vega *et al.* 2003). Vega *et al.* (2003) took the wind into account and concluded its influence is negligible. 2D models were soon shown to be ill-adapted to the modelling of WSPs which, despite they are shallow water bodies, are subjected to influential three-dimensional mechanisms (Wood 1997; Salter 1999; Salter *et al.* 2000; Brissaud *et al.* 2003).

All 3D models investigating the influences of the wind and the pond design on the flow pattern are steady state and isothermal models that do not fully take the impact of the meteorological factors on the pond hydrodynamic behaviour into account. Fares (1998) studied the impact of four wind directions, showing that the wind can generate bottom counter-currents. Banda *et al.* (2006*a*) simulated the wind impact on a pond with shifted inlet and outlet. Four wind directions were tested (both longitudinal and transversal), and the wind effect was shown to be most unfavourable when the wind speed vector has a positive component in the inlet to outlet direction, whereas an opposite wind was found to be beneficial to the pond performance. However, in view of the assumed inlet flow, the inlet water velocity was over-evaluated by a factor 4, which implies that the inlet influence was greatly over-evaluated. The impact of adding baffles in a pond was studied by Shilton (2001),

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Shilton & Harrison (2003) and Shilton & Mara (2005). Two 70%-width baffles dividing the pond in 3 equal parts were found to be an optimal solution regarding the ponds performance and construction cost. However wind effects were not included in the model. Neglecting the wind impact may have been justified by a low wind power compared to the inlet one, but this is not a common situation.

The purpose of this study is to evaluate the impact of the wind velocity and direction and of the pond design on WSPs performance using a non-steady non-isothermal 3D pond model, the full influence of meteorological factors being taken into account. A particular objective is to set up design recommendations leading to optimised performance for a given foot print. As the wind might be detrimental to the microbial decontamination; a result expected from this study is to find out how to minimize the impact of the wind on the performance.

MATERIALS AND METHODS

The hydrodynamic model was derived from the COHERENS model (Luyten *et al.* 1990) and adapted for the modelling of WSPs. The Modified Discontinuous Profile Method (MDPM) high resolution scheme (Badrot-Nico *et al.* 2007) was used to resolve the advection equation which expresses the evolution of temperature and concentration fields. The hydrodynamic and the coupled thermal models were calibrated and validated against experimental data (Badrot-Nico 2007). The simulations were run using cells being 1.5 m × 1.5 m horizontally and 0.20 m vertically.

Four layouts were considered, all based on the same rectangular geometry, the pond area being 1800 m^2 and the length twice the width (Figure 1). The water depth was 1.6 m. In each scenario, the flow rate was equal to 5 L s^{-1}, so that the average retention time was about a week (6.7 d). The inlet was located at mid-depth and the outlet at the water surface. The pond layouts were chosen in order to study the effect of the alignment of the pond inlet and outlet as well as the usefulness of adding baffles and for comparison with the literature. Layouts 1, 2 and 3 are similar to the layouts B, A and G simulated by Persson (2000). The layouts 1 and 2, without baffles, are widespread in many countries. Layouts similar to layout 3 have been the subject of numerical modelling by Shilton & Harrison (2003), Vega *et al.* (2003), Shilton & Mara (2005) and Banda *et al.* (2006*b*). As layouts with two straight baffles were shown to still allow significant short-circuits, a layout with an L-shaped baffle (layout 4) was tested.

Temperature, solar radiation and relative humidity measured on site from April 26th to April 30th 2005 were considered to be representative of the most frequent

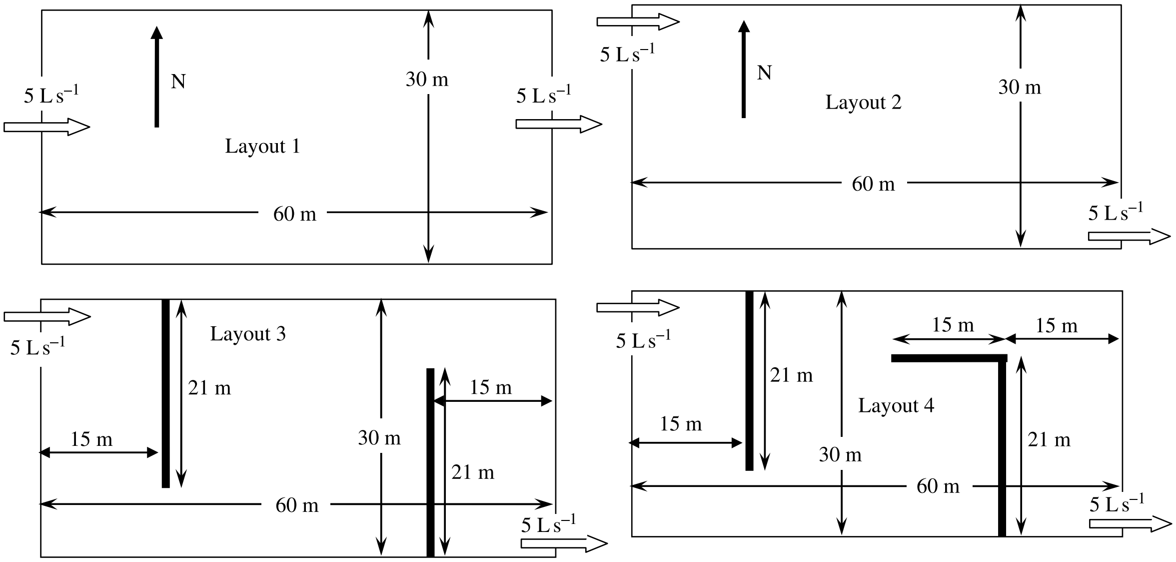

Figure 1 | Pond layouts.

meteorological conditions in coastal areas of Southern France and were used as boundary conditions for all scenarios. These conditions are the same for all scenarios and will not be responsible for the differences between the simulated flow patterns. As the aim of this study is to determine the influence of the wind on the flow pattern and the removal of faecal coliforms, the wind direction and speed were kept constant throughout each scenario and the wind speed and direction measured on site were not used. The simulations were run with wind speeds equal to 2, 4 and 6 $\mathrm{m\,s^{-1}}$. For each wind speed, the impact of the wind was studied for 12 directions equally distributed (angles multiples of 30°). In all scenarios, the inlet temperature was kept constant and equal to 16°C.

The microbial performance was evaluated through numerical tracer tests. The residence time distribution (RTD) was derived using the following equation:

$$f(t) = \frac{Q(t)C_{out}(t)}{M}$$

where $f(t)$ is the RTD, $Q(t)$ is the flow rate at the date t, $C_{out}(t)$ the concentration at the outlet at the date t, and M is the total mass injected in the pond. The pond performance is then evaluated considering a first order microbial decay

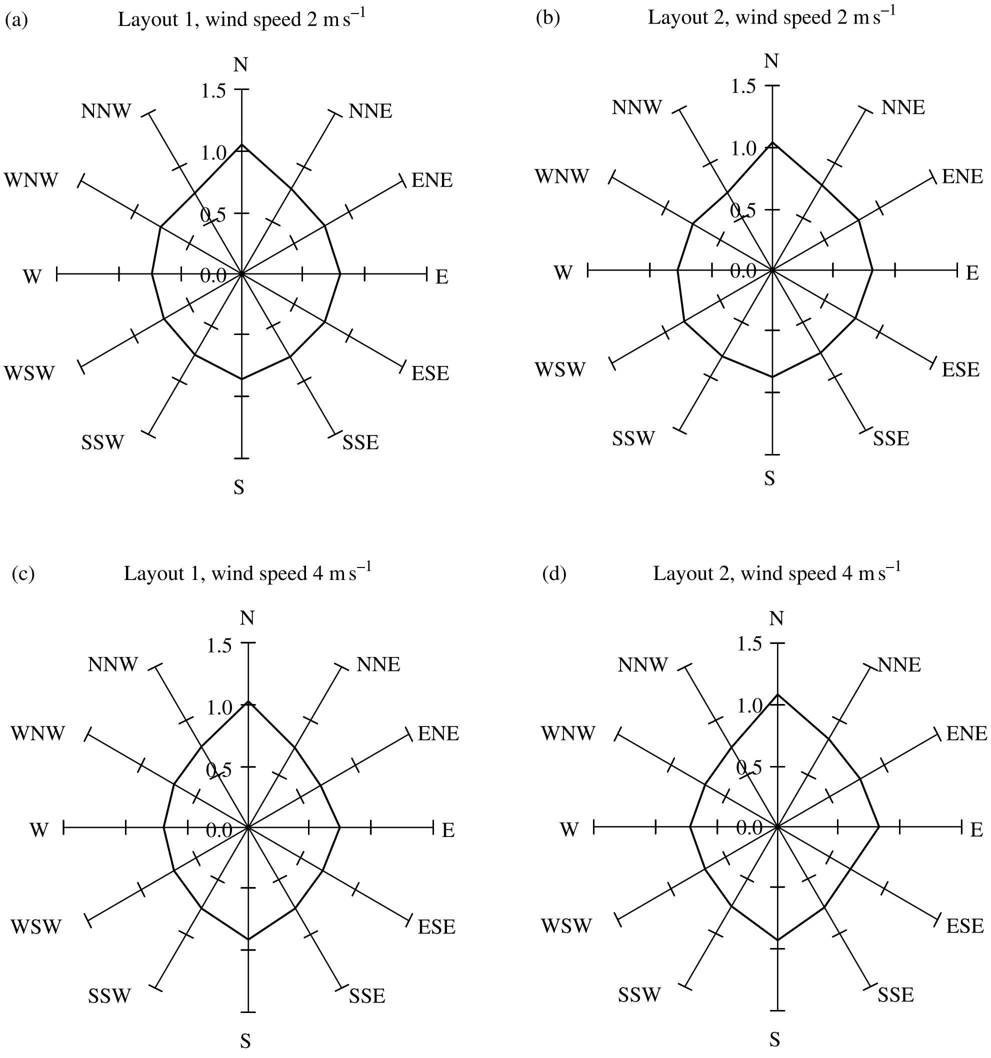

Figure 2 | Layouts without baffle. Bacterial removal (log units) as a function of the wind direction.

and a coliform die-off coefficient k_b of 0.6 d^{-1}, representative of the values determined on a polishing pond of Mèze-France (Brissaud *et al.* 2005).

RESULTS AND DISCUSSION

Layouts without baffle

As shown by the Figure 2a and b, layouts 1 and 2 are sensitive to the wind direction, even at a low wind velocity. The higher the wind component on the West-East (inlet-outlet) axis, the lower the bacterial removal R. With a wind speed of 2 $\mathrm{m\,s}^{-1}$, the bacterial removal for the layout 1 is up to 44% higher when the wind blows laterally ($R_{\max} = 1.05$) than when it blows longitudinally ($R_{\min} = 0.73$). This result is intensified when the wind speed increases (Figure 2c and d). The asymmetry between North and South winds results from the fact that, due to the grid describing the pond, the simulated inlet and outlet were not exactly at the middle of the pond width.

The comparison of the two layouts without baffle shows a similar bacterial removal (Figure 2). For both layouts, there is little difference between West and East winds: in both cases a longitudinal circulation pattern is observed and the flow direction at the bottom of the pond is opposite to its direction at the water surface. Zones of convergence or divergence of the velocity vectors show the existence of vertical currents (Figures 3 and 4). The concentration and velocity vector maps show that the major part of the tracer is transported from the inlet to the outlet, either in the top layer (West wind) or in the bottom layer (East wind). The concentration is higher in the top layer for a West wind and the velocity field mainly oriented from the inlet to the outlet, with higher velocity values than at the bottom (Figure 3). For an East wind, the tracer concentration is higher at the bottom of the pond, where velocity vectors are oriented from the inlet to the outlet (Figure 4).

Opposed to the results by Banda *et al.* (2006*a*) and in agreement with the work of Aldana *et al.* (2005) a wind opposite to the inlet-outlet direction is not observed to be

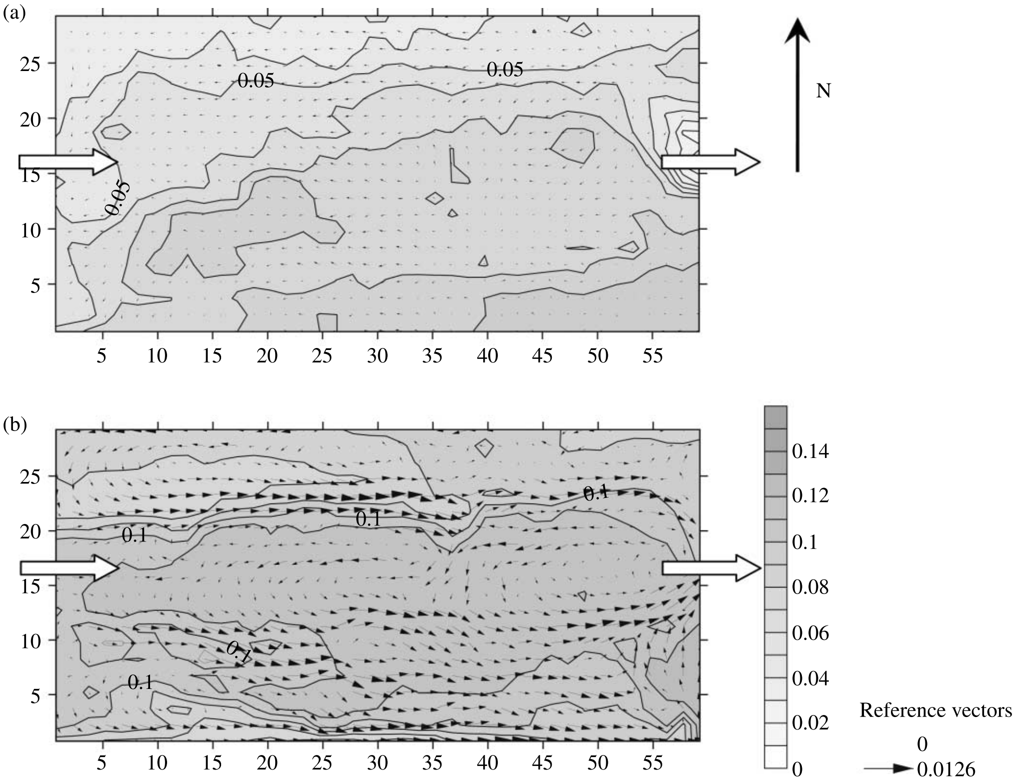

Figure 3 | Layout 1. Water velocity ($\mathrm{m\,s}^{-1}$) and tracer concentration ($\mathrm{g\,m}^{-3}$) at the bottom (a) and the surface (b) of the pond 12 h after injection, the wind coming from the West at a 2 $\mathrm{m\,s}^{-1}$ speed.

beneficial. Indeed, the bacterial removal, R, for the layout 1 is 0.75 log units with no wind and only 0.80 log units with a 2 m s^{-1} wind directed opposite to the inlet to outlet direction. Banda *et al.* (2006*a*) showed no positive effect of a wind normal to the inlet outlet direction while for layouts 1 and 2 there is a clear improvement of the performance.

For a 4 m s^{-1} wind the dissymmetry across the North-South axis is slightly accentuated, all the winds with a West to East component being less favourable than the winds with an East to West component (Figure 2c and d). The privileged flow directions in the surface flow are more visible. For West and East winds, the tracer reaches the outlet very quickly where its concentration is, on a short term, higher by a factor 2.5 than the concentration corresponding to a completely stirred tank reactor (CSTR) hypothesis. This denotes the existence of a hydraulic short circuiting well shown by concentration and water velocity maps. The concentration values are almost homogenous through the pond 12 h after the injection, contrary to the same geometry at lower wind speed.

For simple designs of WSPs, without baffles and with single inlet and outlet, the wind direction may cause up to 50% variations in the bacterial removal. The shift between the inlet and the outlet does not fundamentally modify the sensitivity to the wind direction. When designing WSP without baffles, it is thus recommended to choose an orientation of the pond such that the dominant wind is orthogonal to the inlet to outlet direction, i.e. orthogonal to the longest side of the pond. If a secondary dominant wind exists, the flow direction should preferably have a component from the outlet to the inlet than the reverse. However, this condition cannot be satisfied for several ponds in series.

Geometries with baffles

The addition of baffles modifies the sensitivity to the wind direction, even for low wind speeds. For layout 3 with a

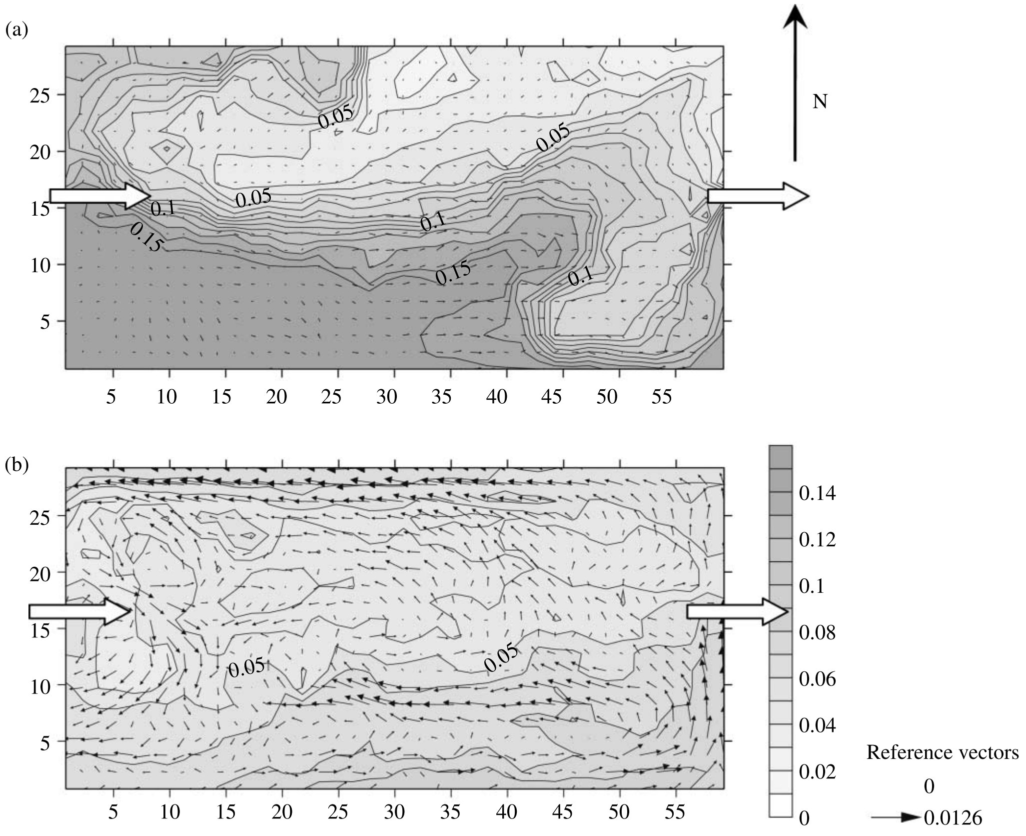

Figure 4 | Layout 1. Water velocity (m s^{-1}) and tracer concentration (g m^{-3}) at the bottom (a) and the surface (b) of the pond 12 h after injection, the wind coming from the East at a 2 m s^{-1} speed.

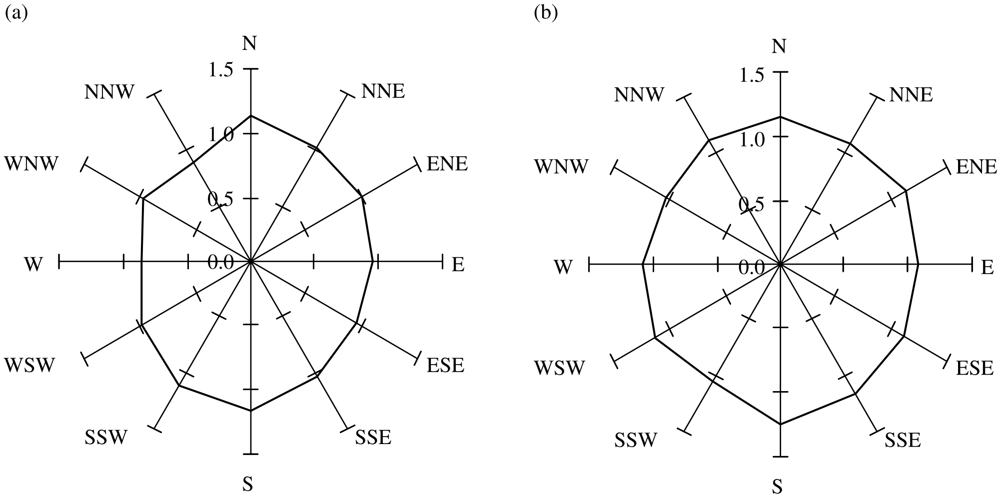

Figure 5 | Layouts with baffles. Bacterial removal (log units) as a function of the wind direction. Layouts 3 (a) and 4 (b) at a wind speed of 2 m s^{-1}.

2 m s^{-1} wind speed, the bacterial removal is in the range of 0.86 to 1.12 log, and higher than without baffles by 10% (N) to 42% (SSW) (Figure 5a). Taking the different mean residence times into account, this removal is in agreement with the results of Shilton & Harrison (2003). Compared to our simulations, the removal calculated by Shilton & Mara (2005) for the same geometry and a lower detention time appears over estimated, but this might be attributable to a die-off coefficient 10 times higher than in the present work. Although the overall performance is improved by the baffles, the wind directions that have a component on the inlet-to-outlet axis generate lower removal. The velocity and concentration map at the water surface 12 h after the injection for a wind coming from the West shows different concentrations in the three parts of the pond (Figure 6). The first baffle creates recirculation and helps mixing in the first part. In the central part, water velocities are higher along the South wall and the second baffle. The North zone of the central part of the pond seems to little participate to the water flow. In the last part, the tracer runs alongside the East wall to the outlet, creating a hydraulic short-circuiting. For a North wind, at the same time, the tracer remains in the first part of the pond. The concentration in the rest of the pond is distinctly lower and the tracer has not reached the outlet. The wind, even at this low wind speed has a clearly visible influence on the flow pattern.

The L-shaped baffle was an attempt to reduce the occurrence of short-circuits. Simulations showed that, at 2 m s^{-1} wind speed, it allows increasing the microbial removal up to 1.03 to 1.24 log units (Figure 5). Moreover, the sensitivity to the wind is smaller than with regular baffles. The smaller removal is higher than the maximal

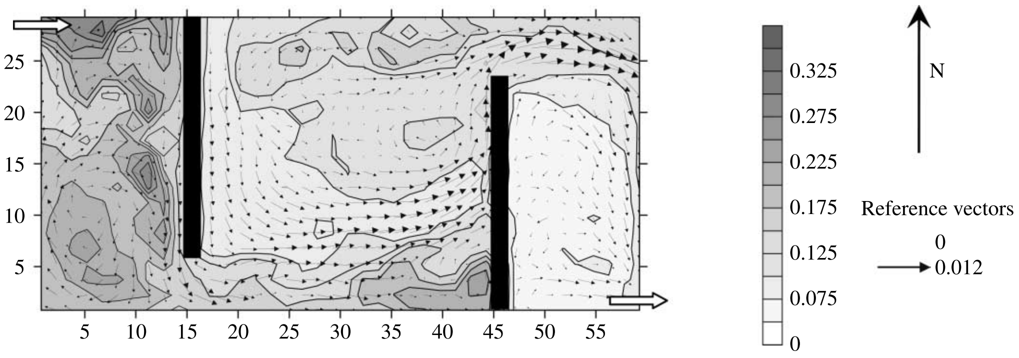

Figure 6 | Layout 3. Water velocity (m s^{-1}) and tracer concentration (m^{-3}) at the pond surface, 12 h after injection, for a wind coming from the West, at a speed of 2 m s^{-1}.

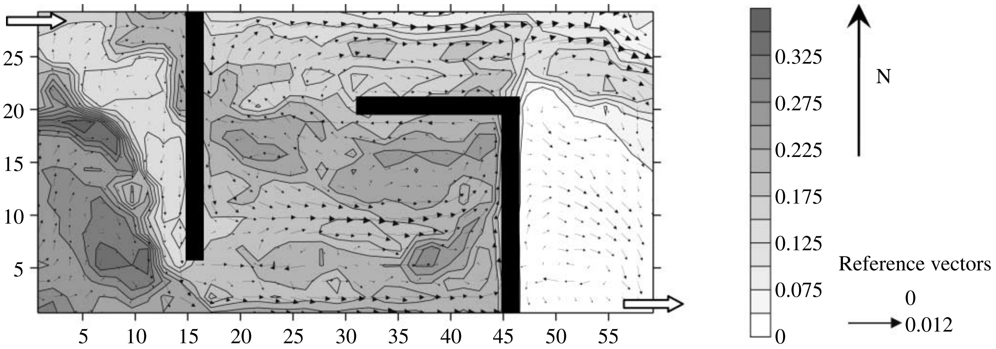

Figure 7 | Layout 4. Water velocity ($m\,s^{-1}$) and tracer concentration (m^{-3}) at the pond surface, 12 h after injection, for a wind coming from the West, at a speed of $2\,m\,s^{-1}$.

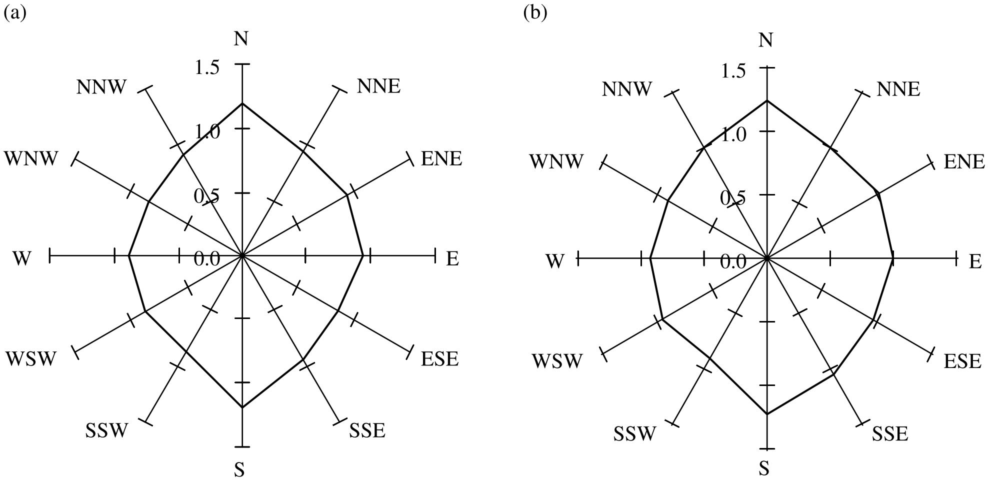

Figure 8 | Layouts with baffles. Bacterial removal (log units) as a function of the wind direction. Layouts 3 (a) and 4 (b) at a wind speed of $6\,m\,s^{-1}$.

removal simulated for layouts without baffles. Velocity and concentration maps show that the "L" baffle enables to reduce the short-circuiting along the walls and the dead zones (Figure 7). Compared to layout 3, the improvement is noticeable for a wind coming from the West, which is the most unfavourable condition, and negligible for a wind coming from the North.

The sensitivity to the wind direction is increased at wind speeds of 4 and $6\,m\,s^{-1}$, the lower removal corresponding to winds with an inlet-to-outlet component (Figure 8). The maximum removal for layouts 3 and 4 with a $4\,m\,s^{-1}$ wind speed is 1.24 log, but the minimum value is only 0.84 log for layout 3 and 0.91 log for layout 4. There are very little differences in the calculated removal when the wind speed varies from 4 to $6\,m\,s^{-1}$.

The design with an L-shaped baffle (layout 4) enables a slight improvement compared to layout 3. It diminishes the sensitivity to the wind direction at low wind speed.

CONCLUSION

In all cases the wind effect was shown to affect significantly the pond disinfection performance. For geometries without baffles, the performance is dependent on the wind direction, the worst being the ones where the wind blows from the inlet to the outlet. Poorer performance comes along higher wind speeds. There are no significant difference between aligned and non-aligned inlet and outlet in un-baffled ponds. The addition of baffles was shown to have a positive impact both on the bacterial removal and on the sensitivity to the wind direction. The usual set of two baffles improves significantly the pond performance, but is still sensitive to the wind. An orientation of the pond such that the dominant wind is orthogonal to the inlet to outlet direction should be always preferred. A L-shaped baffle was found to be able to lower the sensitivity to the wind direction, particularly at low wind speed. The pond performance tends to stabilize for wind velocities higher than $5\,\mathrm{m\,s^{-1}}$. In the most frequent meteorological conditions of Southern France, the improvement of the performance due to the introduction of baffles in the pond design does not exceed 0.3 log units for a die-off coefficient of $0.6\,\mathrm{d^{-1}}$.

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