The impact of wind on Waste Stabilisation Pond performance

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Abstract. A growing body of data suggests that, whereas wind may assist pond mixing, it more often severely damages performance by causing short-circuiting and reducing mean hydraulic retention time (MHRT). It has been suggested that the damaging effect can range in magnitude between 23 and 35%. Experiments were designed to assess the impact of controlled wind conditions on the hydraulic performance of a physical model of a single and a three channel maturation pond and of the identical system in a three dimensional mathematical model. Dynamic similarity was applied to a full scale prototype in constructing the physical model and in controlling wind conditions. In the absence of wind for a centrally aligned longitudinal pond, maximum hydraulic retention time of 1.16 days was achieved in the physical model. The mean hydraulic retention time was reduced by 23% (to 0.89 days) when the prevailing wind was either opposite to or parallel to the direction of flow from the inlet. Similar result were obtained for a 3 channel pond with 5cm open gap, the MHRT was reduced by 24% from 1.78 to 1.36 days. The results from mathematical model HYDRO3D demonstrated over 90% of convergence with the physical model.

Key words: Hydraulic efficiency; mathematical modelling; physical modelling; wind effects; WSP performance.

INTRODUCTION

There are many well-documented papers on the hydraulic behaviour of WSPs, of which only a few deal with the wind effect, and they may be divided in two groups. One group considers that the wind is significant because it reduces the hydraulic performance by increasing short-circuiting, but it can improve the transverse mixing (Agunwamba, 1992). Others consider that the wind is insignificant because the inertial force controlling the mixing is generated partially by the inlet discharge (Shilton, 1999). The published papers on hydrodynamic tracer studies and computational models are more extensive. The majority of these are not reliable since the wind effect was ignored. As a result of the lack of reliable, well-documented case studies the parameters which control mixing and hydraulic pathways in WSPs are not fully understood.

Wind action may play more than one role. Not only does it, determine the velocity distribution and direction, but it also establishes the magnitude of the turbulence diffusion both in the surface layer and also lower down the liquid column (Banks, 1975). There is thus a need to know the impact varying wind directions and velocity distribution produces on MHRT, and hence quality, performance under carefully monitored conditions demonstrating that even slight breezes can have very damaging effects on WSP performance.

The US EPA (1983) established that "wind generates a circulatory flow in bodies of water. To minimise short-circuiting due to wind, the pond inlet-outlet axis should be perpendicular to the prevailing wind direction (side wind). If for some reason the inlet-outlet axis cannot be orientated properly, baffling can be used to control, to some extent, the wind-induced circulation. It should be kept in mind that in a constant depth pond, the surface current is in the direction of the wind and the return flow is in the upwind direction along the bottom". These assertions were apparently based on limited field observations. There has been little systematic research during the past 20 years ago to prove this assumption.

Previous studies carried out by the authors examined the impact of wind on circulation patterns and suggested that the resulting flow paths are complex. A prototype lagoon at Lidsey in England with the prevailing wind blowing along the long axis opposite to the flow direction produced overturn circulation and significant short-circuiting during tracer studies. This resulted in an upward slope of 5 cm over the water surface in downwind direction (Bracho, 2003). Aldana *et al* (1999), in studies carried out on a full scale facultative-lagoon in the University of Zulia's system concluded that the wind effect is most significant in the top 40 cm below the surface.

Matthews *et al* (1997) stated that "wind-induced circulation patterns were prominent under low wind conditions, and wind speed and direction typically affected the results of the dye-tracing experiments", but they did not state the direction and velocity of wind. Others authors, concluded that wind effects on hydraulic efficiency are slight and that wind effects on dispersion and the overall residence time distribution are uncertain, but are probably significant. Based on studies of full-scale lagoons they suggested that the major effect of wind is to promote mixing and not reduction of MHRT. The high wind-induced surface velocities and associated return underflows promote lateral and vertical mixing at the expense of low mixing and advective flow (Thackston *et al,* 1987). However Thackston's studies did not include comprehensive analysis of flow paths under field conditions.

Lloyd *et al* (2002) demonstrated in a full-scale maturation pond in Ginebra, Colombia that the reduction of wind effects by wind breaks reduces mixing and hence dispersion, and significantly increases mean hydraulic retention time thus assisting in improving FC removal. They fenced the channel-maturation pond using a woven plastic wind break 2 m high to achieve these changes.

Arfi *et al* (1993) also agree that particle re-suspension under certain conditions of fetch, wind velocity, bed roughness and bathymetry are induced by wind driven flow. They based their study in a shallow tropical lagoon (1m depth). The wind-induced surface currents are transmitted through an interface layer to the bottom layer. This phenomenon was described by Chu and Soong (1997) as the entrainment law. As wind blows over the water surface the upper layer of the water body is mixed by the wind shear and deepens in the course of time as fluid from the lower moves in the opposite direction is entrained into the upper layer. This phenomenon can be studied using a computational hydraulic model. Guganesharajah (2001) used a calibrated model, HYDRO-3D, to define the mean hydraulic retention time (MHRT) distribution in WSPs including wind effects for a rectangular pond. Phenomena such as a drift wind at the top layer can be study and predict the reduction of MHRT as wind blow hard.

Sweeney *et al* (2002) used an uncalibrated computational model pond (FLUENT 5.5) for a trapezoidal pond. They simulated wind by using a shear stress equation and from the results of their simulation they concluded "the results indicate that a wind direction perpendicular to the direction of bulk flow (side wind) will produce the greatest degree of short-circuiting". Although this contradicts the US EPA assertions, there is significant agreement with their FLUENT 5.5 model prediction and the age-distribution profiles of HYDRO-3D. That is, the increase in wind velocity reduces the mean hydraulic retention time of the pond and also the delay time for tracer beginning to leave the pond is also reduced.

Since wind effects cannot be readily isolated in field studies, other methods such as calibrated computational fluid dynamic (CFD) (Guganesharajah, 2001) and physical models (Aldana, 2004) can be used to better understand the impact of wind on WSPs. These models including both laboratory, computational and pilot-scale ponds, allow tests to be conducted which would have been difficult with full scale WSPs. Thus the aim of this paper is to investigate the impact of wind and pond configuration on pond hydraulics under controlled conditions.

METHODS

Sixty five (65) tracer experiments in total were carried out with the dye Rhodamine WT using the stimulus-response technique with a physical model located in a glass house. Four series of experiments were carried out during the period August 2001 to August 2003 to identify which factors influence the hydraulic performance of WSPs. Series 1 was run considering solely a centrally aligned, longitudinal inlet and outlet arrangement, and with inlet and outlet diagonally opposite. Twenty nine experiments were analysed in still water with a flow rate of $12x10^{-3}$ l/s without wind effects. Series 2 was run with 19 experiments and replicates considering interventions with baffles and multiple inlets. There were three test positions for cross-wise baffles; 1 m from the inlet edge, 1 m from the outlet edge, and both baffles at the same time at the position.

Series 3 was run with 6 experiments and replicates when the physical model used in series 1 and 2 had been converted to a three channel configuration. Three length-wise baffles were constructed within the physical model of 0.30 m width, 0.60 m height and 6 m length. The effects of three gap sizes at the end of each channel, 0.50 m, 0.25 m and 0.05 m, were studied. The results obtained from each experiment were compared. The main objective was to investigate whether length-wise baffles can increase performance in WSPs, compared with the earlier experiments, to determine the best gap size. The discharge of water into and out of the model was set and monitored, and wind conditions were excluded. In an extra experiment a width-wise baffle was installed into each of the three channels at the mid-point using a plastic blind.

Series 4 was run with 9 experiments and replicates of wind effects with inlet/outlet centrally aligned, longitudinal and diagonally opposite in the physical model, and width-wise baffles and length-wise baffles. Wind was created by using an electric fan with a three-speed velocity control in order to study whether or not wind can either compromise or benefit hydraulic efficiency in WSPs. Two methods were used to analyse wind: a physical model in still air and the computational model HYDRO-3D. The nine configurations of the physical model studied are shown in Figure 1. Several parameters were compared including depth, dispersion number (d), average flow rate, NRT and MHRT. Other parameters are included to facilitate comparative analysis including temperature, time that first tracer peak existed (ti), advective flow dispersion index (ti/MHRT) and hydraulic efficiency correction factor (HECF = MHRT/NRT). The results are presented in the figures for tracer age-distribution.

Physical model

Geometry, kinematics and dynamics similarities. A model area on a scale of 1:18 of a full-scale lagoon was constructed of 0.86 m width x 6.60 m length. Several attempts were necessary to achieve the final model specifications including dimensional, geometrical, kinematic and dynamic similarities but not in the depth and hence volume ratios, thus it is a distorted model (Aldana *et al*, 2004).

Wind velocity calibration. It is a challenge to model wind conditions. It is usual to use a wind tunnel to produce the wind effect on the physical model, but it is expensive to build and there was a space limitation to fit it in the available glass-house. A cheap solution was to create the wind effect by using a fan with speed control. In order to achieve similar wind speed as at the site of the prototype (2 m/s) a ratio of 0.05 for geometry similarity was used. Due to the use of a distorted model, the dynamic similarity ratio can not be assumed to define the wind speed in the model. The value obtained by using equation [1] gives 0.1 m/s for wind speed over the physical model.

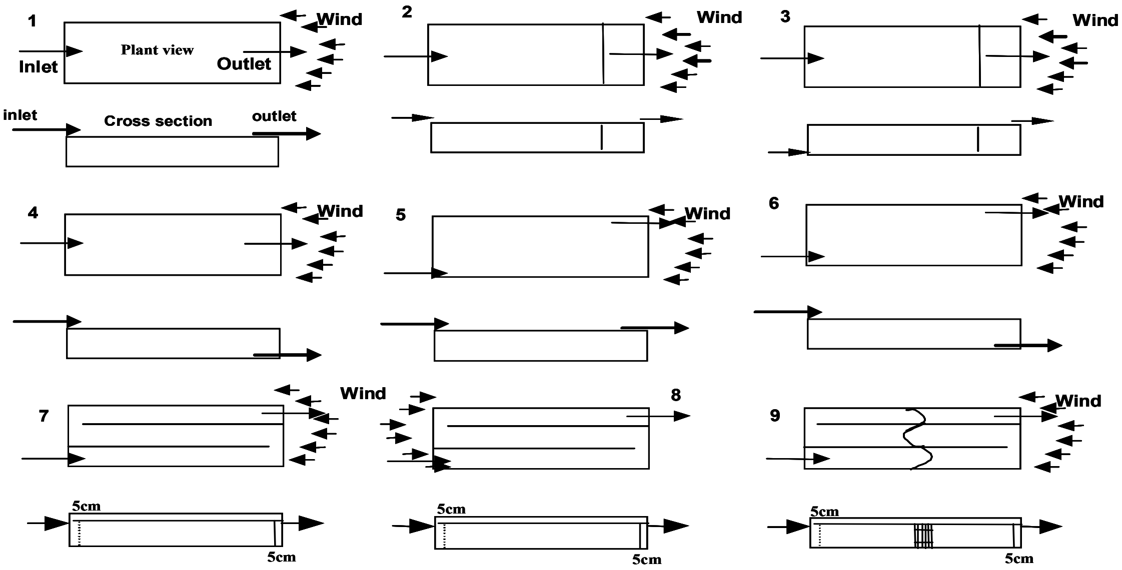

Figure 1. The nine configurations studied. Note: cases 7 and 8 was done with replicate (Not to scale)

$$\frac{V_m}{V_p} = 0.05 \qquad [1]$$

A device called *GeoPack* a hand-held electronic counter was used. This is a stream flow meter for measuring velocity in water. The wind propeller was originally a stream flow meter before being modified by Wong (2003) to increase its sensitivity to wind. In order to correlate the wind propeller count (rpm) with the wind velocity (m/s), the wind propeller had to be calibrated according to an anemometer with a wind logger (ELE International). For this purpose the three devices (the wind propeller, direction indicator, and an anemometer) were fixed on a supporting metal structure. Thus, all three devices moved together (1m, 2m, 3m, 4m and 5m) from the fan. This comparable reading could be taken easily and produced wind velocities ranging from 0.067 to 2.04 m/s, which corresponded to wind propeller counts between 153 and 943 rpm. The calibration curve is presented in Figure 2.

Computational model

The three dimensional computational model (HYDRO-3D) was run with the lowest reliable value wind velocity of 0.25 m/s from the physical model. Hydraulic model runs were done in the presence and absence of wind effects. The criteria for the choice of the experiments from 16 cases (8 without wind and 8 with wind) analysed in the physical model, were primarily high HECF values, as shown in Table

1. However, for particularly low HECF values the centrally aligned inlet and outlet was selected because it represents an arrangement found worldwide and recommended by US EPA (1983).

In order to calibrate the hydraulic model it was necessary to make changes in the dispersion coefficients varying in the range between 1x10^{-2} m^2/s to 1x10^{-5} m^2/s. The 3D-network for the physical model was created using ArcView GIS for experiments 1, 3, 5 and 7. The current vectors were displayed using ArcView GIS for four layers in both experiments analysed, with and without wind. However, this paper presents plots only to the first layer at the top surface.

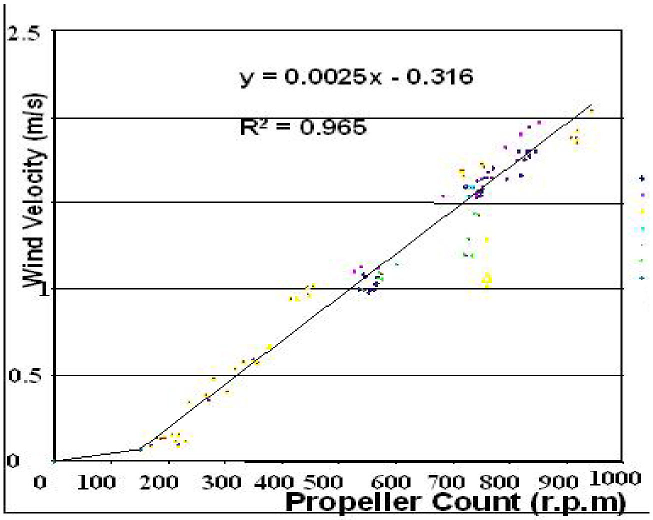

Figure 2. Wind propeller count and wind velocity correlation. After Wong (2003).

Table 1. Selection of physical model configuration and results of hydraulic efficiency correction factors (HECF) for HYDRO-3D simulations. Note: Blank Not determine.

Experiment Number	Experimental network set up in HYDRO-3D	HECF
1	Centrally aligned without wind effect	0.57
2	Centrally aligned with wind blowing opposite	0.41
3	Centrally aligned without wind effect, with width-wise baffle 1m from the outlet	1.0
4	Centrally aligned with wind blowing opposite to the inlet and with width-wise baffle 1m from the outlet	0.32
5	3 channels with 25 cm gap without wind effect	0.90
6	3 channels with 25 cm gap with wind blowing opposite to the inlet	
7	3 channels with 5 cm gap without wind effect	0.92
8	3 channels with 5 cm gap with wind blowing opposite to the inlet	0.70

RESULTS

Physical Model

The impact of wind can be observed clearly in Figure 3 for the commonest worldwide open pond layout (cases 1) recommended by US EPA. The impact of wind can reduce hydraulic efficiency by 23% with high dispersion number (promoting partial-dispersed flow); this was worst (case 4) when the outlet is placed at the bottom by 34%.

The HE for these configurations was 0.41 and 0.46 (cases 3 and 4), respectively from Table 1 (NRT not reported). This MHRT is dramatically reduced by 50-68% (cases 2 and 3) when it is set up with width-wise baffle 1m from the outlet. In contrast the US EPA state “if for some reason the inlet-outlet axis cannot be orientated properly, baffling can be used to control, to some extent, the wind-induced circulation”. Nevertheless, the HE was better for these cases 2 and 3 up to 0.32 and 0.41.

Cases 5 and 6 were carried out with inlet and outlet diagonally opposite and wind blowing opposite to the inlet, these experiments without wind showed one of the most inefficient hydraulic efficiency performance (HE = 0.51) (Aldana *et al*, 2004). The intervention with three channels and wind increases the hydraulic performance cases 7, 8 and 9 by at least 20% (HE = 0.70 and 0.66 and 0.92, respectively). This is correlated with a reduced dispersion number (promoting plug flow). MHRT is increased, in comparison to all the other configurations. The hydraulic efficiency was found similar when the wind was blowing either opposite or parallel. The curves have similar characteristic as shown in Figure 3.

Computational Model

Experiments 1 and 2

Without wind. The first layer shows slight turbulence in the inlet area along the first meter from the inlet. This is due to the shear stress produced by the flow into the basin. In this zone, a velocity of 0.0006 m/s was measured by ArcView GIS, whereas in the middle of the physical model the flow moves very gently (v = 0.00002 m/s) (upper simulation in Figure 4). A streamline moves along the right edge until it arrives near the outlet.

With wind effect. When the wind (0.25 m/s) blows in the opposite direction to the inlet flow there is a high turbulence in the inlet area which is a product of inlet flow and wind shear stress. In the first layer the dominant flow path it is made visible by the arrows moving backwards with similar velocity (0.003 m/s). This picture (Fig. 4 below) clearly shows the dramatic effect that the wind can produce in the very top (0.05 m) layer, the velocity being 100 times higher than the velocity without wind.

Experiments 7 and 8

Without wind. In the absence of wind the three-channel physical model produced a gentle laminar type of flow down the flow direction of the channel, and similar velocities were noted at the wall. The HYDRO-3D simulation of flow paths is in good agreement with observations on the physical model using rhodamine. In the first and the second end of channel gaps increases velocities 100-fold time (v = 0.001 m/s) passing through the gap were noticed as shown in Figure 5.

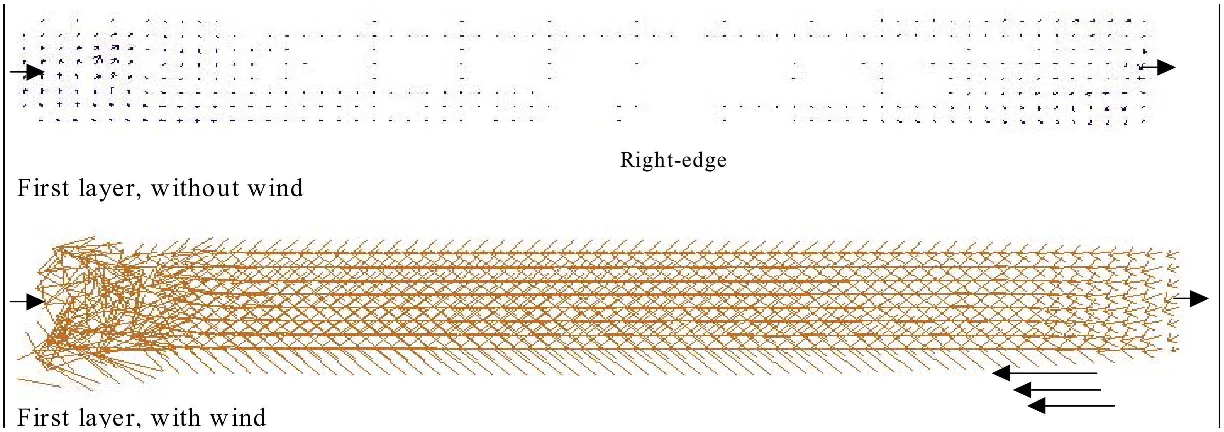

Figure 4. HYDRO-3D simulated current vector velocities for the physical models centrally aligned. Inlet and outlet at the top.

With wind effect. The influence of wind (0.25 m/s) blowing in the direction opposite to the inlet flow in the three channel physical model produced the dominant flow path in this first layer. In the first layer the simulation produced 100 time higher forward velocities (v = 0.0009 m/s) in all three channels but lower velocities at the wall and floor. Since the narrow gap is placed at the bend (0.05 m) the velocity increased at the end of each channel as shown in Figure 5 below.

DISCUSSION AND CONCLUSION

The results from physical and computational models presented clear evidence of a very fine dye-plume travelling at a high velocity in the absence of wind, but a dispersed dye-plume with even higher velocity when wind was blowing opposite to the inlet. There are several factors influencing advective flow: wind stress, viscous effects, boundary shear and inlet discharge, and in this case it is the wind which is reducing MHRT by more than 30%. Other factors accounting for 20% reduction are L/W ratio, inlets and outlets arrangements, wall dividers and baffles. This is in accordance with Sweeney *et al* (2002) results, ponds without wind promotes plug flow characteristic in contrast to ponds with wind (side wind) increases completely mixed conditions, with a rapid increase in longitudinal dispersion at wind velocities above 4 m/s.

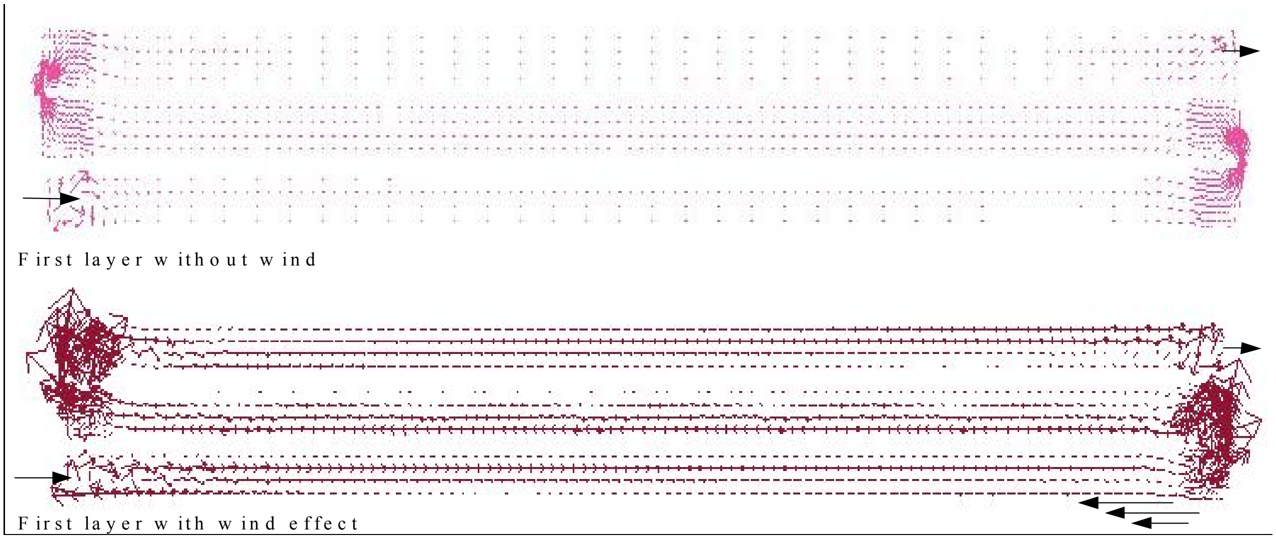

Figure 5. HYDRO-3D simulations of current vector velocities plot for three channel physical model with 0.05 m gap. Inlet and outlet at the top.

In order to establish a relationship between MHRT and NRT a linear regression was done for 44 points from the physical model experiments, and it was added 16 points from full-scale lagoons from Latin American, Caribbean Islands, England, Canada and Australia A equation was developed MHRT = 0.53*NRT for 60 data points and 0.79 r-square. This explains why traditional equations for WSPs design have failed to meet performance specifications: they use nominal retention times calculated from pond volume/flow (V/Q) rather than an estimate of mean hydraulic retention time from a physical or mathematical model (Guganesharajah, 2001). The results produced by HYDRO-3D for a single lagoon (L/W, 1:7.67) with inlet and outlet centrally aligned, were compared with and without wind simulations. The wind blowing opposite to the inlet can produce reduced efficiency (23%) in the uppermost layer as a result of much higher velocity, 100-fold greater than without wind.

The flow path along the direction of wind, but producing short-circuiting in the inlet area with higher velocities through the lagoon moving backwards and forwards at different depth levels. The advantage of the narrow gap (0.05 m) is that the dominant flow path produces guttering in each channel, and movement away from the inlet towards the outlet and overturn, returning on the walls towards the inlet again. This movement appears to produce the longest flow path travelling within the lagoon, and obviously it should increase the MHRT. In particular, it is clear that baffles and channels (>L 8 :W 1) both provide substantial hydraulic improvement. By contrast inlet/outlet arrangements are unimportant if the ponds are channel shaped due to vanishes the momentum transfer and the inertial force effects at the inlet. As turbulent flow is diminished axial flow is increased and plugs flow is promoted so other factors as flow instabilities and inlet type are reduced even more at the outlet.

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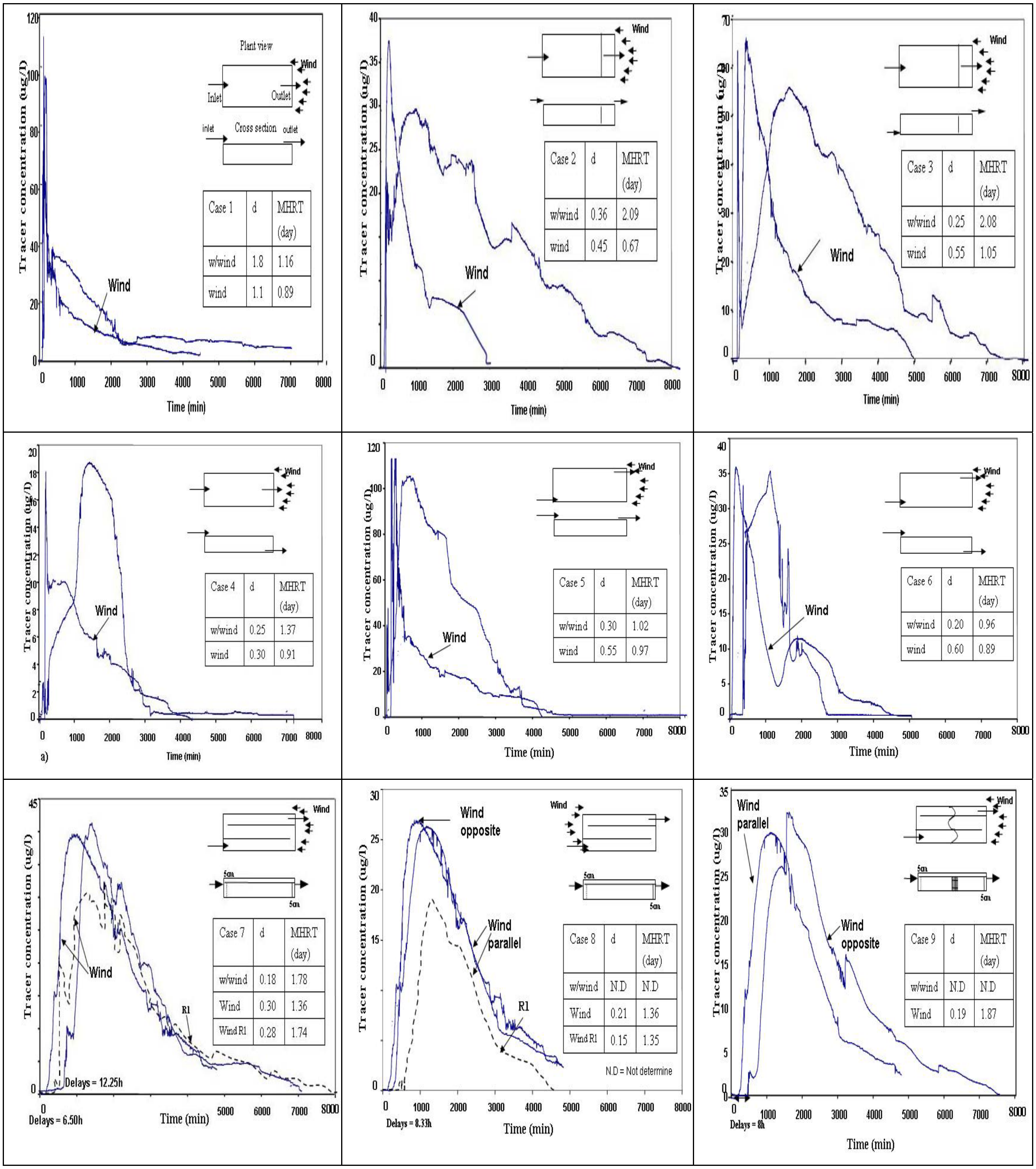

Figure 3. Comparison of the impact of the wind effect for the nine cases studied on age distribution of Rhodamine WT in the physical model.