# Hydrodynamic evaluation of a full-scale facultative pond by computational fluid dynamics (CFD) and field measurements

Ricardo Gomes Passos, Marcos von Sperling and Thiago Bressani Ribeiro

## ABSTRACT

Knowledge of the hydraulic behaviour is very important in the characterization of a stabilization pond, since pond hydrodynamics plays a fundamental role in treatment efficiency. An advanced hydrodynamics characterization may be achieved by carrying out measurements with tracers, dyes and drogues or using mathematical simulation employing computational fluid dynamics (CFD). The current study involved experimental determinations and mathematical simulations of a full-scale facultative pond in Brazil. A 3D CFD model showed major flow lines, degree of dispersion, dead zones and short circuit regions in the pond. Drogue tracking, wind measurements and dye dispersion were also used in order to obtain information about the actual flow in the pond and as a means of assessing the performance of the CFD model. The drogue, designed and built as part of this research, and which included a geographical positioning system (GPS), presented very satisfactory results. The CFD modelling has proven to be very useful in the evaluation of the hydrodynamic conditions of the facultative pond. A virtual tracer test allowed an estimation of the real mean hydraulic retention time and mixing conditions in the pond. The computational model in CFD corresponded well to what was verified in the field.

**Key words** | CFD, computational fluid dynamics drogue, dye, full-scale facultative pond, GPS

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## INTRODUCTION

Waste stabilization ponds are a natural and widespread technology for sewage treatment, especially in tropical climates. Their main advantage is the conceptual simplicity, no mechanization and no sludge handling for most of the operational horizon. However, the major limitation lies in the large land requirements (Mara 2003; von Sperling & Chernicharo 2005; Shilton 2005). The performance of stabilization ponds may be related to several factors, such as loading rates, weather conditions, influent quality and pond geometrical configuration.

The knowledge of the hydraulic behaviour is very important in the characterization of a pond. This behaviour may be influenced by mixing characteristics, presence of dead zones, short-circuiting, sludge accumulation and fluid velocities. Those characteristics are directly related to several factors, such as flow rate, inlet size, inlet position and orientation, outlet position, pond geometry and baffles, temperature and density effects, and wind (Shilton & Sweeney 2005). Since these elements are complex, they are not considered in performance models that assume idealized hydraulic patterns in the ponds. An advanced characterization may be achieved by carrying out measurements with tracers, dyes and drogues (floats with adaptations) or using mathematical simulation.

Among the methods mentioned above, most researches in stabilization ponds use the stimulus–response technique with tracers. Levenspiel (1999) presents one of the best-known theoretical references about this subject.

Drogues are floating objects arranged in water bodies for the measurement and determination of the speed and flow pattern. In the study of a stabilization pond, Mangelson (1971) used drogues to make a general observation of the flow streams, noting that they did not move directly to the output. Mangelson also suggested that the position of the inlet pipe was the main factor responsible for the flow patterns observed in the pond. Frederick & Lloyd (1996)

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used 100 oranges as drogues, introduced into the inlet piping of a facultative pond, in order to visualize the flow pattern. As in Mangelson's work, no quantification of the hydraulic dispersion was done.

Apparently, the first quantitative monitoring with drogues in stabilization ponds was performed by Shilton & Kerr (1999). The authors tracked the drogues using theodolites, recording their position. A series of readings over time made it possible to obtain velocity vectors of the flow. The drogues were fitted with a float filled with water (to minimize the area exposed to wind action), connected to PVC plates of 20 cm × 20 cm in cross form, which served as a submerged 'sail'. After that, Shilton & Bailey (2006) used drogues in a reduced-scale pond (prototype dimensions of 2.715 m × 1.750 m × 0.125 m).

Besides the use of tracers, dye and drogues for investigation and inference of the hydrodynamic behaviour of ponds, several authors mention computational fluid dynamics (CFD) as a promising tool to obtain more detailed knowledge of the flow inside the lagoons. Daigger (2011) makes a discussion on the prospects for future development and use of models for wastewater treatment, reporting the large gap in the area and the need for greater attention to available tools such as CFD.

The current study involved experimental determinations and mathematical simulations of a full-scale facultative pond in Brazil. The CFD model showed major flow lines, degree of dispersion, dead zones and short circuit regions in the pond. Drogue tracking, wind measurements and dye dispersion were also used in order to obtain information about the actual flow in the pond and as a means of assessing the performance of the CFD model.

By incorporating the CFD tool, a representative diagnosis of the hydrodynamic conditions was obtained, reinforcing the use of this tool as an important aid in performance evaluations of ponds. Regarding this last point, some authors, such as Shilton *et al.* (2008), report that there is little scientific evidence on the validation of CFD models in full-scale ponds.

## METHODS

### Facultative pond under study

The facultative pond was in operation for 27 years, treating the effluents from the international airport of the city of Belo Horizonte, Brazil. Because the airport was functioning below its capacity, the produced wastewater flow and load were below the design value, and the pond operated during all this period at underloaded conditions. The average flow during this 27-year period was 8.0 L/s, which led to an average theoretical hydraulic retention time (HRT) of 193 days in the pond and a mean surface organic loading rate of 44 kg 5-day biochemical oxygen demand per hectare per day. The dimensions of the facultative pond, which has a trapezoidal shape, are: north side length = 190 m; south side length = 145 m; inlet end width = 118 m; outlet end width = 126 m. The dyke's internal slopes are 1:2.5 (vertical:horizontal) and the liquid depth is 2.90 m The inlet is divided into two pipes that advance approximately one-third into the pond length. The inlet pipes have a 90° curve directed to the bottom, through which the influent is released into the pond. The pond performance is described in Passos *et al.* (2013).

### Fieldwork

The main fieldwork activities comprised wind measurements and tests with drogues and dye. Wind measurements (speed and prevailing direction) were performed for 6 days at various locations in the area, on the edges of the pond and immediately above its surface (using a boat). The values of mean wind speed and prevailing direction were entered as boundary conditions (BC) in the hydrodynamic model.

A dye (amaranth) was used for a preliminary visualization of the flow pattern. The solution was injected instantaneously – featuring a pulse input – in the Parshall flume at the preliminary treatment (influent to the facultative pond), and also on the sides of the pond and near the inlets and outlet, in order to obtain visual information about the streamlines in different regions of the pond and further comparison with the results from the CFD model.

Oranges and an equipment mounted especially for this purpose were used as drogues. The oranges were released near the inlets. Due to their high susceptibility to wind drag, they were used primarily to observe the wind influence on the surface. The drogue made as part of this research was based on the scheme presented by Shilton (2001), with a float connected to an inverted submerged 'sail' (Shilton & Kerr 1999). In their work, the flow drove the submerged 'sail' and the drogue path was obtained by means of theodolites positioned on the sides of the pond. The equipment mounted in the current study is innovative, in that it includes a geographical positioning system (GPS) to record the drogue's path. The drogue shown in Figure 1(a) had a stretch of PVC pipe (75 mm, half-way submerged) connected by two aluminium brackets to acrylic plates of 200 × 200 mm. The PVC pipe functioned as a float and in the inner part was

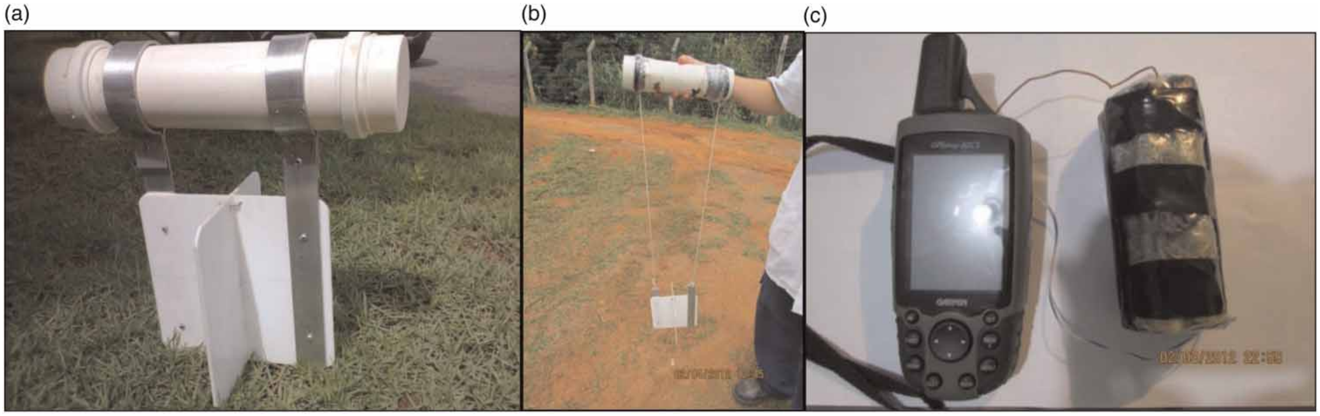

**Figure 1** | (a) Prototype of the drogue mounted to record the flow in the pond, (b) modified drogue with adjustable length, to follow the flow at any depth in the ponds, and (c) GPS and battery adapted for use in the drogue.

inserted a GPS, programmed to record automatically the route taken by the equipment during the period that it remained in the pond. The float was sized so that the void volume was sufficient to ensure buoyancy for all the equipment and to float at the lowest possible exposure to wind. Subsequently, the design of the drogue was modified so that it was possible to adjust its level according to the depth of interest. In place of the aluminium straps, two adjustable ropes were attached to the drogue (Figure 1(b)), leading to a depth of submergence of the 'sail' in the pond of 1.20 m. The GPS and battery were introduced into the float and the drogue was left near one of the inlet pipes, remaining for 6 days at the pond. The trajectories were compared with those obtained from the CFD model.

After reviewing the literature, it is believed that this work is the first to use a GPS attached to a drogue, obtaining automatically the path travelled by the equipment in the pond.

## CFD modelling

The methodological steps of the CFD modelling consisted of building a three-dimensional geometry that represented the pond, the development of a mesh of finite volumes, defining BCs, calculation methods, additional equations and, finally, processing. The CFD software used was 11.0 Ansys®. The package included a mesher and a pre-processing, processing and post-processing module (11.0 CFX®).

The geometry should represent the domain of simulation, so only the volume occupied by the liquid in the pond was considered, with the current depth of the pond operation. The meshing method used in CFX was the finite volume method. A superficial mesh was generated of unstructured triangular elements on the pond geometry, through the Delaunay triangulation method, and from it was derived the volumetric mesh, through AFVM method (advancing front volume mesher), standard in CFX. Moreover, a mesh independence study was made, performing simulations on the same physical and boundary conditions in progressively finer meshes until a mesh was obtained in which a greater refinement did not significantly alter the simulation results.

The fundamental equations of conservation of mass, momentum and energy, which are the basis of CFD models, are available in several textbooks (e.g. Versteeg & Malalasekera 2007). Besides these equations, another one has been added to the model in order to simulate a tracer test in the pond (Equation (1)) resulting from a virtual tracer pulse injection during the first time step (6 h)

$$\text{Tracer} = [\text{kg}\,\text{s}^\wedge - 1] * \text{step}((\text{t} - 6[\text{h}])/1[\text{h}]) * \text{step}((12[\text{h}] - \text{t})/1[\text{h}]) \quad (1)$$

A velocity inlet BC was assigned to the locations where the fluid arrives in the pond (two entries).

For the pond outlet, the 'opening' BC was used, in which it was possible to adjust the relative pressure (set to null). The 'outlet' BC was also tested, but it is more recommended when one knows exactly the direction of the output arrays. In the previous simulations, tests with the output condition 'outlet' did not lead to a good convergence. For the slopes, a wall 'no slip' BC was defined, with tangential velocity to zero on the interface and smooth roughness, since the material that makes up the slopes has this characteristic (compacted clay). For the pond surface, 'opening' and 'wall' BC were tested. In the wall BC the addition of shear stresses with defined intensity in any direction is possible, a situation that does not occur with 'opening' BC. Therefore, in order to consider the wind influence, the second condition (wall) was chosen.

For the entire domain, the properties of the fluid were assumed to be those of the water (density = 997 kg/m³; molar mass = 18.02 g/mol; dynamic viscosity = 8.899 × $10^{-4}$ N.s/m²; thermal conductivity = 0.6069 W/m.K; specific heat capacity = 4181.7 J/kg.K), with average temperature measured in pond of 24.7 °C. The approximation of the wastewater properties to those of water was adopted due to the lack of experimental data and records in the literature, and also due to the similarity between both fluids in terms of flow properties. Moreover, in all consulted works regarding the use of CFD in stabilization ponds, the authors used water as fluid or did not mention it. In relation to suspended solids present in the wastewater, Alvarado *et al.* (2011) report that they do not affect the fluid properties defined for simulation.

The turbulence model used in the simulations was the SST (shear stress transport – hybrid model of k-$\varepsilon$ and k-ω). The SST model consists of a transformation of the k-$\varepsilon$ model for a k-ω formulation and subsequent addition of the corresponding equations. Generally, the k-ω model is multiplied by a coupler function 'F' and k-$\varepsilon$ model by a function '1-F'. 'F' becomes equal to unity in the logarithmic region (near the surface) and zero outside it. Thus, in the boundary layer, the k-ω model was used, and at the edge and outside the boundary layer, the k-$\varepsilon$ model was used.

The simulations were run under steady state and transient conditions. RMSE (root mean square error) of $10^{-4}$ was defined as the convergence criterion for all variables. For transient simulations, the criterion for completion of the processing step was the total simulation time (5760 h; equal to three times the theoretical HRT pond), with adjustments of time step looking for the greatest stability as possible for the simulations (6 h already produced satisfactory results).

## RESULTS AND DISCUSSION

### Fieldwork

Measurements with an anemometer showed that the prevailing winds blew westwards, from outlet to inlet, with an average speed of 10 km/h. The paths taken by the oranges were substantially influenced by the wind. All the oranges went to the west side of the pond, in the direction of the prevailing winds, and remained there.

The dye released into the Parshall showed that the flow was not being distributed equally between the two inlets, and it was estimated that about 80% of the flow was directed to the north pipe inlet. From the dye tests in the pond, it was possible to observe these flow patterns, and most records demonstrated circular movement of the fluid in the pond (mix pattern).

Approximately half of the drogue was submerged and there was no substantial influence of the wind, different from the oranges, which were clearly propelled by the wind. The trajectory obtained with the drogue in the pond is shown later (Figure 3(b)) and corresponded well to what was found in the field. When exported to Google Earth® software, the trajectory was positioned exactly where it should be, a fact confirmed when checking the release point.

The arrow in Figure 3(b) indicates the location where the drogue was released in the facultative pond, next to the north entrance (which received most of the flow). The solid line before the arrow corresponds to the trajectory of the boat until the release point. The flaws in the recorded pathway with the movement of the drogue may have occurred due to loss of signal during bad weather (rain or overcast skies). From Figure 3(b) and the foregoing observations, it is observed that the drogue movement at the facultative pond was circular, in counter-clockwise direction.

The end point of the trajectory did not correspond to the point at which the drogue was rescued. After this point, the drogue was found near the same place it was released and, after that, on the south side of the pond, suggesting that it was still moving in a counter-clockwise direction, possibly with a similar trajectory to that recorded. The circular movement pattern was also observed in the dye tests. Shilton (2001) reports several flow patterns obtained from tests with drogues in ponds. The trajectories of the drogues were basically circular for all tests, with the trajectory usually dictated by the location of the fluid inlet.

### CFD modelling

After independent tests, the volumetric mesh was determined with 19,067 nodes and 73,084 tetrahedral elements.

For flow analysis and comparison with field data, a plan at the same depth of the 'sail' of the drogue was created (therefore at the same plane where the flow drove the equipment). Figure 2(a) shows velocity vectors in each grid

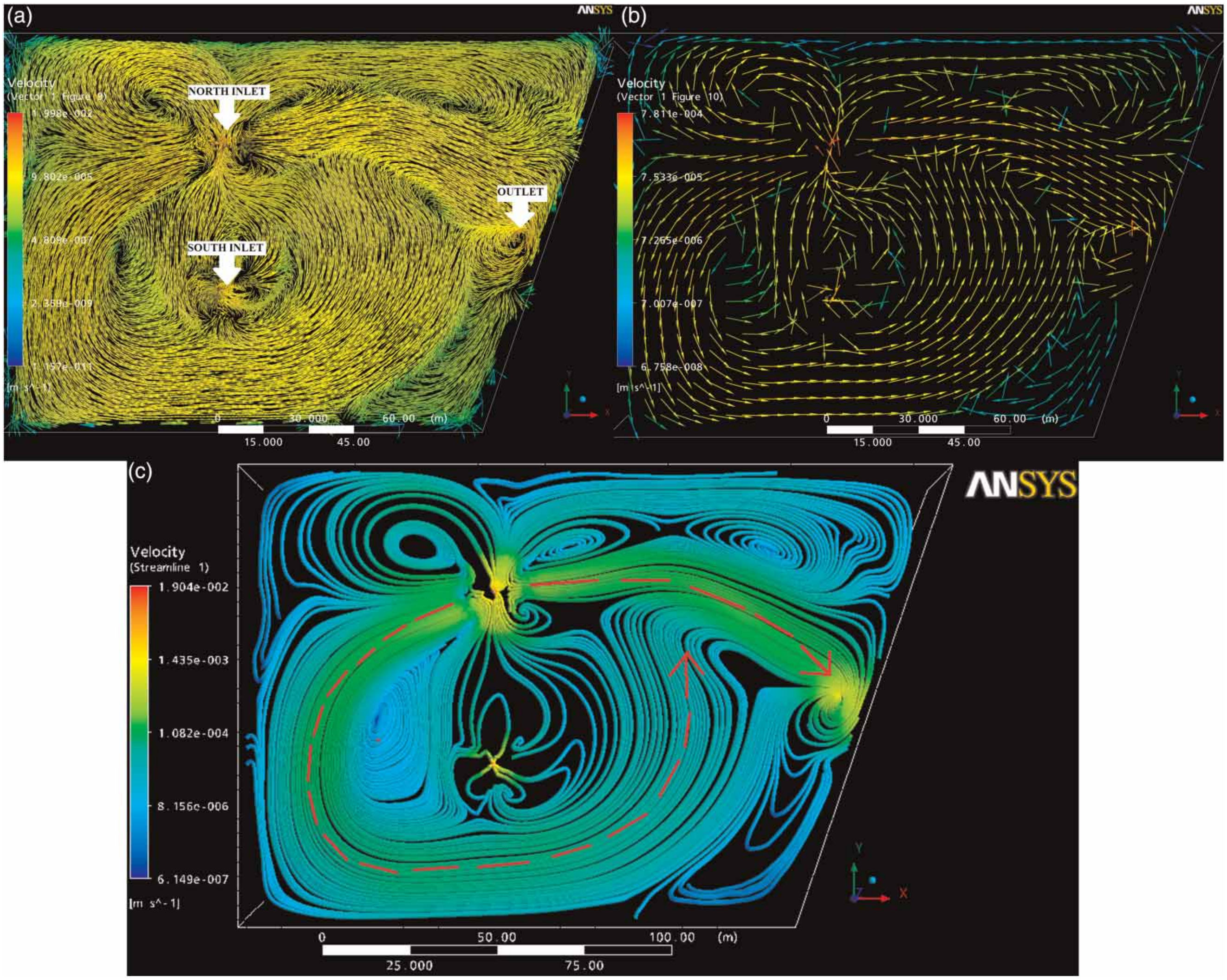


**Figure 2** | (a) Three-dimensional velocity vectors obtained with the CFD model in the facultative pond – XY plane in $Z = 1.70$ m, (b) velocity vectors uniformly distributed in the facultative pond – XY plane in $Z = 1.70$ m and (c) stream lines in the facultative pond – XY plane in $Z = 1.70$ m.

element at a depth of 1.20 m. Figure 2(b) shows the same velocity vectors in lower density and spread uniformly in geometry to facilitate viewing. Recirculation zones and short circuits are seen, as well as dead zones at the edges and corners of the pond. As expected, higher velocities near the inlet and outlet devices are observed. It is also possible to observe the great influence of the north inlet of the pond, which receives higher flow, dictating the behaviour of most of the velocity vectors. Figure 2(c) shows the streamlines at the same plan, confirming the trends illustrated by the velocity vectors. The colours vary with the velocity value (as can be seen in the online version of the paper available online at http:www.iwaponline.com/wst/toc.htm).

There is a clear streamline coming out of the north entrance and moving in the pond in a counter-clockwise direction. The north entrance is also responsible for streamlines that promote a short circuit. Both patterns are shown by dashed lines in Figure 2(c). Generally, there is a high degree of mixing in the pond.

The current flow that moves in the pond in a counter-clockwise direction, shown in Figure 2(c), is very close to the pathway of the drogue (Figure 3(b)). In order to show this, the two figures are placed side by side for comparison (Figure 3). This similarity suggests that the hydrodynamic model in CFD represented well the actual conditions of the pond.

Figure 2(c) also shows the recirculation zones and dead zones, mainly located near the north edge of the pond and corners, coinciding with the areas of greatest accumulation of sludge in the bathymetry performed by Passos *et al.*

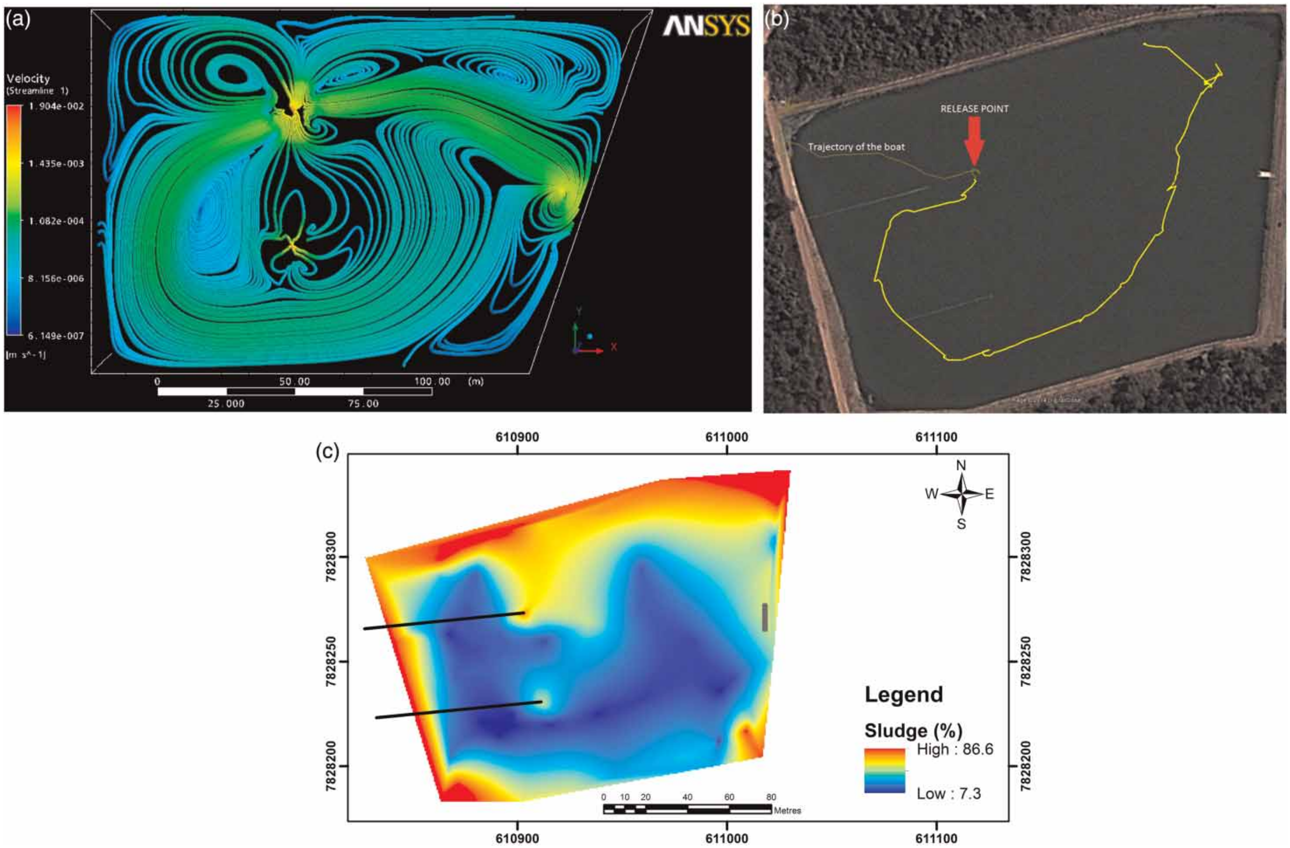


**Figure 3** | Comparison between (a) the flux lines obtained by modelling, (b) the path obtained with the drogue and (c) the map of sludge accumulation, expressed as percentage of the net pond depth – from 7.3 to 86.6% (Passos *et. al.* 2013).

(2013) in the same pond. Confirming this fact, Alvarado *et al.* (2011) also suggested higher sludge accumulation in dead zone regions, low speed zones and inlet region. Figure 3(c) shows the bathymetric map of the pond, with the percentage of sludge accumulated in terms of the pond depth.

Regarding wind, a great influence on the surface of the pond was noted, causing all the velocity vectors to be pointed in the same direction. This influence decreased along the depth, so that full wind effect on flow was observed only at the surface layer of the pond (about 5 cm). In fact, several researches suggest that the input devices in ponds generally impose flow conditions that in most times are sharper than wind (Shilton 2001; Shilton & Harrison 2003a, b).

The real HRT of the pond was estimated by analysing the test with the virtual tracer. The normalized curve of the tracer concentration showed a peak at 24 days, corresponding to 30% of the theoretical HRT. Through curve tracer discretization, the mean HRT of 87 days was obtained, which is very close to the theoretical HRT that occurred during the test period (80 days). The earliest evidences of the tracer at the outlet were observed around the 16th day. After 42 days of simulation, a second peak was found, corresponding to the arrival of the tracer coming from the southern pipe of the pond. From this point, the 'tail' of the curve decreased more slowly.

From the virtual tracer curve, it was possible to determine the dispersion number '*d*' of the pond, which was 0.28. According to Metcalf & Eddy (2003), this value refers to a condition of high dispersion ($d \geq 0.25$).

## CONCLUSIONS

It was noted that the prevailing winds in the pond blew from outlet to inlet, considerably influencing the flow at the surface layer of the pond. This influence was verified with the observation of oranges that have been released on the surface of the pond and through CFD modelling.

The drogue, designed and built as part of this research, presented very satisfactory results. Apparently, the wind did not influence the trajectory of the drogue, nor was there loss of signal due to immersion in the fluid. The pathway recorded corresponded to that seen in the field and, when exported to Google Earth® software, represented very closely where it should be, a fact confirmed when checking the release point. A limitation of the GPS memory was found; however, adjustments in the storage data method of the GPS can be made in order to reduce the frequency of storage and consequently increase the time memory usage.

The CFD modelling has proven to be very useful in the evaluation of the hydrodynamic conditions of the stabilization pond, reinforcing a trend that has been consolidated with recent worldwide research. From the model, it was possible to verify the occurrence of short circuits, dead zones, recirculation zones, vortex and dispersion of constituents. Virtual tracer tests allowed the estimation of the real HRT and the dispersion number. It was also noted that the inlet, outlet, dead zone and recirculation regions were related with the main areas of sludge accumulation.

Based on the hydrodynamic field measurements, it was evident that the CFD model behaved similarly to the field observations, even if only from a qualitative point of view. It is thus believed that it can be used as an aid in decision making for future hydraulic improvements in the pond, such as flow splitting equalization. However, for a more refined analysis, a quantitative validation is still needed.

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