# Computational Fluid Dynamics modelling of different detention pond configurations in the interest of sustainable flow regimes and gravity sedimentation potential

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## Abstract

This study presents the results of the flow regime evaluation, by means of computational fluid dynamics (CFD), of a vegetated detention pond located at Waterlooville, Hampshire, UK. Alternative pond layouts were assessed for the same flow conditions on the basis of recommendations made in the literature. The results were validated by comparing the maximum computational velocities for the same case using different numbers of mesh elements. It was found that the development of a CFD model of detention ponds is intricate but feasible. The main findings were (i) the present design performed well in terms of flood risk management but the flow patterns could result in questionable treatment efficiency; (ii) vegetation seems to promote horizontal recirculation and turbulence; (iii) triangular and elliptical pond designs showed very poor performance; (iv) the most appropriate design for the given location and hydrological regime is an elliptical pond with a central emergent/submerged island.

Keywords: Simulation modelling, SuDS, Engineering design, Integrated water management

## Introduction

Recent rapid industrialisation and urbanisation have triggered increases both in the amount of pollutants on road surfaces and in the volumes of surface runoff, posing a major threat to receiving water-bodies (Helmreich *et al.*, 2010). To alleviate stormwater impacts, control measures, known as sustainable drainage systems (SuDS) have been developed during the past 35 years (Tixier *et al.*, 2011). One such scheme is the detention (or retention) pond, which has low maintenance requirements and an efficient treatment performance (Persson, 2000; CIRIA, 2007; Hong, 2008). Effective treatment entails the removal of suspended material improving water quality downstream while reducing the potential for flooding by attenuating the peak of the flood hydrograph. Efficient pond geometry can help to reduce horizontal velocity gradients by encouraging a more uniform flow profile ("plug flow") and minimising the amount of recirculation (Persson, 2000; Peterson *et al*., 2000). An additional factor influencing the hydraulic performance of pond systems is the presence of aquatic vegetation. Vegetation in open-channel systems may contribute to increased flood risk by decreasing the discharge capacity, while increasing turbulence (Chao *et al*., 2006; Fu-sheng, 2008; Souliotis and Prinos, 2011). In a detention pond, vegetation is desirable for treatment and aesthetics. Consequently, the effect of vegetation must be considered in conjunction with the influence of geometry on flow.

Many authors have considered the hydrodynamics of ponds and constructed wetlands, on the basis of the assessment of different impact parameters. These parameters may include the effect of vegetation (Serra *et al.*, 2004; Chao *et al.*, 2006; Stovin *et al.*, 2009; Saggiori, 2010), design properties (Nameche and Vasel, 1998; Persson, 2000; Suliman *et al.*, 2006; Khan *et al.*, 2009; Carleton and Montas, 2010), wind (Kadlec and Wallace, 2009) and temperature (Torres *et al*., 1997). Persson (2000) evaluated 13 pond configurations using a 2-D numerical model and found that a submerged berm or an island close to the inlet improved the hydraulic performance in terms of short-circuiting, effective volume, and the amount of mixing. Jansons and Law (2007) evaluated more realistic pond shapes than those of Persson (2000) and suggested that the most hydraulically efficient pond shape was elliptical with a large island in the middle. Furthermore, Thackston *et al.* (1987) showed that length to width (L:W) ratio is the most important factor affecting hydraulic efficiency. However, the hydrodynamic evaluation of ponds has in most cases been undertaken using physical tracer experiments that are expensive, time consuming and sometimes impractical (Liwei *et al.*, 2008; Khan *et al.*, 2012). Therefore, the use of numerical models as design tools can lead to a much better understanding of the flow patterns in ponds. Most recently the numerical model of choice has entailed the use of Computational Fluid Dynamics (CFD).

CFD is a sophisticated engineering tool for evaluating flow behaviour in structures such as sedimentation basins (Al-Sammarraee and Chan, 2009), combined sewer detention tanks (Dufresne *et al.*, 2009), storm-water ponds (Peterson *et al*., 2000; Stovin *et al*., 2009; Saggiori, (2010); Khan *et al*., 2012), and wetlands (Liwei *et al*., 2008). Although there have been many promising studies on the evaluation of hydrodynamics in ponds, no design criteria have yet been agreed following such approaches. In addition, most studies are based on the evaluation of particular layouts without studying the suitability of other pond designs. The study of multiple pond geometries for a given location might enable the development of an optimum design in terms of flow characteristics.

The aim of the present study was to evaluate the flow patterns within a vegetated pond located at Waterlooville (Hampshire, UK) using the Ansys Fluent 12.1 CFD code (Ansys®, 2009). The investigation focused on the differences in flow patterns between the existing vegetated pond and a hypothetical non-vegetated pond with the same geometry in order to assess the effects of the vegetation on flow. Other designs were also evaluated in terms of the optimal flow characteristics that could be achieved for the same footprint. Our findings provide information on the use of CFD for actual problems arising in the design of detention ponds where space limitations apply. The evaluation of different pond geometries could contribute to the identification and standardisation of configurations that reduce the risk of flooding and erosion downstream of the ponds, by reducing flow velocities and promoting sedimentation. This is of vital importance from a designer's point of view where the practicalities of construction must be considered along with operational efficiency.

## Materials and methods

### Study Area

The study site is located at Waterlooville, Hampshire, UK (Latitude=50.881315, Longitude= -1.037575). Here a vegetated pond receives road runoff from a "bio-retention area" and a swale adjacent to a major road over a length of L=80 m. The plan area of the system is A=51x26 (m²) (Fig.1) including two basins (B1 and B2) and a raised berm between them. The storage capacity is 304 (m³) and the permanent water depth (H) is 1 (m), rising to a maximum water depth of 1.6 (m) at the outlet. The bed is flat and the gradient (x:y) of the basins side slopes is 1.8:1. The inlet (A) is a trapezoidal channel with an invert level of +1.2 m (relative to the bed; +0.0m) and L=1 m with the depth of flow ($H_{Inlet}$) rising to 0.4 m. Points B, C and D (Fig.1) indicate the positions of sediment traps. A hydro-brake flow control chamber regulates the outflow (E) leading to a rectangular outlet and the treated water is directed to the adjacent River Wallington via a swale. The design properties in terms of inflow for the 1:30 and 1:100 years events are 70 and 100 l/s, respectively. The basins slopes were planted after construction with two different types of emergent plants (reeds), namely (i) *Phragmites australis* (P.A) and (ii) *Typha latifolia* (T.L); more recently the whole of the flow area (within the basins) has become covered by the two types of emergent vegetation.

In order to create a realistic CFD model, the inflow was measured during storm events via a calibrated Valeport Model 801 electromagnetic open-channel flow meter (Valeport, Devon, UK). The inlet discharge [Q=0.064 (m³/s)] and H=1.5 m assigned to all models described here was the highest obtained from 7 monitored storm events (see Table 1). The depth of flow at the inlet for the specific storm event was $H_{Inlet}$=0.3 m. The depth of flow H= 1.5 m of the system was measured at a point with known elevation [raised berm= (+) 1.1 m]. The flow meter was used to measure the time-averaged velocity ($U_T$) in the same direction as the flow (sampling time=30 s) and at $H_{Inlet}/2$ m (Hamill, 2001).

### Vegetation

The vegetation cover (VC) was measured using quadrats of A=0.5 m² on 31 January 2012. The survey included 20 random sampling points in the shallow-water part and 20 random sampling points in the deep-water region. Two different populations, in terms of their location, were identified (Fig.2). All statistical results were obtained using the Minitab® software (Minitab®, 2009). For the shallow water part ($VC_S$), the survey indicated median values of 186 (P.A) and 20 (T.L) per square meter. For the deep water region ($VC_D$), the survey indicated median values of 45 (P.A) and (22 T.L) per square meter. In addition, the survey indicated a median plant diameter ($D_P$) of $D_p$=0.01 m for the P.A and $D_p$=0.035 m for the T.L (see Fig.2). The side slopes of both the basins connect the deep and shallow parts. $VC_D$ starts 2m in from the bottom of the side slope (+0.0m) while $VC_S$ covers the remaining part of the basins. There is no emergent vegetation outside the basins.

## Model characteristics

*In terms of the alternative designs (see Fig.3), several elliptical configurations were evaluated, on the basis of recommendations made by Persson (2000), Jansons and Law (2007), and Khan et al. (2012). A triangular pond was also studied as was as a standard oval pond with a sediment fore-bay, as recommended by CIRIA (2007). The latter configuration had multiple outlets, rather than just one, to examine the effect of multiple outlets on flow patterns (Suliman et al., 2006). All the inlet and outlet cross sections of the alternative designs were rectangular. The dimensions of the alternative cases were generally smaller compared to the current design in the interest of optimising the use of available space. Model assumptions*

As a first assumption, it was considered that a steady state simulation could represent the flow regime during the storm event. According to Khan *et al*. (2012), the application of transient conditions is irrelevant in such circumstances, where it is mainly the evolving flow patterns that are of interest. The influent flow was uniformly distributed over the cross section because of convergence issues (Ansys®, 2009). The same constraint was applied to the outflow. The hydro-brake was not represented in the model due to design and convergence issues. A porous media condition was used to simulate the presence of vegetation (Liwei *et al*., 2008; Ansys®, 2009; Stovin *et al*., 2009; Mattis *et al*., 2012). Boundary conditions (BC) for the inlet and outlet were "velocity_inlet" and "outflow" respectively. Velocity inlet is a BC, available in Ansys® Fluent, for incompressible flow that is uniformly distributed over a cross section; flow velocity, hydraulic diameter of the channel (at the inlet), and turbulent intensity (see Eq. 2) must all be assigned. The outflow is a BC, available in Ansys® Fluent, used to model flow exits where the details of the flow velocity and pressure are unknown prior to the solution of the flow problem; it did not require any numerical input. These BCs were implemented by assigning "velocity_inlet" (with the input of the aforementioned variables) and "outflow" at the inlet and outlet faces (areas) respectively. Details on how to calculate the hydraulic diameter and the Reynolds number can be found in Hamill (2001). The free surface was modelled as a symmetry boundary condition (Ansys®, 2009; Stovin *et* al., 2009; Saggiori, 2010) and the walls were modelled as adiabatic walls (Khan *et al*., 2009, 2012) with a roughness height of zero, because for a large body of slow moving water the wall roughness value has a minimal effect on the bulk water flow (Tu *et al*., 2008; Khan *et al*., 2009, 2012).

*Model equations*

The 3D Navier-Stokes equations for steady, incompressible flow in combination with the "realisable" k-ε turbulence model (Shih *et al.*, 1995), for calculating the turbulent stresses, were solved by the Fluent CFD code (Ansys®, 2009). The "realisable" k-ε turbulence model was chosen to predict the shear stresses due to its superior performance compared to the standard k-ε turbulence model (Ansys®, 2009; Tu *et* al., 2008). The "realisable" k-ε turbulence model differs from the standard k-ε model in that it contains (i) an alternative formulation for the turbulent viscosity and (ii) a modified transport equation for the dissipation rate ε, derived from an exact equation for the transport of the mean-square vorticity fluctuation (Shih *et al.*, 1995). The term "realisable" means that the model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows. The standard k-ε model is not "realisable" (Ansys®, 2009). The turbulent intensity I is given by:

$$I= \frac{u'}{U} \tag{1}$$

where $u'$ is the root-mean-square of the turbulent velocity fluctuations and U is the mean velocity. Turbulent intensity at the inlet was calculated using Eq. 2 as dictated by the software.

$$I= 0.16[Re^{(-0.125)}] \quad (2)$$

where Re is the Reynolds number. The value of I indicates how turbulent the flow is; e.g., Re=50000 results in approximately I=4 % (Ansys®, 2009). A full description of the turbulence model equations can be found in the Ansys Fluent theory guide (Ansys®, 2009).

The effect of vegetation was simulated using the porous media condition, in which an empirically determined flow resistance is integrated into specified cell zones of the model (Ansys®, 2009). Porous media were modelled by the addition of a momentum source term to the 3D Navier-Stokes equations. The source term is composed of two parts: a viscous loss term (Darcy’s Law) and an inertial loss term (Ansys®, 2009; Tsavdaris *et al.*, 2013). Using the Ergun equation (a semi-empirical correlation applicable over a wide range of Reynolds numbers) the appropriate constants can be derived (Ergun, 1952). The software identifies the permeability and inertial loss coefficient in each component direction (x, y, z) $\alpha$ (Eq.3) and $C_2$ (Eq.4) respectively (Shucksmith, 2008; Ansys®, 2009; Stovin *et al.*, 2009; Saggiori, 2010)

$$\alpha = \frac{D_p^2}{150}\frac{e^3}{(1-e)^2}$$

(3)

$$C_2 = \frac{3.5}{D_p}\frac{(1-e)}{e^3} \quad (4)$$

Where $\varepsilon$ is the porosity (Eq.4) of the porous zone and $D_p$ is the stem diameter.

$$\varepsilon= 1-[(V_t - V_f)/ V_t] \quad (5)$$

In Eq.5 $V_t$ is the total volume (volume of reeds plus fluid) and $V_f$ the volume of fluid. All the porous zone parameters were calculated via Eq. 3, 4, and 5. Further details of the theory of porous zones can be found in the Ansys Fuent 12.1 theory guide (Ansys®, 2009) and are not discussed here.

*Grid density and geometrical properties*

The geometry of the Waterlooville pond system was created in DM. The coordinates of the depth contours were measured in AutoCAD 2007 (Autodesk, Hampshire, UK) and were defined in 3D within DM. The original design was provided by Mayer Brown Ltd (Isle of Wight, UK). The defined geometry was then transferred to the Geometry and Mesh Building Intelligent Toolkit (GAMBIT) software (Ansys®, 2009). The mesh method used was tetrahedral patch conforming and the advanced size function for curvature and proximity was enabled, as suggested by Tu *et* al. (2008). Tetrahedral patch conforming was the only method able to generate a valid and good quality mesh for the given designs. Due to the complex curvature and shape of the ponds, hexahedral, pyramidal or prismatic elements did not generate usable meshes. In order to avoid problems at the interface between fluid zones and vegetated (porous) zones, GAMBIT offers an option that combines all the zones of the body of fluid (“named selection”). Thus, no BCs need to be assigned between porous and non-porous regions (interface) because the software identifies the body of fluid as a whole while maintaining the ability to assign porous zones to different regions within the computational domain. This approach depends on the design of porous zones as independent bodies of fluid while being subparts of a single body of fluid in the Design-Modeller (DM), which forms part of the ANSYS Workbench 12.1 software. Details of the design properties for each pond layout can be found in Table 2. $VC_S$ and $VC_D$ were assigned to particular regions, on the basis of the survey findings. The academic version of the software has a limit of 512000 mesh elements so the mesh for all the models was developed to give a non-skewed fine unstructured mesh with a number of elements close to 512000. However, Khan *et al.* (2009, 2012) showed that for such problems grid density does not seem to influence the evolving flow patterns. Since all the cases have similar dimensions and identical flow properties, the effect of varying the number of mesh elements was assessed for case (a) to ensure the validity of the CFD results (See Table 3). Tu *et al*. (2008) reported that if the velocity magnitude does not change when the number of mesh elements is changed, the solution can be considered accurate. It was found that any number of mesh elements greater than 400000 (elements) produced similar flow patterns and velocity distributions; on the basis of these findings, and bearing in mind that the finer the mesh the more accurate the results (Tu *et al*., 2008), a minimum of 450000 elements was chosen in all cases. Moreover, Tu *et al*. (2008) showed that the inflow and outflow faces should be placed at distances of L > 10 x H from the main water-body; where H here refers to the depth of flow at those specific locations. Consequently, all the inflow and outflow structures of the studied designs were placed approximately 3 m from the main water-body, as $H_{Inlet}$=0.3 m for all cases.

*CFD model set-up*

The model solves the governing non-linear and coupled equations sequentially, and several iterations of the solution loop must therefore be performed before the minimum convergence criterion is fulfilled (reduction of $10^3$ order magnitude on the scaled residuals from the continuity, momentum and turbulence equations). The average number of iterations required for a converged solution was approximately 1500-3000. The models were run under steady state conditions to obtain the solution for the 3 components of velocity, pressure, momentum and turbulence. All equations were discretised using the second order upwind scheme (Ansys®, 2009). The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) was used for pressure-velocity coupling and the Green-Gauss-Node-Based method was used for the evaluation of gradients, as suggested by Katz and Sankaran (2012).

## Results and Discussion

To produce the flow patterns for each of the pond systems considered, streamlines were developed in ANSYS CFD-Post (Ansys®, 2009). Streamlines enable a detailed investigation of the flow patterns, velocity distributions and eddy formations within the computational domain (Tu *et al*., 2008). The streamlines show velocity magnitude ($U_{CFD}$ m/s) as defined in the software (Ansys®, 2009). Turbulent intensity is defined by Eq. 1. Fig. 4 shows the evolving flow patterns for all the cases. Fig. 5 shows the numerical range of turbulent intensity (I %) for all cases.

### Waterlooville detention pond system

As can be seen from Fig. 4 the flow patterns of the non-vegetated and vegetated detention pond systems slightly differ. Case (a) had velocities in the range of 0 - 0.0412 m/s and 0.0412 - 0.0625 m/s within the basins and berm, respectively. In addition, 3 recirculation zones can be seen, two in B1 and one in B2. Conversely, case (b) had $U_{CFD}\approx 0.0325 – 0.0575$ m/s across the pond system. The vegetation seemed to slightly increase the amount of mixing (in the basins), although a vegetated computational domain caused some horizontal recirculation between the shallow and deep vegetation. The horizontal recirculation patterns at the deep-shallow interface may promote the re-suspension of sediments and affect performance in terms of sediment removal. Moreover, Fig.5 shows that the amount of turbulence differed in magnitude. Case (a) had a generally lower I (Max I≈4.44 %) than case (b), with increasing values just before and just after the berm. On the other hand, case (b) had a maximum I≈7.31 % (upper part of B2) with a random pattern throughout the entire system. In addition, the berm for case (b) had I≈4 % compared to I≈1 % for case (a). These results show that the vegetated pond system (case b) did not differ considerably in terms of velocity magnitude to the non-vegetated system (case a) but that it did differ in turbulent intensity, as also observed by Saggiori (2010), possibly due to the different turbulent velocity fluctuations. Other relevant studies have also reported that vegetation affects the structure of the flow by increasing the turbulent characteristics (Fu-sheng, 2008; Souliotis and Prinos, 2011). Overall, the geometry of the pond as is exhibited a pronounced range of turbulent intensities (Fig. 5) compared with the other cases, suggesting that the current design performs well in terms of flood safety but its treatment efficiency remains uncertain.

## Alternative designs

*Oval and triangular pond systems*

The oval pond (case c) showed velocities in the range 0 – 0.025 m/s throughout its geometry (Fig.4). The velocity gradually reduced towards the centre of the pond, while a recirculation zone developed at the sediment fore-bay. Downstream of the midpoint, the flow configuration was uniform with very low velocities ($U_{CFD}$<0.05 m/s). The use of multiple outlets seemed to promote the uniformity of the velocity distributions. In contrast, recirculation was far more pronounced in the triangular pond (Fig.4). In general, this system contained low velocities with $U_{CFD}$≈0.022 m/s across the whole pond, with four noteworthy regions of zero flow. Nevertheless, the intense recirculation patterns at the sediment fore-bay indicated insufficient mixing. In addition, such flow arrangements might enable the re-suspension of sediment and possibly promote the transport of pollutants towards the outflow although the velocities were very low compared to those at the inlet. Dufrense *et al.* (2010) reported that deposition clearly occurs as a function of the flow patterns in any given case. Case (d) showed very little mixing with stagnation zones being prevalent. The flow distribution suggests poor performance under high flow conditions. Additionally the turbulent intensity for both these configurations (Fig. 5) was generally low compared to the actual Waterlooville pond.

*Elliptical pond systems*

Case (e) exhibited recirculation patterns after the inlet and in the lower central area of the geometry (Fig.4). The submerged island appeared to assist in producing uniform flow and a reduction in velocity with $U_{CFD}$<0.04 m/s after the central part. On the other hand, case (f) demonstrated more accentuated recirculation compared to case e, also with $U_{CFD}$<0.04 m/s (Fig.4). The recirculation occurred after the inlet area and at the upper and lower parts of the geometry, throughout the computational domain. Fig.4 shows that case (g) had minimal stagnation zones and recirculation flows throughout its entire geometry. Only after the inlet and upstream of the emergent island does there seem to be some recirculation, but this was inconsequential compared to the other pond configurations. Case (g) had a distinctively uniform velocity profile with $U_{CFD}$≈0.019 m/s after a distance of approximately L/3. The elliptical pond system with a vegetated island (case h) showed a unique flow pattern (Fig.4). It seems that vegetation created horizontal recirculation, as for case (b). In all other designs the recirculation was vertical. $U_{CFD}$ was generally low within the vegetated island ($U_{CFD}$≈0.018 m/s) and slightly higher at the edges of the island and the edges of the pond ($U_{CFD}$≈0.04 m/s). As expected, chaotic mixing caused increased turbulence within the pond system (Fig.5). Turbulent intensity was much higher than in the other elliptical ponds with I≈4 % just upstream and just downstream of the vegetated island. Turbulence decreased within the island (I≈3 %) and at the edges of the pond (I≈2 %), but overall this particular case showed a highly turbulent flow profile compared to the other cases. Case (f) appeared to have similar flow arrangements to case e, with stagnation zones and low mixing within the computational domain. This flow behaviour indicated poor performance in terms of treatment and sedimentation. Conversely, cases (e) and (g) showed remarkable flow spreading. The submerged island (case e) caused a decrease in the magnitude of recirculation and promoted uniform velocity/turbulence distributions (Khan *et al*., 2009; Su *et al*., 2009). Moreover, the emergent island (case g) seemed to be more efficient in impeding recirculation patterns and promoting uniform velocity/turbulence profiles (Persson, 2000; Jansons and

Law, 2007). Finally, all the non-vegetated elliptical ponds exhibited the lowest turbulent intensity (Fig. 5) suggesting the efficient promotion of mixing and “plug flow” conditions.

On the basis of the findings of Al-Sammarraee and Chan (2009) and Dufrense *et al.* (2010), cases (e) & (g) are possibly the most efficient in terms of settling efficiency. On the other hand, the vegetation in case (h) seemed to promote uniform velocity (magnitude) distributions but with random and chaotic flow spreading. Vegetation altered the flow profiles upstream and downstream of it (Souliotis and Prinos, 2011), with a possible negative impact on overall performance. Furthermore, the increased turbulence due to vegetation (Souliotis and Prinos, 2011; Tsavdaris *et al*., 2013) might influence the treatment performance of the system. In light of the foregoing results, we believe that the most appropriate design for the promotion of “plug flow” conditions (for the given location) and sediment deposition, is an elliptical detention pond enhanced with a centrally located subsurface berm or emergent island.

## Conclusions

Flow patterns were investigated in a vegetated and a non-vegetated detention pond system located at Waterlooville, Hampshire, UK. The evaluation was conducted by means of a series of CFD simulations. In addition, further design layouts were assessed for the given location on the basis of recommendations made in the literature. The following conclusions can be drawn:

1) Vegetation in detention ponds does not increase the velocity magnitude compared to non-vegetated ponds, but could possibly increase turbulence and enable horizontal recirculation especially at the interface of different vegetation covers, thereby possibly influencing treatment performance. The current as built design performs well in terms of flood safety but the evolving flow arrangements might result in problematic treatment efficiency.
2) An oval pond with multiple outlets seems to perform well under storm conditions with respect to flood risk, but shows uncertain treatment ability.
3) Triangular and elliptical shaped ponds show poor performance in promoting uniform flow profiles; the hydraulic and treatment efficiency of these layouts is therefore questionable.
4) An elliptical pond with a central vegetated island is effective in hydraulic terms and promotes mixing but the increased turbulent intensity due to chaotic flow patterns might reduce the treatment efficiency of such a configuration.
5) Finally, the most appropriate design with respect to flood risk management and gravity sedimentation potential appears to be an elliptical shaped pond system with either a subsurface central berm or an emergent central island.

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Figure 1: Schematic view of the pond system. A, inlet; B, C, and D, sediment traps; E, outflow.

Figure 2: Boxplots with median (line) values of vegetation cover with respect to shallow and deep water for *Phragmites Australis* (P.A) and *Typha Latifolia* (T.L); Boxplots with median (line) and mean (circle with cross) values of plant diameter for P.A and T.L

Figure 3: Schematic view of the geometry of the studied cases; (a) Non-vegetated (Waterlooville, UK) detention pond; (b) Vegetated (Waterlooville, UK) detention pond; (c) Oval detention pond with sediment fore-bay; (d) Triangular detention pond; (e) Elliptical detention pond with submerged island; (f) Elliptical detention pond; (g) Elliptical detention pond with emergent island; (h) Elliptical detention pond with vegetated island; green blocks indicate deep water ($VC_D$) vegetation

Figure 4: Velocity streamlines of all the studied cases

Figure 5: Boxplots of the range of turbulent intensity (I) for all the studied cases

Table 1: Daily precipitation, maximum depth of flow and inlet discharge for all monitored storm events for the detention pond located at Waterlooville. All precipitation data were obtained from www.wunderground.com.

| Storm Event | $H_{max}$ (m) | $Q_{max}$ ($m^3/s$) | Daily Precipitation (mm) |
|---|---|---|---|
| 26/10/2011 | 1.17 | 0.004 | 6.1 |
| 01/12/2011 | 1.22 | 0.008 | 7.1 |
| 12/12/2011 | 1.34 | 0.047 | 14.5 |
| 24/01/2012 | 1.25 | 0.007 | 7.1 |
| 04/03/2012 | 1.39 | 0.051 | 12.4 |
| 23/04/2012 | 1.5 | 0.064 | 16.3 |
| 08/06/2012 | 1.44 | 0.034 | 16.8 |

Table 3: Identification of the suitable number of mesh elements on the basis of maximum modelled velocity ($U_{CFD}$) for case (a), resulting in a valid solution.

| Location | Max $U_{CFD}$ (m/s) | Mesh Elements (n) |
|---|---|---|
| Basin 1 | 0.038 | 110000 |
| Basin 2 | 0.043 | 110000 |
| Basin 1 | 0.04 | 220000 |
| Basin 2 | 0.049 | 220000 |
| Basin 1 | 0.058 | 307000 |
| Basin 2 | 0.06 | 307000 |
| Basin 1 | 0.06 | 400000 |
| Basin 2 | 0.062 | 400000 |
| Basin 1 | 0.06 | 480136 |
| Basin 2 | 0.062 | 480136 |

Table 2: Design properties of all cases; the term “Elliptical islands” refers to the island assembly in all elliptical ponds; the submerged island in case (e) has a +1.2 m elevation with respect to the bed of the pond; the outlet which is aligned with the inlet of case (c) has an area $A_{out}$=0.3 m² and the two remaining outlets have $A_{out}$=0.15 m². The porous zone parameters are dimensionless; n denotes number of mesh

elements. 1/α, permeability coefficient, ε, porosity, $A_{in}$, inlet area, $A_{out}$, outlet area, $C_2$, inertial loss coefficient, H, water depth, L, length, Q, flow rate, $VC_D$, vegetation cover in deep water, $VC_S$, vegetation cover in shallow water, W, width.

| Case | Q ($m^3/s$) | H (m) | $A_{in}$ ($m^2$) | $A_{out}$ ($m^2$) | Side slope (x,y) | L (m) | W (m) | 1/α | $C_2$ | ε | Mesh (n) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| a | 0.064 | 1.5 | 0.44 | 0.564 | 1.8:1 | 51 | 26 | | | | 480136 |
| b | 0.064 | 1.5 | 0.44 | 0.564 | 1.8:1 | 51 | 26 | | | | 441687 |
| c | 0.064 | 1.5 | 0.45 | 0.3;0.15;0.15 | 1.8:1 | 40 | 20 | | | | 416667 |
| d | 0.064 | 1.5 | 0.45 | 0.6 | 1.8:1 | 50 | 20 | | | | 488976 |
| e | 0.064 | 1.5 | 0.45 | 0.6 | 1.8:1 | 40 | 15 | | | | 446253 |
| f | 0.064 | 1.5 | 0.45 | 0.6 | 1.8:1 | 40 | 15 | | | | 459085 |
| g | 0.064 | 1.5 | 0.45 | 0.6 | 1.8:1 | 40 | 15 | | | | 455965 |
| h | 0.064 | 1.5 | 0.45 | 0.6 | 1.8:1 | 40 | 15 | | | | 511991 |
| Elliptical islands | | | | | | 20 | 4 | | | | |
| $VC_D$ | | | | | | | | 76 | 2.58 | 0.98 | |
| $VC_S$ | | | | | | | | 2177 | 13.3 | 0.97 | |

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