

## Modelling the Effect of Flow Structures on Canal System Residence Time

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### Abstract

A modelling study was carried out using separate 3-dimensional circulation model and flushing model components of WQMAP to investigate the residence times of Oyster Cove, an artificial canal system connected to the adjacent Saltwater Creek estuary, Gold Coast, Australia. The flow between the canal system and estuary is controlled via a system of uni-directional and bi-directional structures. To validate the circulation model and the influence of the flow structures, a detailed field experiment was carried out using flow meters, tide gauges and fluorescent dye. Following the validation process, the model was used to examine the existing mixing dynamics and residence time of the canal estate. Finally, the model was used to compare a hypothetical design alternative to the existing layout and quantify the effect on the canal's residence time by changing the position of the flow structures and using different combinations of flow structures.

### Introduction

Oyster Cove, located on Australia's Gold Coast, is an artificial canal system connected to its adjacent estuary, Saltwater Creek, and a neighbouring lake system, Lake Serenity, by a system of uni-directional and bi-directional flow structures (see Figure 1). Oyster Cove has a typical depth of 4 m and a surface area of 0.2 km<sup>2</sup>.

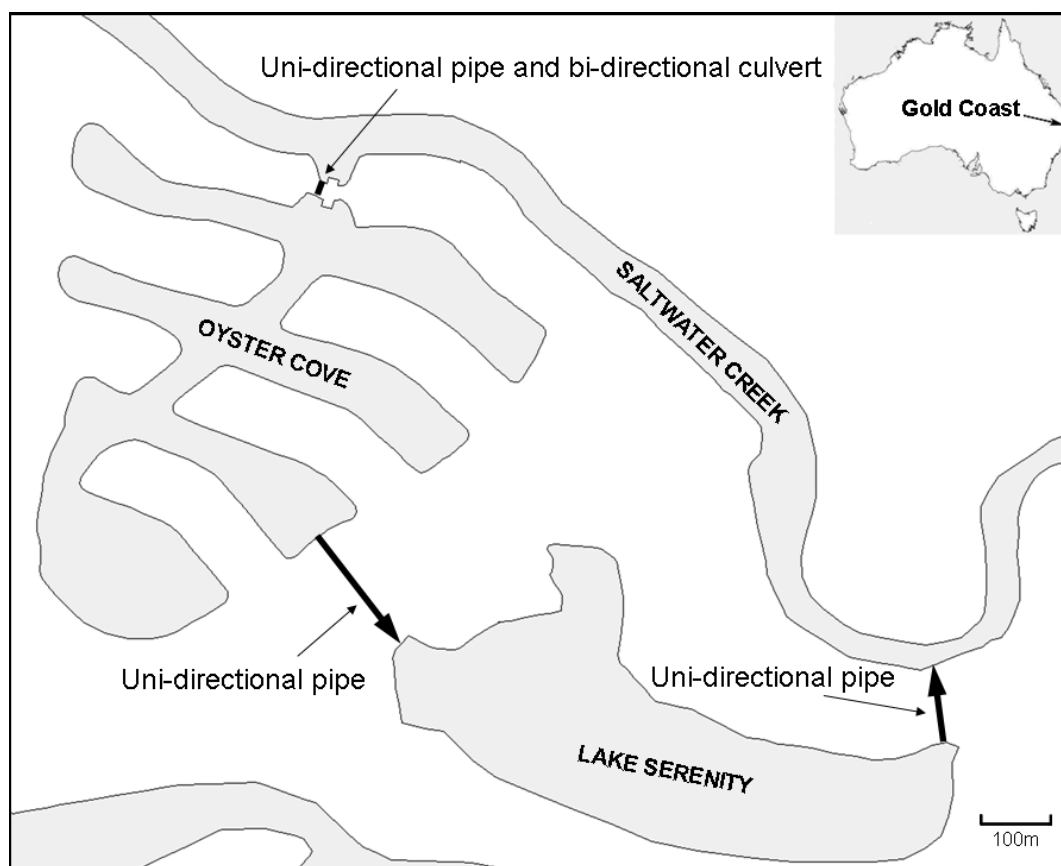
Oyster Cove is connected to Saltwater creek via a fully submerged uni-directional pipe, 1.2 m in diameter with a hinged metal plate to serve as the directional flow controller. The connection also features a 1.2 m x 1.2 m box culvert with a slope of 1:20 with the higher end inside Oyster Cove positioned at a level 0.4 m above mean sea level.

The tidal range in Saltwater Creek is 1.2 m which results in a tidal range within Oyster Cove of 0.4 m. Due to the complex design of Oyster Cove and its restricted exchange of water with Saltwater Creek, it is prone to potential water quality issues associated with longer than usual residence times, such as algal blooms and anoxia (low dissolved oxygen). Consequently, an extensive field study was carried out to evaluate and quantify the exchange of water through the system of flow structures and to gain an understanding of the flow and mixing dynamics between the lake and estuary.

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The results of the field study were used to validate a 3-dimensional barotropic and flushing model, as well as formulate the internal algorithms to represent the flow structures. Subsequently the model was used to compare the residence time of the canal estate based on the existing and proposed placements of flow structures.



**Figure 1.** Layout of Oyster Cove, Gold Coast, Australia and its connections to the adjacent Saltwater Creek estuary and neighbouring water body, Lake Serenity.

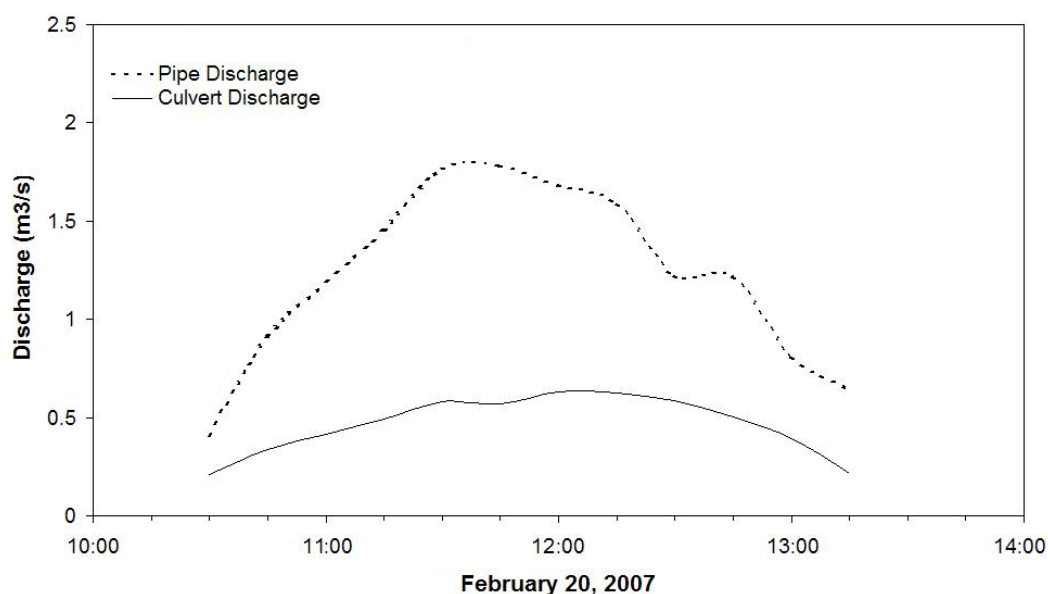
## Field Study

In addition to previous studies of the hydrodynamics of Saltwater Creek (Benfer et al., 2007) this field study was carried out in two stages and was designed specifically to evaluate the hydrodynamic behaviour of the connection between Oyster Cove and Saltwater Creek and to observe the circulation in the vicinity of the flow structures.

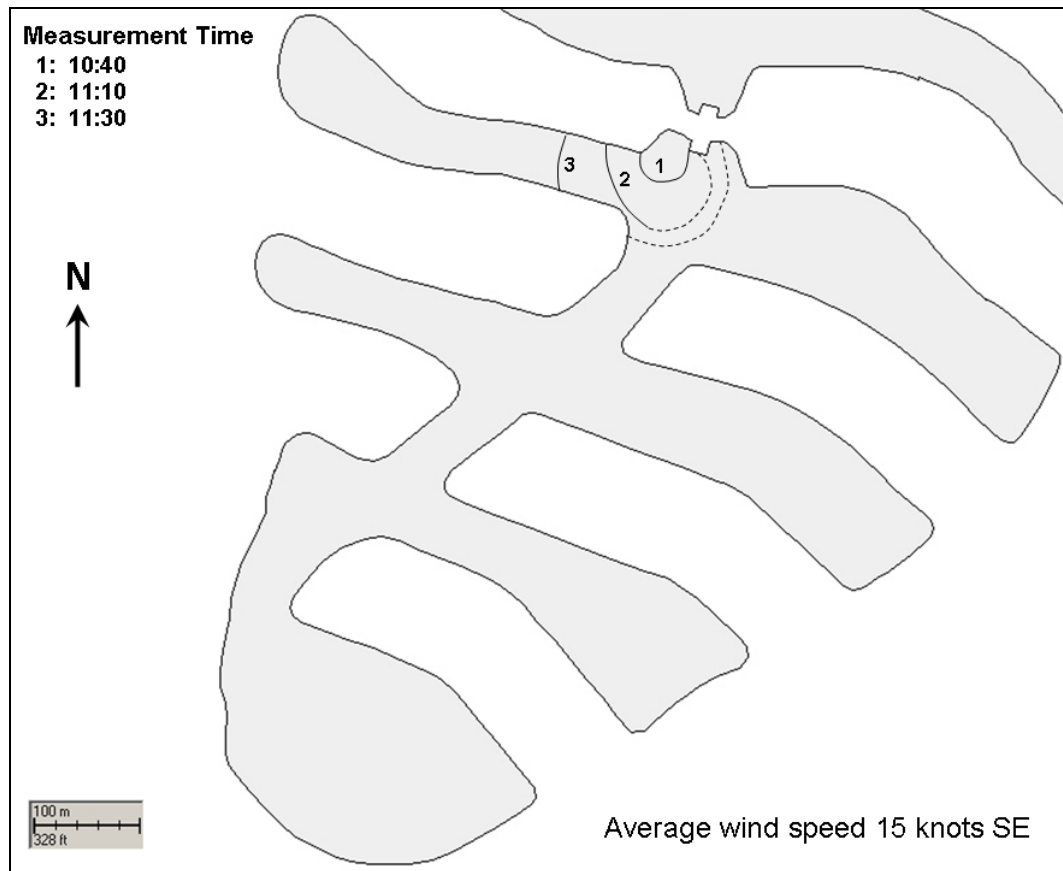
The first phase involved making water elevation measurements inside Oyster Cove and in Saltwater Creek for a 30-day period. The second phase also included measuring water elevations as before but also measuring the discharge rates of the two flow structures and the circulation inside Oyster Cove, using a flow meter, fluorescent dye, and a fluorometer.

The fluorescent dye (rhodamine) was released at the flow structures when inflow into Oyster Cove began so the leading edge of the inflow could be tracked. The movement of the dye was evaluated primarily by visual inspection and the fluorometer was used across a predefined grid to verify these observations and to continue measuring when the dye was diluted below visible levels. Figure 2 shows the position of the leading edge of the dye as a function of time during the experiment. The positions represented by solid lines were confirmed by the fluorometer while the dashed lines were visually evaluated only.

Figure 2 shows the corresponding discharge through the flow structure connecting the two water bodies. Figure 3 shows that at 10:40 (EST), shortly after the initial dye release, the inflow was still relatively low ( $<1 \text{ m}^3/\text{s}$ ) and the dye had moved 40 m into Oyster Cove. At 11:10, thirty minutes later, the inflow had increased and the leading edge of the dye had moved approximately 100 m away from the inlet into the canal towards the central corridor and the first western arm. The leading edge of the dye was not detected on the eastern side at this time. By 11:30 the inflow was at a maximum (approximately  $1.75 \text{ m}^3/\text{s}$ ) and the leading edge of the dye in the southerly direction was undetectable. The dye had moved up into the western arm approximately 120 m from the inlet. The movement of the dye demonstrated how the momentum produced by the jet at the inlet in the shallower section of the system caused new water to push across the surface layers towards the corner of the western arm and the central corridor and how the 15-knot wind from the southeast forced part of it up the western arm. The vertical profile of the dye concentration was measured by profiling the water column with the fluorometer over the predefined grid.



**Figure 2.** Discharge through the flow structure between Oyster Cove and Saltwater Creek during the field study.



**Figure 3.** Movement of the leading edge of the dye during the field study. Note solid leading edge positions were confirmed by the fluorometer and dashed lines were visually assessed only.

### **Circulation and Flushing Model**

The models used to evaluate the circulation and residence times in Oyster Cove for this study were WQMAP's hydrodynamic (Orthohydro) and flushing (Orthomass) modelling components. Details of the hydrodynamic and flushing models are given in Muin (1993), Muin & Spaulding (1997), Kim et al. (2003) and Zigic et al. (2005).

#### ***Hydraulic structure routines***

For this study specific numerical subroutines were created to describe the flow between the two water bodies and the inclusion of the flow structures. For each time step the flow through the river cells was governed by the surface elevation of the adjacent water cells. The subroutine included controls for direction and volume of water discharged.

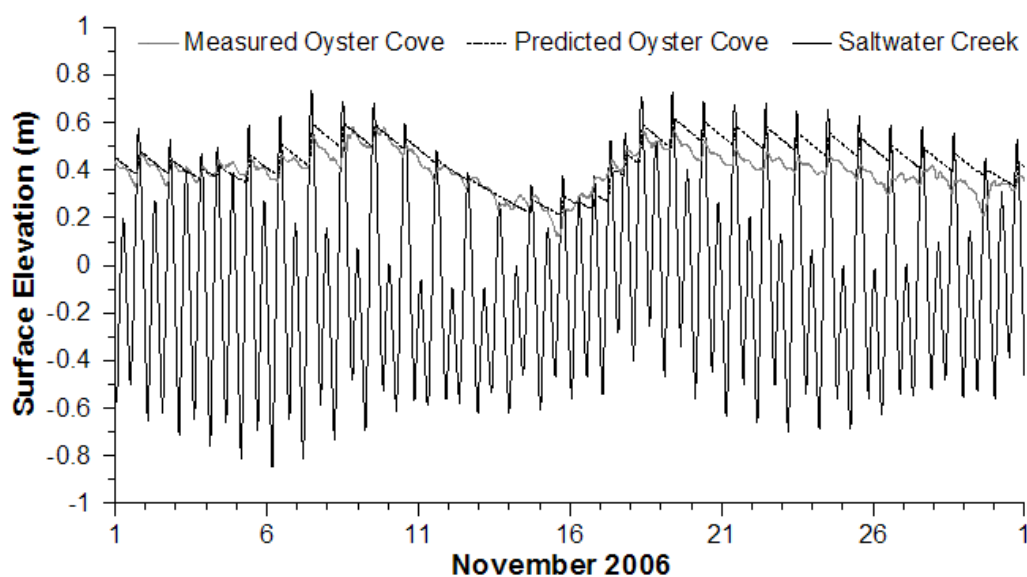
Polynomial equations were fit to the data from the dye study to simulate the discharge through the flow structures within the model. The uni-directional structures used at Oyster Cove employ a hinged metal plate to control the flow direction and

depending the plate size different amounts of hydrostatic pressure was required to initiate flow and the pipes and culvert were also heavily bio-fouled. Hence, no empirical formula was found to accurately represent the flow through these structures and the best way to represented the flow numerically was with the polynomial equations.

The hydraulic subroutine was not applied to the connection between Oyster Cove and Lake Serenity, however, analysis of the elevation data set indicated that the flow between Oyster Cove and Lake Serenity could be simulated by a time averaged discharge value of  $0.14 \text{ m}^3/\text{s}$  in the model because a near-constant head difference was maintained between the two water bodies.

### *Comparison of lake surface elevations*

Measured surface elevation data from Saltwater Creek and Oyster Cove was used to validate the hydraulic structure subroutines, since a comparison of surface elevations within Oyster Cove ensured that the correct volume of water entered the system. Due to the limitations of the grid resolution, the structure cells could not exactly match the physical dimension of the flow structures, for this reason flow velocity through the structure cells were not included in the validations. For the first part of the modelling validation process, surface elevation data from Saltwater Creek was used to set the open boundary conditions of the model and surface elevation data from Oyster Cove was used to verify the model results. Figure 4 shows good agreement achieved in the comparison of measured and predicted surface elevations inside Oyster Cove along with the measured surface elevation of Saltwater Creek over an extended 30-day period. The maximum error during this period was approximately 10 cm.



**Figure 4.** Comparison of measured and predicted surface elevations inside Oyster Cove along with the measured surface elevation of Saltwater Creek .

### ***Comparison of dye release***

The model was then run for the period of the dye study to validate the circulation within Oyster Cove. The open boundaries for this simulation were derived from a larger estuarine model of Saltwater Creek and its surrounding estuaries (manuscript in preparation). The model also included locally recorded winds to create wind driven circulation throughout Oyster Cove. Winds were measured by the Australia Bureau of Meteorology, for a nearby weather station at the Gold Coast Seaway.

The predicted currents from the circulation model were used in the flushing model to determine if the wind-induced circulation was being modelled correctly. Figure 5 shows the results of the model at corresponding times when measurements were taken during the dye study. The simulated movement of the released pollutant in the surface layer in the model is very similar to that of the field study with the leading edge moving towards the central corridor and up the western arm. It is worth noting that model predicted wind induced surface currents moved in the direction of the wind and setup an opposing bottom flow along the arms.

### **Design Alternatives**

Using the circulation model the existing pipe configuration and several alternative designs were investigated. The models using alternative designs were run under identical conditions to the existing configuration for a 50-day period. All model results were then compared to select the most improved alternative design.

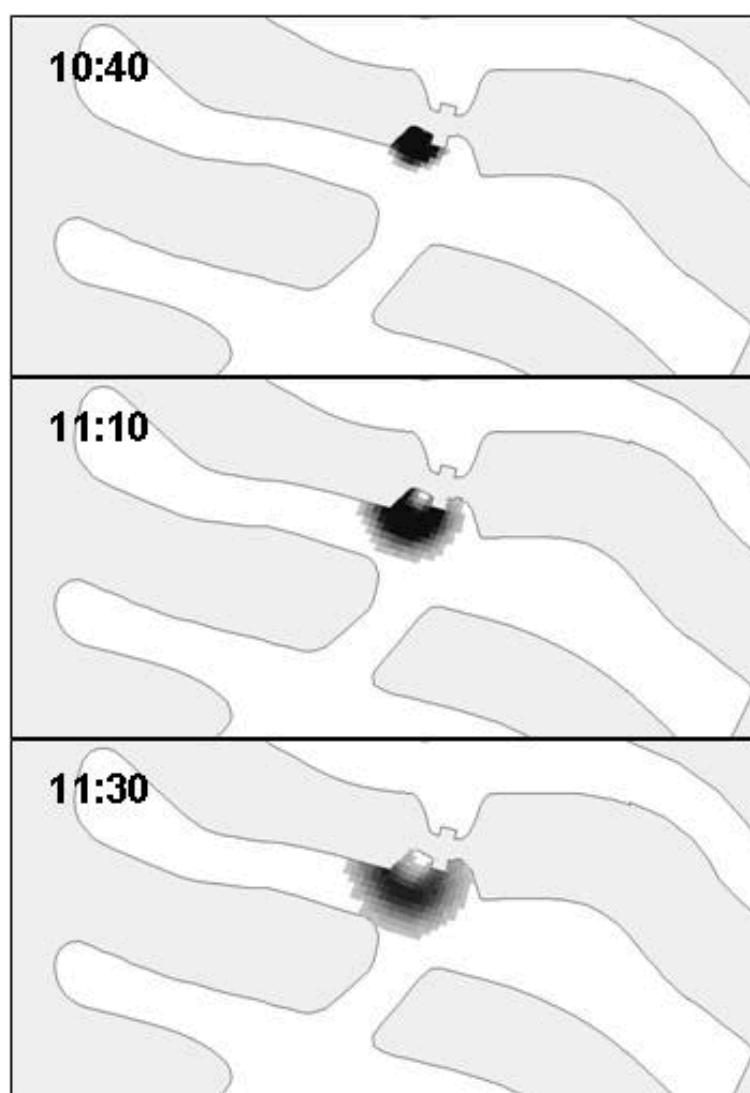
The existing configuration (Design 1) had a partially submerged culvert and a fully submerged uni-directional pipe at location “A” shown in Figure 6 and single fully submerged uni-directional pipe at location “B”; the improved alternative design (Design 2) used two fully submerged uni-directional pipes at “A” and also the connection to Lake Serenity was moved from “B” to “C” and two fully submerged uni-directional pipe were used instead of only one.

Figure 7 compares the change in surface elevation inside Oyster Cove for the Design 1 and Design 2 for a selected 20-day period. The daily oscillation was slightly larger for Design 2. However, the daily averaged elevations for both configurations remained similar.

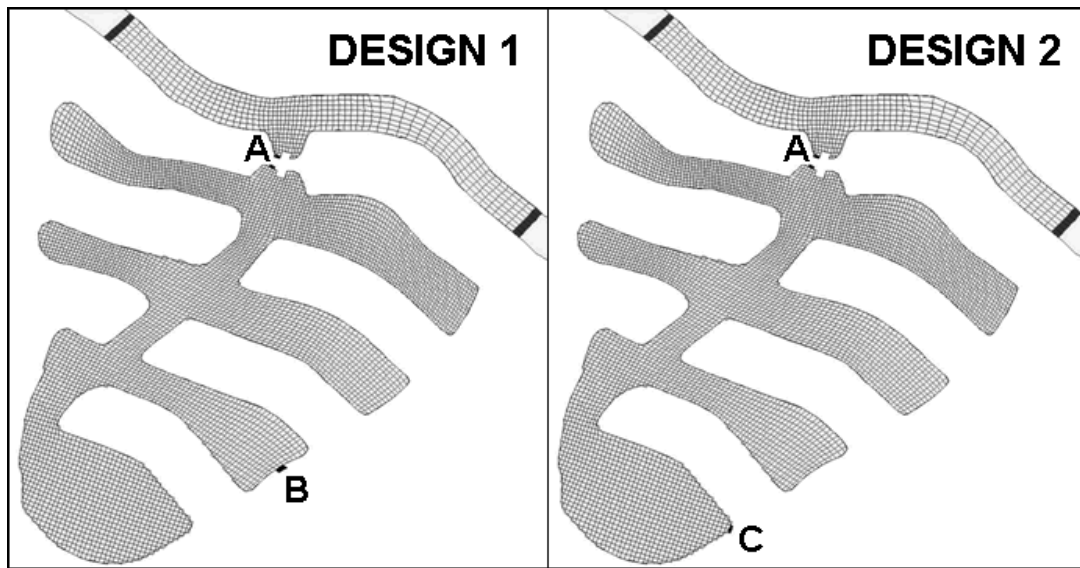
Figure 8 shows the results of the flushing model for the two designs at 10, 20, and 30 days for the middle depth layer. For the purpose of this study the e-fold residence time was adopted as the measure of flushing, that is, any parcel of water with a concentration below approximately 37% is considered flushed. It is evident from Figure 8 that Design 2 is the better design. Design 2 was fully flushed in 25 days whilst the first design did not. The flushing model run for Design 1 indicated incomplete flushing of the system even after 50 days.

The model results of Design 1 suggested water entering the canal would move along the central corridor and would exit via the third eastern arm, where the outlet flow structure to Lake Serenity was located. Design 1 leaves the southern most section of Oyster Cove isolated from the flushing process.

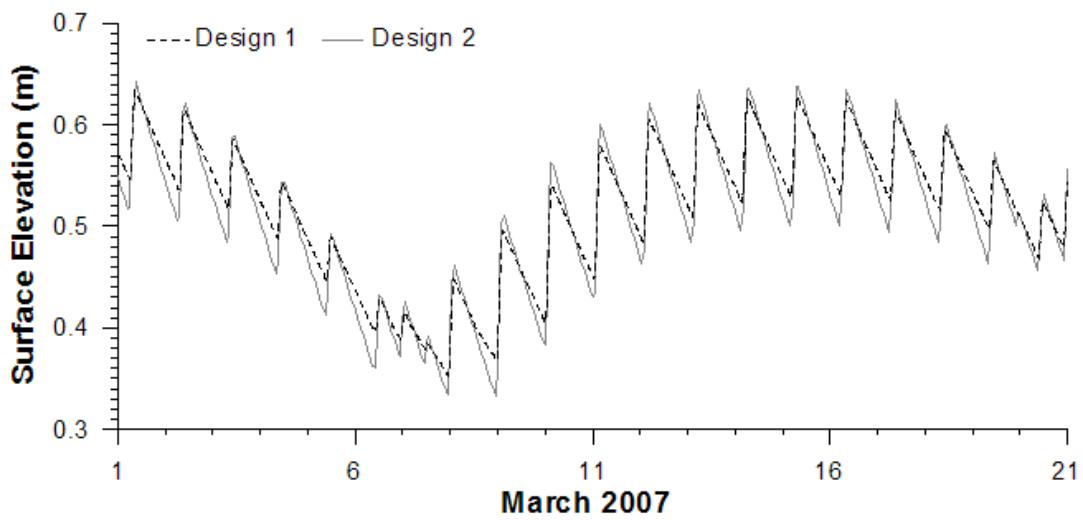
Moving the flow structure connecting Oyster Cove to Lake Serenity to the southernmost section of Oyster Cove ensured water was forced to flow through more of the canal to exit the system, hence removing the isolation of that southernmost section. Also, by replacing the bi-directional culvert at the front of the canal with a second uni-directional pipe, water that entered the system was forced to flow through the canal system to the exit at the back, rather than exiting through the culvert during the subsequent ebb tide. Both of these options helped reduce the residence time whilst causing little change to the existing tidal conditions inside Oyster Cove.



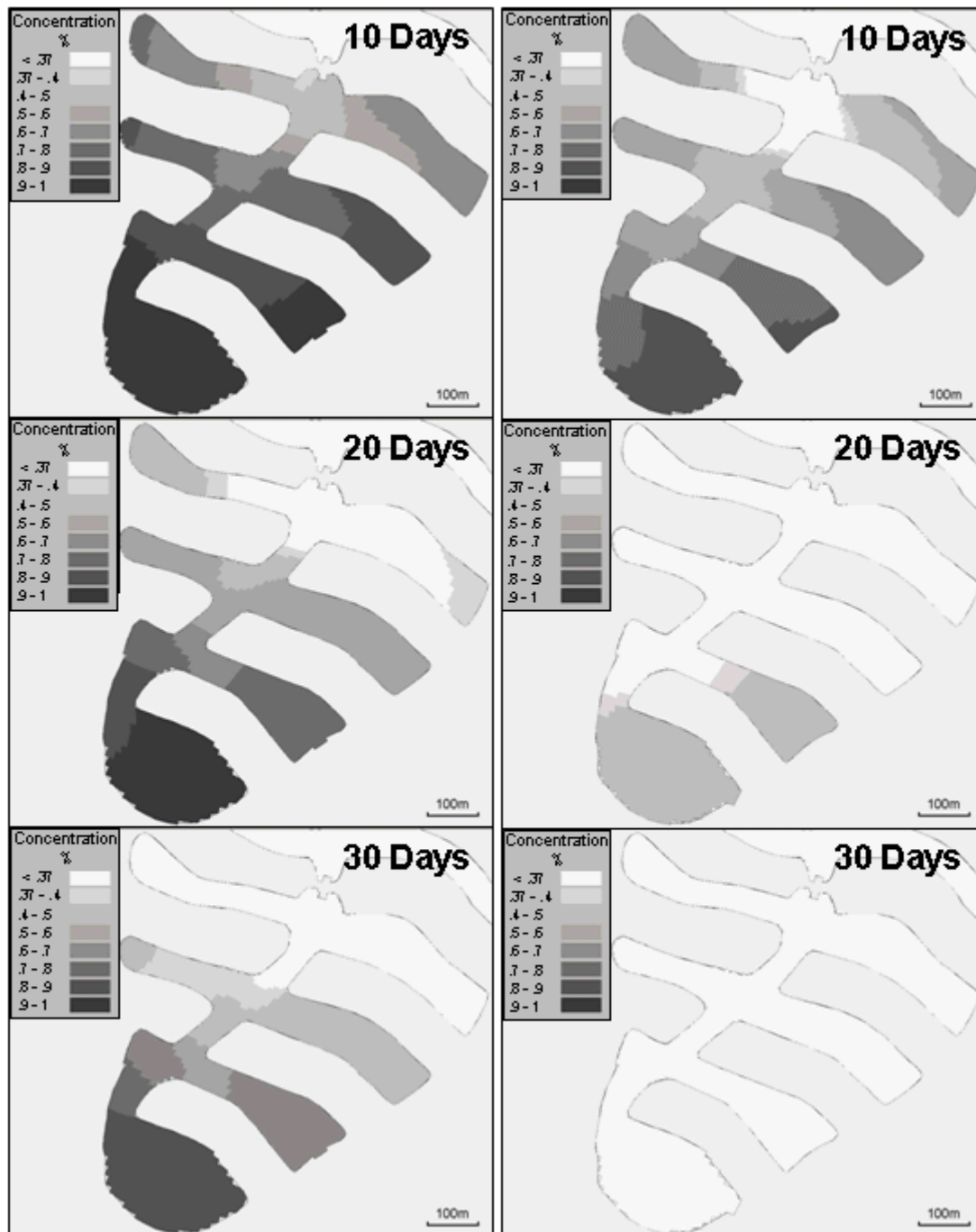
**Figure 5.** Model predicted dye concentrations at times corresponding to field observations.



**Figure 6.** Location of the flow structures for the design alternatives used to determine the influence of the type and position of the flow structures.



**Figure 7.** Comparison of surface elevation inside Oyster Cove for a 20-day period for Design 1 (dark dashed line) and Design 2 (lighter continuous line)



**Figure 8.** Comparison of modelling results from 30-day flushing simulations for Design 1 (left) and Design 2 (right)

## **Discussion**

Canal systems are primarily designed with limited tidal exchange for two main reasons: (a) to provide privacy and security for the residents; and (b) to ensure that there are no detrimental effects to the adjacent estuary, such as an increase in the tidal prism.

The comparison of the two designs in this study indicated that the type and positioning of the flow structures for Oyster Cove were critical in ensuring there was enough water exchange and circulation within the system. The options used in this study were to change one of the inlet structures to a uni-directional pipe and change the location of outlet and results showed the residence time was drastically improved.

The design options that this numerical model can simulate include: flow structure type (uni- or bi-directional and size); flow structure position and number of flow structures (single or multi inlets and outlets); and maintaining minimum and maximum water levels through employing different pipe sizes, timed openings or overflow weirs. Also, while wind was used in this study, it's worth mentioning that an alternative approach could be to not use wind, which would remove the wind induced mixing dynamic, to represent a true "worst case".

Canal system designs are becoming more and more complex to accommodate the increasing demand for more waterfront lots per housing estate. By using numerical models as a decision support tool during the design process, the health of these water systems can be simulated prior to construction to guarantee superior flushing performance.

## **Conclusion**

The flow structure subroutines presented in this study performed well simulating the exchange of water between the canal system and the adjacent estuary. The polynomial equations used to govern the flow rates through the flow structures worked well, however, a more detailed study of these types of structures in the field could resolve a suitable empirical formula in the future.

The flushing model clearly demonstrated the benefits of choosing appropriate flow structures to reduce the residence times of canal systems. The model creates a powerful decision support tool to maintain healthy canal systems.

## **Acknowledgements**

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