Flow and solute fluxes in integrated wetland and coastal systems

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Received 18 July 2005; received in revised form 30 July 2006; accepted 9 September 2006
Available online 1 November 2006

Abstract

Details are given of an experimental study of the flow and tracer transport processes in an integrated wetland and coastal basin. A novel physical model was constructed to enable observations and measurements to be made of groundwater transport through a sand embankment between a wetland and coastal area. This was an idealised scale model of the West Fleet Lagoon, Chesil Beach and the adjacent coastal waters, located in Dorset, UK. An extensive set of data of the seepage fluxes through the embankment was collected by monitoring the varying water level and velocity distributions on both sides of the embankment. The transport behaviour of a conservative tracer was also studied for a constant water level on the wetland side of the embankment, while running a continuous tide on the coastal side. Time series pictures of the concentration distributions of the tracer were filmed using a digital camcorder. An integrated surface and groundwater numerical model was also used in this study to assist in the analysis, with the numerical model predictions being compared with the images recorded from the experiments. Details of the physical model, experimental procedures and the equipment used in the study are reported in this paper.

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Keywords: Hydraulic modelling; Groundwater flow; Tidal hydrodynamics; Solute transport; Numerical modelling; Integrated models

1. Introduction

In recent decades, increased attention has been paid to the environmental issues of interaction between beach groundwater tables and the adjacent shallow coastal waters. Li et al. (1997) undertook a numerical modelling study to investigate tide-induced beach water table fluctuations. Larabi and De Smedt (1997) studied seawater intrusion into unconfined aquifers and Morita and Yen (2002) studied the rainfall-runoff processes and the interactions between surface and groundwater flows. Similarly, wetlands and mangroves have also been studied extensively, due to their important roles and influences on the aquatic ecosystem. The growing recognition of the values and functions of wetlands and mangroves presents a direct challenge to the traditional objectives of water management for specific sectorial purposes and raises questions about the meaning of better water management (Franks and Falconer, 1999).

A large number of physical and mathematical models have been developed and deployed to study the hydrodynamic processes involved in groundwater, surface waters and wetland systems. Following a detailed literature review, it was found that most effort so far has been focused on investigating individual processes within these systems. However, current knowledge on the integrated process relating to tidal, groundwater and shallow wetland flows is rather limited. Hence, the emphasis of this paper has been to study the interaction between wetlands and coastal waters through shallow groundwater flows. A new approach for integrated physical modelling of groundwater and surface water flows has been developed and is outlined herein.

According to Hughes (1995), field studies provide the best data, but they are usually expensive and involve too many parameters. The interpretation of field measured results also
often proves to be difficult. In contrast, physical models are less expensive, generally enable data to be collected easily, and provide controlled data; furthermore they may also include more important aspects of the problem. Falconer (1992) not only noted that physical models could be generally used as an additional engineering design tool, but added that for coastal studies the model domain often needed to be significantly scaled down both vertically and horizontally. One disadvantage with physical models in connection with flow and solute transport studies is a technical constraint related to scaling. However, for modelling solute transport in porous media, Harris et al. (2000) pointed out that physical models also offer major time-scaling advantages. For example, pore fluid seepage at prototype scales, i.e. over a period of years, can be simulated in the model in a matter of hours. Esposito et al. (2000) outlined that in predicting the transport of liquids containing hazardous chemical substances in soil and groundwater bodies has proved to be an extremely challenging exercise. They added that both mathematical and physical models have been developed to quantify such movements.

This paper is focused on creating an idealised scale model of a wetland system and the adjacent coastal waters. The model consists of a coastal region and a wetland region, with these being separated by a sand embankment. A series of experiments have been undertaken to study the influence of the coastal tidal flows on the wetland system and, in particular, the transport of a dye tracer between the coastal region and the wetland through the embankment. The data acquired through this study also provide a valuable database for further model calibration and validation. An integrated surface and groundwater numerical model was also developed for this study to assist in the analysis, with the numerical model predictions being presented together with the physical model results.

2. Physical model details

This section details the physical model configuration, measurement devices, tidal parameter specifications and the sand embankment properties. Details are briefly given of the features of Fleet Lagoon and Chesil Beach, followed by details of the physical model configuration, etc.

The scope of this laboratory study was not to recreate a scale model for a particular case study, but to investigate the hydrodynamic and mixing processes in an integrated coastal, groundwater and wetland system. For this purpose Fleet Lagoon and Chesil Beach were considered as a typical wetland—coastal site and were chosen to identify a typical prototype set up for this study. The Fleet Lagoon is a shallow coastal lagoon, trapped behind the Chesil Beach, and sited northwest of Portland Hill (in Dorset) along the south coast of England (see Fig. 1). The flow structure within the lagoon is primarily governed by tidal currents through a narrow opening to Portland Harbour, with the lagoon being linked to the adjacent coastal waters by groundwater passage through a sand ridge, namely ‘Chesil Beach’, which is approximately 150 m wide and 12.5 km long; see Robinson et al. (1983) and the UK Marine web site http://www.ukmarinesac.org.uk/activities/lagoon/14.

With regard to the significance of Fleet Lagoon, Johnston and Gilliland (2000) reported that the lagoon is one of the

![Fig. 1. General location of the prototype.](image-url)
largest and best studied lagoons in the UK and has been identified as a Special Area of Conservation (SAC). It is considered to be one of the finest examples of its physiographic type in the UK, and one of the most important sites in Europe. Generally speaking, Fleet Lagoon consists of two separate parts, namely the East and West Fleet. There is no opening to West Bay through the beach, but the Fleet is connected to the English Channel at its south eastern end through Portland Harbour. It is therefore tidal and saline, with a few streams draining into the lagoon from a small catchment area of about 50 km². It is also very shallow, varying in depth from 3 to 5 m in the first 2 km between the tidal entrance at Smallmouth and The Narrows. Here the lagoon is marine in character, with a strong tidal exchange to the sea. It then widens out to 2.5 km in the area known as Littlesea, where the depth is between 0 and 1.2 m below chart datum, intersected by a narrow channel of up to 4 m deep. The tide is strongly attenuated in this region and penetrates only weakly into the remaining 8 km of the lagoon, known as West Fleet which has a depth of between 0 and 1.2 m (see Robinson, 1983). West Fleet has demonstrated a significant lack of flushing and circulation characteristics as compared to those observed from the East Fleet (see Westwater et al., 1999).

In establishing the dimensions and hydrodynamic characteristics of the physical model, these characteristics were based on the tidal and geometric properties of West Fleet Lagoon and the adjacent coastal area. However, as the main aim of the study was to get a better understanding of the hydrodynamic and transport processes through wetlands and coastal embankments, it was decided to set up an idealised model of an integrated wetland and coastal system. For geometric simplicity, both undistorted and distorted scale models were first considered. A distorted model was then chosen since the laboratory tidal basin at Cardiff University’s Hyder Hydraulics Laboratory was not able to cope with the parameters required for an undistorted model. In dimensionally scaling the prototype, the physical model was developed upon the basis of dynamic similarity through the Froude law, in order to maintain similar gravitational characteristics to those found in the prototype. From studies undertaken by Westwater et al. (1999), Johnston and Gilliland (2000) and Kennedy (2001) on the Fleet Lagoon, typical values of the West Fleet Lagoon were chosen and used in the physical model design. A brief description of the model similarity and characteristics are presented below.

According to Hughes (1995), keeping the Froude Numbers equal, in the model and prototype yields:

\[
(F_N)_p = (F_N)_m \quad \text{or} \quad \frac{v_p}{\sqrt{g_p l_p}} = \frac{v_m}{\sqrt{g_m l_m}} \tag{1}
\]

where \(F_N\), \(v\), \(g\) and \(l\) are the Froude Number, average velocity, gravitational acceleration and the length of the prototype and model, respectively.

As reported in the above cited references, the length of the West Fleet is about 7000 m and the average width of Chesil beach is 150 m. Also, the average velocity of the tidal currents in the prototype is about 0.6 m/s and, according to the initial experiments, the same velocity in the tidal basin was found to be about 0.014 m/s, with Eq. (1) yielding a length of 3.80 m in the model. As the angle of steel bracket supports, which were used in construction of the surrounding walls, required a spacing of 0.20 m at any side of the model, then the model length was reduced to 3.60 m and the model scale was found to be 1/1900, with the top width of the embankment being calculated as 0.08 m. The corresponding average water depth and vertical scaling were unacceptable and therefore a distorted model approach was adopted.

The construction dimensions based on the distorted model criterion for the physical model simulations are illustrated in Fig. 2. As shown in Fig. 2a, the physical model had a length of 3.07 m, a width of 3.60 m and a depth of 0.33 m, and was sited in the tidal basin of total length 6.48 m, width 4.00 m and total depth 0.40 m. Fig. 2b illustrates a longitudinal section of the model. The embankment had the following dimensions: length of 3.60 m, top width of 0.08 m, bed width of 1.40 m, total height of 0.33 m, including 0.06 m free board, and side slopes of 1:2 (vertical:horizontal); this embankment separated the idealised model wetland from the model coastal waters. The wetland dimensions were: 0.54 m bed width and 1.20 m top width. As mentioned previously, a sluice gate was located in the corner of the model, to control the constant water level behind the model embankment and also for the purpose of flushing (see Fig. 2, details a and b). Table 2 summarises the main dimensions of the prototype and the physical models.

As a part of the experimental programme it was planned to study the behaviour of a conservative dye tracer for a constant water level on the wetland side of the embankment and with a tide operating on the coastal side. In order to create this condition, a sluice gate and a pipe were installed behind the embankment on the far side of the model (see Figs. 2 and 3b). The combination of the source and overflow-gate (sink) kept the water level constant, with a fluctuation of about 4 mm of the water level being measured during the experiments. It should be noted that initially it was planned to undertake the dye tracer experiments in the same manner as for the hydrodynamic experiments, where fluctuations in the water level were recorded behind the sand embankment. However, during the tests it was found that passage of the tracer through the sand embankment, with a fluctuating tide level downstream, took an excessively long time. Moreover, monitoring and analysis of the performance of the tracer movement was difficult, if not impossible, to monitor. Therefore, it was decided to monitor the spreading of the tracer for different tides in front of the sand embankment, while the depth of water behind the sand embankment was kept constant. Constant amplitude and period tides were produced in the tidal basin by a vertically oscillating weir, shown to the left end of the tidal basin in Fig. 2. The basin was fed by a water supply at a constant rate entering through a perforated manifold. To minimise the lateral variation in the velocity and to reduce artificial circulation in the model area, a 30 mm thick honeycomb baffle was located near the weir.
In this study non-cohesive sands were used to create the model embankment. The average grain diameter of the sand was 1 mm as it was important to control the validation limits of Darcy’s law within the sand embankment. According to Bear (1972) in practically all cases Darcy’s law is valid as long as the Reynolds number, based on the average grain diameter, does not exceed a value of between about 1 and 10. Calculations showed that for the sand used in this study the average Reynolds number was about 7. A series of experiments were carried out, according to the British Standard Methods No. BS 1377: Part 5: 1990, to determine the permeability and the specific yield of the sand. The results showed that the average value of the sand permeability was 0.995 mm/s and the average value of the specific yield was 29% (see Fig. 3a).

For the tidal conditions simulated in the model the period was set to 355 s, the mean water level was set to 214 mm and the tidal range set at 120 mm. All tests were commenced at high tide, so that the initial depth of water on both sides of the embankment was initially 274 mm (see Figs. 4 and 5). Water levels on either side of the embankment were recorded using wave probes, which worked on the principle of measuring the current flowing past a probe consisting of a pair of parallel stainless steel wires.

Velocity data were acquired using a Nortek acoustic Doppler velocimeter (ADV). This type of current meter uses an
acoustic pulse, emitted from a central emitter, which is then retrieved through three acoustic sensors to give the reflected Doppler shift in the reflected acoustic pulse from particles within the flow. From these meters the data were transmitted via a conditioning module to the PC, where the data were interpreted to give an instantaneous velocity at a specific point in the flow and specified in Cartesian co-ordinates.

For the dye tracer monitoring studies, imaging technologies were considered as a universal tool for visualising, digitising and analysing phenomena in experimental studies (see Allersma and Esposito, 2000). In this study the transport processes of a dye tracer were filmed using a digital camcorder, which was equipped with a wide angle lens. The camera was positioned on the ceiling, right over the physical model to provide optical measurements of the tracer migration through the physical model. In Fig. 2 the limits of the filmed area are highlighted by points P1, P2, P3 and P4. It should be noted that points P2 and P4 were not fixed and they moved along the flow direction, according to the tide levels. The use of image processing allowed non-disturbing measurements to be made of the tracer plume migration. A grid pattern was painted over the physical model floor to show the essential scale for the model calibration (see Fig. 3a). A tracer releasing device was also developed, which comprised a wide low-depth reservoir, connected flexible tubes and 18 nozzles (see Figs. 3b and 6a). Each nozzle had an independent valve and was drilled into
the main line at 0.20 m intervals. The device was fixed on the instrumentation beam, which could be moved along the model.

3. Experimental details

All experiments were started at high water and the initial water elevation was fixed at 274 mm on both sides of the sand embankment. Water elevations were then recorded at the middle point of the physical model cross-section on either side of the embankment and for an average of 10 tidal cycles. Fig. 4 shows a drawing of the physical model, including the location of the sampling points, with the water elevation data being collected and recorded at the locations a and b, shown in Fig. 4.

Velocities were collected at eight locations, from points L1 to L4 on the left-hand side and from points R1 to R4 on the right-hand side, over three tidal periods and at each location. The probe used was the downward orientation type, and was positioned in such a manner that the x-axis was in the direction of flow. The probe was moved from one location to the next using the access platform and the instrumentation beam, with data being collected at elevations of 128 mm below the mean water level (see Fig. 5). Based on integrating a logarithmic velocity profile, it can be shown that the theoretical mean velocity occurs at an elevation of approximately 0.6 of the depth below the free surface (Chow, 1973).

A solute of potassium permanganate, of concentration 5 g/l, was used as a tracer for the dye concentration plume experiments. Tracer release experiments were carried out in two ways: (a) the tracer was released at 18 points along a line, and (b) the tracer was released at one point (see Fig. 4 points 1–18). The release device was calibrated before each experiment and the tracer was released just behind the sand embankment in the model wetland. The transport processes were filmed from the start of each test, using the digital camcorder, to monitor the spreading of the tracer for different tides in the model coastal area. During these experiments the water depth within the wetland area was kept constant at high water level and the discharge of the tracer was 1.26 ml/min. Fig. 6 shows the migration of the dye tracer within the model wetland, with the discharges through the nozzles being calibrated using the nozzle valves for all cases. It should be noted that the sand embankment and physical model tidal basin were flushed after each experiment. For this purpose fresh water was used.

With regard to processing the data, the measured water level time series were processed using a spreadsheet, with measurements made on both sides of the physical model being plotted on the same graph. The velocity measurements were made throughout the tidal cycles and were subsequently time averaged over each 10 s interval. The resulting time averaged velocities were then plotted on a spreadsheet, together with the numerical model predictions.

The numerical model used in this study was an integrated free surface and groundwater flow model. The surface model was based on an existing depth integrated two-dimensional model named DIVAST (Depth Integrated Velocities And Solute Transport model, developed originally by Falconer (1976, 1984)). The groundwater model used was called GWK (Ground Water Key), which was developed to simulate the flow and solute transport processes in porous media. The two models were dynamically linked, which allowed an automatic transition between the surface and groundwater flows at the intertidal zone (see Ebrahimi, 2004).

Video films of the tracer concentration distributions were recorded and transferred to a computer and a set of suitable images were obtained using the Studio DV version-8 package. These images were subsequently compared to the numerical model predictions.

4. Results and discussion

4.1. Water levels

Fig. 7 shows the measured water levels on both sides of the sand embankment. On the coastal side the maximum recorded tidal range was about 116 mm, with the level of high water being 60 mm relative to mean water level and the level of low water being –56 mm, over a tidal period of 355 s. On the wetland side the water elevation was initially measured at 62 mm at high water, but it reduced rapidly over the first three tidal cycles. After that the fluctuating water level stabilised at between 22 mm and 1 mm, for high and low waters respectively. The reduction in the amplitude of the tidal wave was therefore about 81%. In addition to this amplitude reduction, there was also a significant phase difference of about 90 degrees between the water waves on the two sides of the embankment. When the coastal side was at high water, the wetland side was at
mid-flood. In contrast, when the tide on the coastal side was approaching mid-ebb, then the tide on the wetland side had reached high water. Due to non-linear effects the water level profile was particularly asymmetric on the wetland side of the embankment.

4.2. Velocities

Velocity data were collected at eight points along a cross-section, across the physical model, and at the locations specified in Fig. 4. The results recorded at the measuring points L1, R1, L4 and R4 are shown in Fig. 8a–d, respectively. The numerical model predicted velocity distributions are also reproduced on these figures.

The maximum measured velocity was found to be about 9.2 mm/s when the flow was directed towards the wetland and was about 8.9 mm/s when the flow was directed away from the wetland. The difference between the velocities measured at the various locations was small. This highlights the uniformity of the flow across the basin.

4.3. Tracer concentrations

Tracer concentration distributions were predicted using the numerical model and are reproduced, together with the corresponding photo images taken at various stages to illustrate the dye tracer behaviour. By comparing the size of the tracer plumes in the video shots and the concentration contour levels...
in the numerical outputs, it was found that it was possible to relate the tracer plumes to the model predictions.

4.3.1. Line tracer release

As stated previously, the tracer release was always started at high water. The general behaviour of the dye tracer, established from the video film and model predictions, is described below. It should be noted that in discussing these results, the high water level was used as reference point.

Fig. 9a shows the video recorded and model predicted concentration distributions for the first mid-flood level after the release of tracer. At this stage the flow velocity at the coastal side was directed towards the wetland, thus the tracer concentration level at the coastal side was low. The model predicted concentration contour level 2, which represented a concentration level of 0.1 g/l, agreed best with the recorded plume. From mid-flood to high water there was only a slight increase in the concentration level (see Fig. 9b), as the plume was still being held back by the flow. However, at high water the tracer was leaching more towards the coastal region through the sand embankment, although the concentration distribution was not fully uniform.

At high water the flow velocity on the coastal side started changing direction. As the velocity gradually increased from high water to mid-ebb, there was a clear increase in the concentration level. Another point worth noting was the high concentration of tracer that occurred on the left and right hand sides of the model away from

![Fig. 9. Behaviour of line release dye tracer over different tides.](image-url)
the central line; this can be seen clearly for the contour levels 3 and 4 in Fig. 9c. This appeared to be affected by the presence of the entrance edges of the physical model (see Fig. 2, points P1 and P3). Two small local diversions in the flow were created near these edges, which led the tracer to move to the sides of the model.

At low water the water level difference between the wetland and coastal area was greatest and the flow velocity within the embankment reached its maximum. Therefore, at this stage the solute transport rate (or tracer flux) from the wetland to the coastal region was also greatest. It can be seen from comparing Fig. 9c and d that at low water there was a significant increase in the concentration level. The tracer concentration distribution in the cross-sectional direction also became more uniform.

Fig. 9e illustrates the concentration distributions for the second mid-flood. Both physical model observations and numerical model predictions showed higher concentrations across the entire coastal region monitored. At high water the tracer plume was again being pushed back towards the wetland, thus the concentration level started to decrease again (see Fig. 9f).

4.3.2. One-point tracer release

In a similar procedure to the one-point release a second experimental programme was undertaken to study the solute transport processes when the tracer was released at the central point. The same hydrodynamic conditions were applied as for the first experiment.

Fig. 10 shows the tracer concentration distributions after the release of dye tracer, with details of these plots being given in Table 1. Pictures of stages 1–3 were not included, because there was no clear appearance of tracer before stage 4. It can be seen from the figures that the size of the tracer plume generally increased with time. At mid-flood the predicted concentration level 2, corresponding to a concentration of 0.1 mg/l, was shown to give the best agreement with the video observation (see Fig. 10a). The length of the tracer plume at this time was 1220 mm and the width was 500 mm. At this stage the tracer was held back by the tide as the tidal flow was directed towards the model wetland.

Fig. 10b shows the concentration distribution at high water. Since the water surface gradient was very small, the velocities across the computational domain were found to be close to zero. Both recorded and predicted concentrations increased, with contour level 2 having a length of 1250 mm and width 590 mm. However, the recorded tracer plume had moved slightly towards the right hand side of the basin. Several reasons can be considered for this diversion. It may be explained by the concept of dispersion of a contaminant in a porous medium, as outlined by Wang and Anderson (1982), wherein the dispersion is due mainly to heterogeneity of the medium and is a result of the existence of a statistical distribution of flow paths and of flow velocities around local heterogeneities. The small circulation caused by the sink on the left corner may be another reason (see Figs. 2 and 3b for the location of the sink). The third reason was that during the experiments the tracer was not distributed uniformly over the water depth. At some locations the tracer might spread closer to the basin floor than others, where the flow currents used to transport the tracer became weaker.

Fig. 10c–e represents the concentration distribution of the tracer from mid-ebb to mid-flood. As the water elevation fell from high water to low water, the tracer passed through the embankment at a higher rate. Generally speaking, at this stage the recorded and model predicted concentrations distributions agreed well. At low water, the size of the plume was largest (see Fig. 10d), where the length of contour level 2 was 2880 mm and the width was 760 mm. At the second mid-flood the tracer flux became lower and was caused by the rising tide in front of the embankment (see Fig. 10e). At the second high-water (see Fig. 10f), the length of the plume was approximately twice that shown in Fig. 10b, at the previous high water. Finally, it was observed that for a short period around high-water, the shape of the plume changed rapidly and the plume appeared to be dispersed quickly. From these figures it was also clear that the concentration of the tracer increased over the tidal cycles, as the tracer colour changed from a light-red colour to a dark-red colour.

5. Summary and conclusions

Details are given herein of the challenges associated with flow and solute transport interaction between wetland basins and coastal systems. A case study was considered, namely Fleet Lagoon, where the lagoon is separated from the coastal zone by a sand embankment. At this site salinity and nutrient levels in the hydro-ecologically sensitive lagoon are highly dependent upon the flow and solute transport fluxes through the sand embankment, which depends upon the water elevation in the lagoon relative to the tidal elevation in the adjacent coastal waters.

An experimental study was undertaken to determine the hydrodynamic and solute transport processes for an idealised linked surface and groundwater flow system, based on a scaled physical model of the west Fleet Lagoon and the adjacent coastal waters. The main aim of the experimental study was to investigate the seepage and the associated transport behaviour through a sand embankment, with tidal forcing being the driving factor. Water levels and velocities were measured at several points along a cross section within the physical model. A novel mechanical device was developed to release dye tracer for in-line and point source release patterns within the embankment and into the lagoon. Dye concentration levels were recorded using a digital camcorder and graphical images at different tidal phases and the data were analysed to study the transport processes. Due to the size of the physical model and the non-negligible sand adsorption and desorption of the tracer into the embankment, it was difficult to generate accurate concentration distributions through the embankment. To overcome this difficulty, numerical model predictions were therefore presented, along with the physical model results to assist in the analysis of the flow and solute transport processes through the embankment.
Table 1
One-point release tracer characteristics

<table>
<thead>
<tr>
<th>Time-stage number</th>
<th>Time, start of tracer (s)</th>
<th>Time from beginning of the video film (s)</th>
<th>Tide level in front of the dike</th>
<th>Tidal elevation (mm)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>263</td>
<td>High water level</td>
<td>+60</td>
<td>Start of tracer</td>
</tr>
<tr>
<td>2</td>
<td>89</td>
<td>352</td>
<td>Mid-ebb</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>197</td>
<td>460</td>
<td>About low water level</td>
<td>−56</td>
<td>Appearance of tracer in front of the dike</td>
</tr>
<tr>
<td>4 (Fig. 9a)</td>
<td>267</td>
<td>530</td>
<td>Mid-flood</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>5 (Fig. 9b)</td>
<td>355</td>
<td>618</td>
<td>High water level</td>
<td>+60</td>
<td></td>
</tr>
<tr>
<td>6 (Fig. 9c)</td>
<td>444</td>
<td>707</td>
<td>Mid-ebb</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>7 (Fig. 9d)</td>
<td>533</td>
<td>796</td>
<td>Low water level</td>
<td>−60</td>
<td></td>
</tr>
<tr>
<td>8 (Fig. 9e)</td>
<td>622</td>
<td>885</td>
<td>Mid-flood</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>9 (Fig. 9f)</td>
<td>710</td>
<td>973</td>
<td>High water level</td>
<td>+60</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10. Behaviour of one-point release dye tracer over different tides.
The main conclusions from the study can be summarised accordingly:

(i) Tidal forcing was the dominant factor that governed the integrated flow and solute tracer transport processes investigated in this study. The magnitude of the tidal range was significantly reduced when the water flowed from the model coastal region to the wetland, through the embankment. There was also a large phase difference between the seaward tidal elevation and the basin elevation in the lagoon, with the phase in the wetland being about 90 degrees behind that of the coastal waters.

(ii) The difference between the water elevations in the coastal and wetland basins controlled the velocity field and hence the tracer flux passing through the embankment. For a line source input, a close relationship was identified between the tidal dynamics and the tracer transport processes. For a point source input the study revealed that the tracer plume developed quickly in an approximate elliptic form, passing through both the porous medium and the free surface domain. Also, as the tide rose from low to high water, the discharge of the tracer from the wetland basin to the coastal areas continued. The number of tidal cycles was an important parameter when considering the size and location of the tracer plume.

(iii) The hydrodynamic and solute transport processes in a combined wetland and coastal water system are very complex. Numerical modelling has been shown to be effective in complementing physical model experiments for developing an understanding of the processes involved.

In numerically modelling flow and solute transport processes through porous media, the inclusion of the seepage flux and the adsorption process tend to give better results due to the importance of these factors in the modelling phenomena. Also, in the context of this study, salinity effects were not investigated. However, this constituent may have an important impact on the solute distribution, and to a lesser extent on the hydrodynamic parameters. Therefore, the inclusion of salinity in the numerical model and the collection of new laboratory data with salinity included for model validation would undoubtedly provide an improvement in the model applicability, especially for practical case studies. Also, in order to improve on the accuracy of the developed model, and extend the applicability of this study, then the application of the numerical model to Fleet Lagoon would be improved with the inclusion of: wind effects, long shore currents and other such hydrodynamic factors as deemed relevant at the time of field data acquisition.

Acknowledgements

The first author would like to acknowledge the support of the Iranian Ministry of Science, Research and Technology and the University of Tehran in supporting this research project at Cardiff University.

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