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Verification of a Three Dimensional Advection Dispersion Model Using Dye Release Experiment

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Abstract

The study aims to investigate transport processes within the entrance of a coastal lagoon through estimating the advection-dispersion coefficients of the estuary. To this end, an extensive observational data set including water level variation and current has been used for the hydrodynamic calibration of the model. Simulation of water quality variation with time requires mathematical modelling based on the advection and dispersion phenomenon. The advection-dispersion model is setup using a MIKE3 software platform. The model is calibrated using data obtained through monitoring the dilution and movement of a tracer (Rhodamine WT), which is introduced into the water column during a number of experiments at various locations within the study area.

Introduction The city of Gold Coast, Australia, with a population of 450,000 discharges about 110 ML/D of domestic wastewater after partial treatment to the adjoining marine water body. Under the current Gold Coast Wastewater disposal plan, wastewater is being disposed at the Broadwater lagoon tidal entrance (Seaway). The Broadwater is a semi enclosed coastal lagoon, located between latitudes 27.98-27.75S and longitudes 153.39-153.43E, in the state of Queensland, Australia, (figure1). The release is conducted through two diffusers located on the northern and southern banks of the Seaway, discharging approximately 55 and 65 mega litres of wastewater per day respectively into the seaway during the flood tide. Under the current scheme, the discharge starts approximately half an hour after the high slack water and ceases almost half an hour before the low slack water. The Gold Coast is located in one of the fastest growing regions in Australia, resulting in having more than 180 mega litres per day wastewater to be released at the Seaway. Managing this excess wastewater requires the construction of expensive infrastructure, such as a new pipeline from wastewater treatment plants to the Seaway. An alternative interim solution to the problem is to increase the duration of the release by between 1.5 to 3 hours. This can be achieved by starting the release between one and two hours before the high slack water, resulting in having part of the wastewater coming back into the Broadwater during the flood tide. The aim of this paper is to develop a tool that can be used to examine viability of this interim solution (in terms of meeting water quality objectives for receiving waters on the Gold Coast).

Studies of wastewater outfalls to coastal water have historically been undertaken using numerical hydrodynamic and transport models. In order to undertake this investigation and to assist in optimizing the release schedule a numerical (hydrodynamic-transport) model of the Broadwater has been developed as part of this study. It must be kept in mind that the correct numerical simulation depends on how accurately the model reflects the real physical conditions in the study area, and also on the type of boundary conditions. Once the accuracy of the model has been established, numerical models may be used to simulate a large number of different cases, making it a useful tool for optimizing the release options. To this end, this study also includes a dye release field experiment on the Broadwater. The results of this experiment are then used to verify the accuracy of the numerical model.

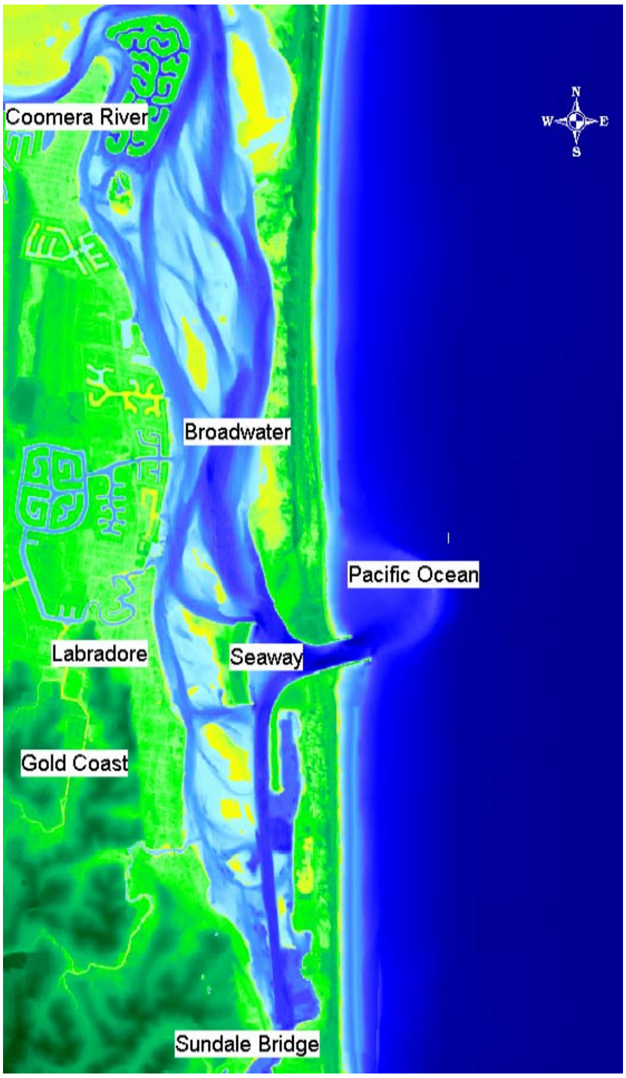


Figure 1. Study area

Data Collation

In order to verify the predictions of the numerical model, it was necessary to gather a comprehensive set of current, water level and advection/dispersion data. To this end 10 measurement stations were established within the study area, as shown in Figure 2 and Table 1.

Measurement Stations		
Station ID	**Location**	**Data Type**
a	Seaway	Current
b	Southern Channel	Current
c	Northern Channel	Current
d	Seaway	Water level
1	Seaway	Dye concentration
2	Northern Channel Flood	Dye concentration
3	Northern Channel Ebb	Dye concentration
4	Labrador Channel Flood	Dye concentration
5	Labrador Channel Ebb	Dye concentration
6	Southern Channel Flood	Dye concentration
7	Southern Channel Ebb	Dye concentration

Table 1. Locations and type of measurements.

Figure 2. Measurement stations

Hydrodynamic Data

Hydrodynamic calibration of the model was undertaken against a set of data collected during January 2005 [1], [2]. This data set includes current and water level measurements.

The purpose of current data collection was to collect observations of the spatial and temporal variations in tidal current at the seaway and its approach channels. A broadband 1200 kHz Acoustic Doppler Current Profiler (ADCP) was used for collecting current velocity data. The ADCP was interfaced with a differential GPS receiver to enable positioning of each ensemble. Clock synchronization between the GPS and the computer, which controlled the ADCP, allowed an accurate positioning of the ADCP output data. The ADCP was oriented to look downward into the water column and was operated in “bottom tracking” mode, i.e. velocities were measured with respect to the bed. The instrument was mounted to a mast, which was rigidly attached to a small survey vessel. Three transect lines within the study area were determined for current measurements as shown in Figure 2. The boat repeatedly navigated these transect lines approximately 60 times, with the ADCP continuously collecting current data. The ADCP survey was conducted during a minimum of one tidal cycle. To ensure that a full tidal cycle had been recorded, the measurements were extended at least one hour either side of low and high slack water. On this basis every data collection session took between 14 to 16 hours for each of the high and low tidal range events. The first bin was 0.8 meter below the transducer and the bin length was 0.5 metres.

Water level measurement was undertaken using a GreenSpan CTD350 capable of measuring water level, salinity and temperature. The recording time interval for gauge was set to 15 minutes with an averaging interval of 10 seconds (to minimize the impact of ripples, wind generated waves, localized boat wash, etc.) The sensor sampled the water level, temperature and conductivity at a rate of 1 sample per 2 seconds. This gauge measures absolute pressure. Water pressure readings were corrected for the variations of three parameters, namely atmospheric pressure, salinity and temperature, once the data was downloaded from each gauge. The atmospheric pressure record was derived from the Bureau of Meteorological station at the Gold Coast Seaway. Salinity and temperature were needed to calculate water density variations at the measurement sites. Temperature was measured directly by the CTD350 and salinity was calculated from the measured conductivity (using UNESCO Practical Salinity Scale). Once the density of water was calculated, it was applied to the readings to convert pressure readings to water depth. Measurements show that density variations within the water column were minor within the study area. This situation can be attributed to the study area being relatively shallow and to the mixing processes being strong. On this basis, density variation inside the water column was not applied to the readings. To adjust measured water level to a known vertical datum, all tidal gauges were surveyed relative to benchmarks. The result from each gauge is a time series representing the variations in water surface elevation relative to the Australian Height Datum which is a standard vertical reference representing mean sea level in the region.

Advection Dispersion Data

The Griffith University research vessel, R.V. Triton, a 5m catamaran equipped with a novel pumping system, delivers a steady flow of dye at a known concentration and depth, thus creating a steady plume that is fixed in both space and time. A second research vessel, R. V. Scylla, equipped with a Differential Global Positioning System and a recently calibrated YSI rhodamine sonde, streams near real-time data into digital storage whilst moving across the dye plume.

Continuous introduction of dye was chosen to minimise the maximum dye concentration levels needed and enabled a dye to be released at depth with the same density as of the surrounding water. The spread and dilution of the dye can also be determined with minimal mixing effects caused by the monitoring vessel.

Dye Dispersion

A stable platform was fixed in position carrying a pump/dye mixing system and a Sontek 1.5 MHz ADCP recorded water velocities and direction throughout the survey period. Once system checks were completed, clean seawater was pumped through the mixer box enabling the flow rate to be adjusted to around 4 l/s giving a discharge flow of 0.5 m/s through a 150mm diameter discharge pipe placed 1 metre below the surface. Releasing the first marker drogue into the water started the survey and a 2.5 litre container filled with 40-ppm dye concentrate was allowed to flow into the mixer box. A restricted nozzle ensured uniform flow and a sample was taken for later verification of dye concentration, nominally 1.5 ppm. Every twelve minutes a drogue was released and a sample taken from the mixer box. The discharge was terminated after the release of the 6th marker drogue, sixty minutes after the start. Figure 3 shows schematically the dye release system that was developed as part of this study.

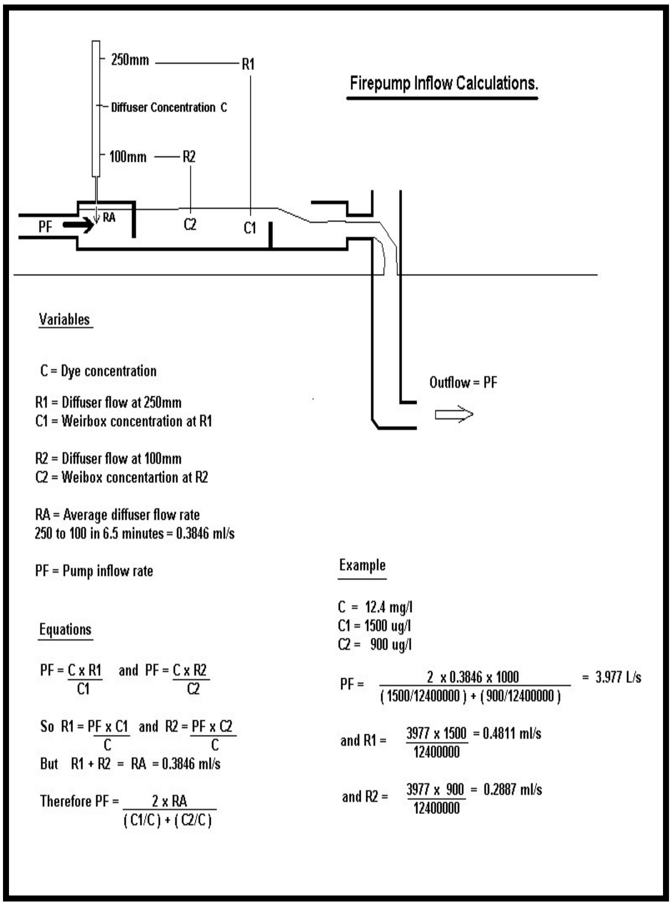


Figure 3. Schematic of dye release system

Dye Monitoring

A second vessel was fitted with a differential GPS system and a multi-parameter probe (YSI 6600) connected to a YSI flow cell which measured and recorded rhodamine, turbidity, temperature and conductivity.

Whilst underway, water was pumped to the instrument using a diaphragm pump via a reinforced tubing with an inlet located 1 metre below the surface. The vessel speed was kept below 1 m/s to give good positional accuracy and to minimise false spikes caused by turbulence and air entrainment at the pipe inlet. The near real-time presentation of the data on the survey vessel enabled field samples to be taken during high rhodamine concentrations for later analysis in a laboratory to confirm the field values being recorded. Figure 4 to 7 show the results of dye measurements at stations 6 and 4 during flood tide conditions.

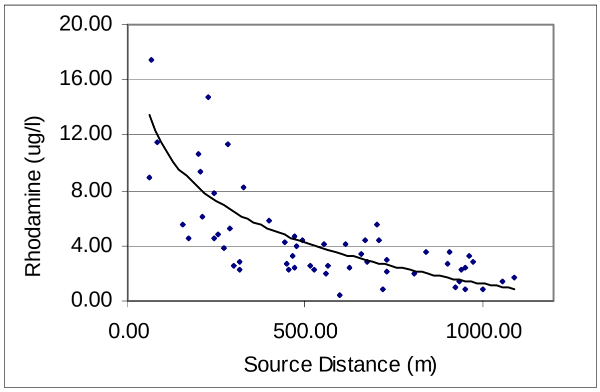


Figure 4. Rhodamine Levels and Distance from Source Seaway South

Figure 5. Rhodamine levels and locations

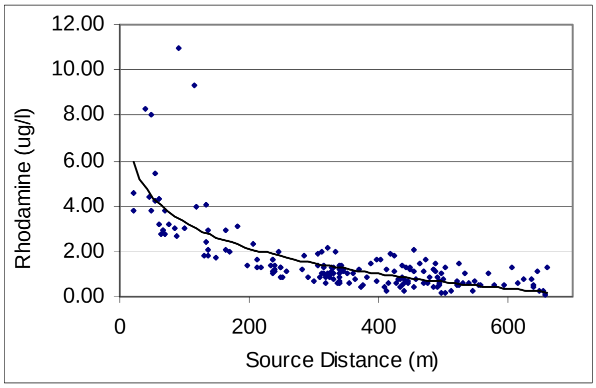


Figure 6. Rhodamine Levels and Distance from Source Labrador Channel

Figure 7. Rhodamine levels and locations

Drogue Tracking

Two drogue types were used for the survey, a 50mm x 250mm concrete and foam filled pvc pipe for surface currents and a larger 120mm x 1000mm foam filled pvc pipe with an aluminium vane set at 1 metre below the surface.

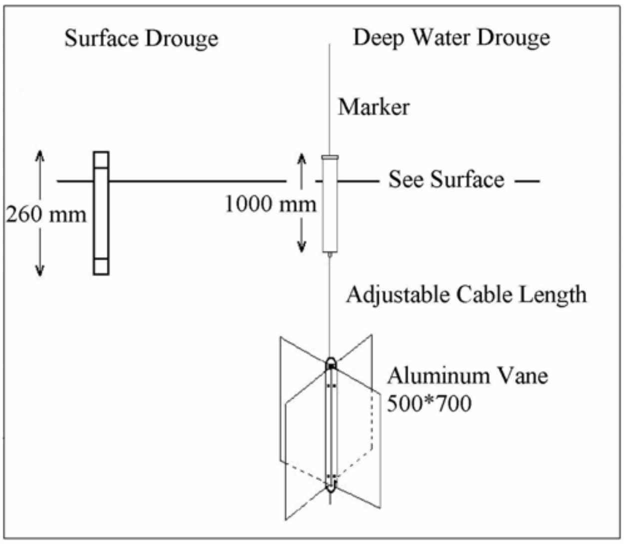


Figure 8. Schematic of drogue design

Data Filtering

During the field trials, background fluorescent measurements were found to be variable, ranging from –3 ug/l to 4 ug/l depending on the water body, calibration zero values used and the sampling rate of the YSI 6600. As the DGPS logging rate was 5 seconds a high band pass filter was incorporated by setting the YSO logging rate to 1 hertz and recording the rhodamine maximum encountered in each 5 sec interval. Field trials also indicated that if the survey vessel travelled faster than 0.9 m/s erroneous values caused by turbulence at the pipe intake were produced. During post processing a filter was introduced to remove any values where the survey vessel is in excess of 0.9 m/s. The narrow nature of the dye plume produces a large number of low values recorded near the plume. For clarity of presentation, a second high band pass filter was introduced that removes these lower rhodamine values. (Rh < 4.2118 Ln (-0.0065 * source distance).)

Numerical Modelling

Numerical modelling was conducted using MIKE software (DHI). Mike3 is a professional engineering software package for three-dimensional free-surface flows. It simulates unsteady flow taking into account density variations, bathymetry and external forcing such as wind, tidal elevations, currents and other hydrographic conditions. For this study we have used a standard $k-\varepsilon$ model to account for turbulence. In this model the eddy-viscosity is derived from turbulence parameters k and ε as:

$$\nu_t = c_\mu \frac{k^2}{\varepsilon}$$

where k is the turbulent kinetic energy per unit mass (TKS\D), ε is the dissipation of TKE and c_μ is an empirical constant.

The bottom shear stress is determined by a quadratic friction law

$$\frac{\vec{\tau}_b}{\rho_0} = c_f \vec{u}_b \left|\vec{u}_b\right|$$

where c_f is the drag coefficient and $\vec{u}_b = (u_b, v_b)$ is the flow velocity above the bottom.

Wind stress $\vec{\tau}_s = (\tau_{sx}, \vec{\tau}_{sy})$ is simulated as the surface stress applied over the study area. The stress is given by the following empirical relation:

$$\overline{\tau}_s = \rho_a c_d \left|u_w\right| \overline{u}_w$$

where ρ_a is the density of air, c_d is drag coefficient of air, and $\vec{u}_w = (u_w, v_w)$ is the wind applied 10m above the sea surface.

Model Setup

Model setup was undertaken in three steps: grid generation; boundary condition definition and calibration. A flexi mesh in 6 equally spaced layers represented the study area. Although the grid generation process in MIKE3 is performed automatically, the user can influence the size of the mesh and their resolution at various locations across the model area by introducing break lines and setting maximum grid size parameter. As shown in Figure 9, the resolution of elements has been progressively increased from the open ocean boundary towards the Broadwater. The area inside the Broadwater, the tidal entrance and the ebb shoal outside of the tidal inlet were represented with adequately fine elements to account for complex flow pattern and bathymetric variability in these areas.

An earlier study of the region [3] demonstrated that the energy of incoming waves from the Pacific Ocean is mainly absorbed by the breakwaters and their impact on the Broadwater hydrodynamic and mixing processes is insignificant. On this basis the waves propagation was not modelled in this study. The impact of wind can potentially be substantial and has been included in the model. Wind is modelled as a time varying surface stress, uniformly distributed across the study area. Wind speed and direction was collected from the Bureau of Meteorology climatological station at the Seaway.

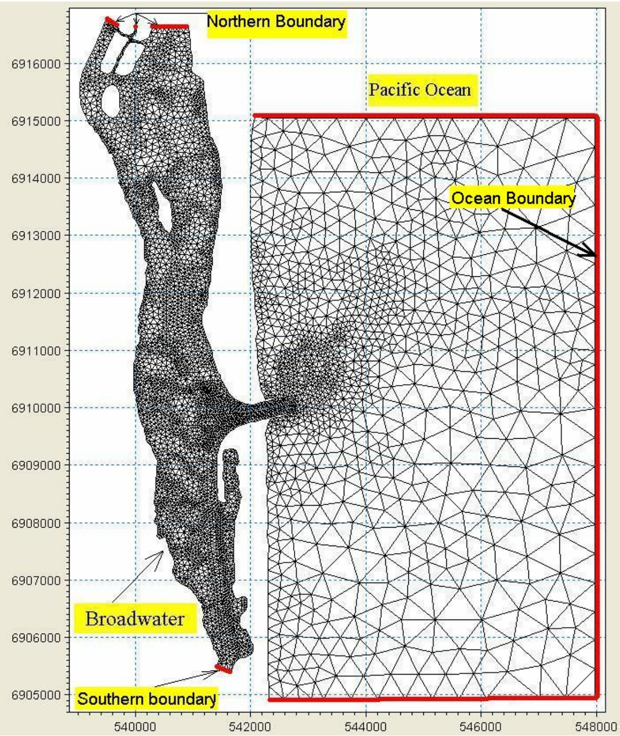


Figure 9. Discrimination of study area

Boundary Conditions

The model has three boundaries, as shown in figure 1. The Southern and Northern boundaries are inflows, which are transferred from an already calibrated and validated global model of the region [4]. The open ocean boundary is water level variations time history due to tide. The tidal prediction is based on tidal constituents that are obtained from long term tidal measurements at Snapper Rock (approximately 20 km South of the Gold Coast Seaway).

Hydrodynamic Calibration

Calibration was achieved by varying roughness value. The calibration was performed against water level measurement at a location inside Broadwater and discharge at three locations as shown in figure 2. The discharge is calculated using the velocity data that was collected by an ADCP along three transacts, (namely 1, 2 and 3, figure 2) on 12 January 2005. Figures 10 to 13 show the comparison between the model results and measured discharge for this period of time.

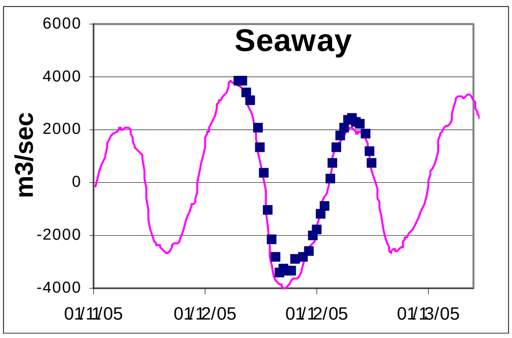


Figure 10. Flow discharge variations (solid line is model results)

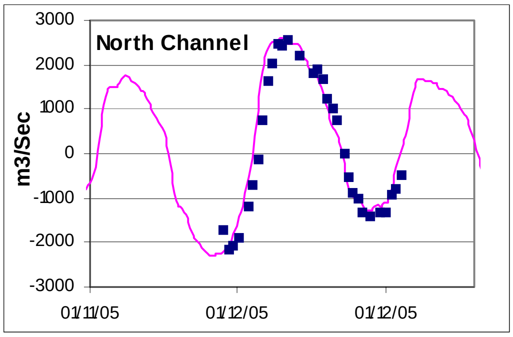


Figure 11. Flow discharge variations (solid line is model results)

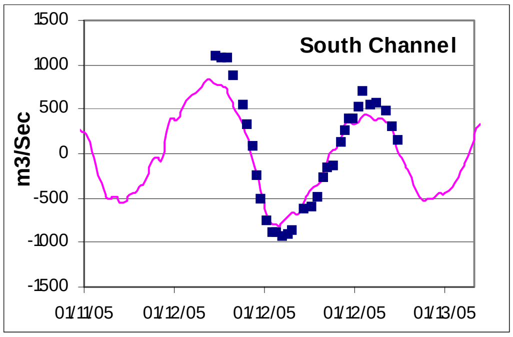


Figure 12. Flow discharge variations (solid line is model results)

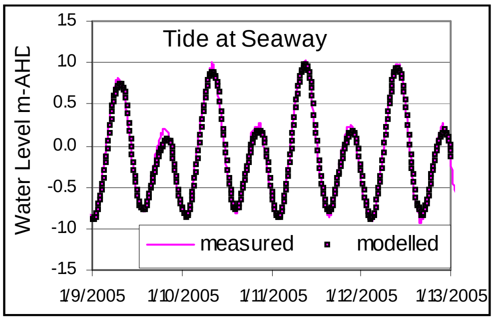


Figure 13. Water level variations (solid line is model results)

This comparison shows that there is a very good match between the measured data and model results, indicating the suitability of the model from hydrodynamic point of view for carrying out the study further to cover transport processes within the Broadwater.

Advection Dispersion Calibration

Calibration of the advection and dispersion performance of the model was undertaken using data obtained through monitoring the dilution and movement of a tracer dye (Rhodamine WT), introduced into the water column during a number of experiments at various locations within the study area. Monitoring and tracking of the dye plume was achieved using marker drogues and a DGPS fixed survey vessel recording rhodamine concentrations.

The results of the advection dispersion calibration can be seen in figures 14 and 15.

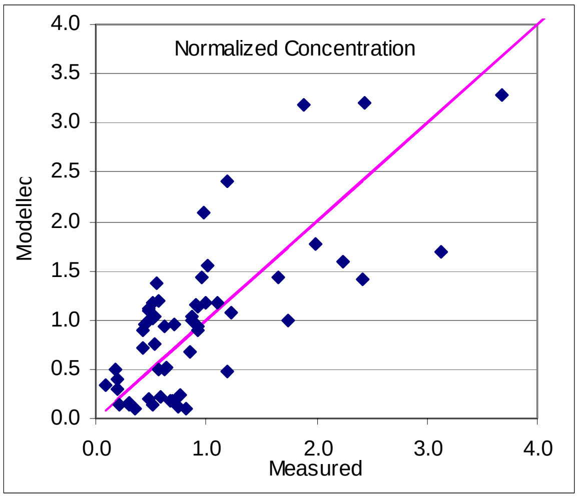


Figure 14. Comparing modelled and measured concentrations (south channel during flood tide)

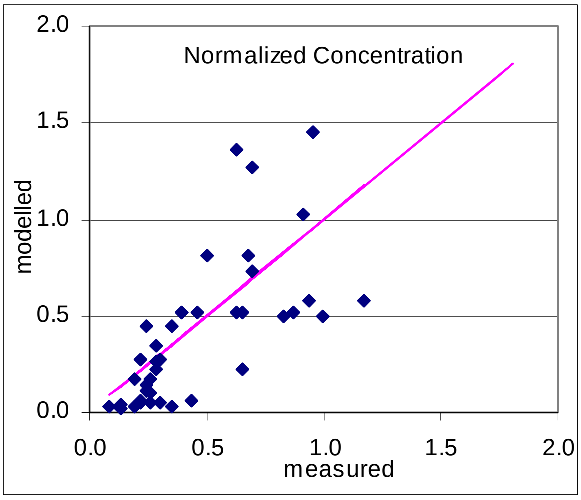


Figure 15. Comparing modelled and measured concentrations (north channel during ebb tide)

These figures compare the normalized concentration of dye at stations 6 and 4 during the flood tide that obtained from measurements and numerical modelling. A limited degree of data scatter of around the 45^0 line indicates a relatively good agreement between the model results and measurements.

Verification of Model Using Drogue Data

Although the drogues were designed primarily for monitoring and tracking of the dye plume, they provide a unique set of data reflecting the advection characteristic of the flow field within the study area. On this basis the particle-tracking module of the software was used to numerically simulate the movement of the drogues.

Figure 16 shows a comparison between the measured track of drogues and the track obtained from the model in the north and south channels during flood tide. As it can be seen, there is a good general agreement between particle tracks in the model (shown with solid while lines) and the location of the drogues (shown with red crosses).

Figure 16. Drogue tracks (solid line is model simulation and red crosses are measured)

Discussion and Conclusion

Figures 17 and 18 shows the outcome of the modelling as the result of dye release at station 2 during the flood tide after 10 minutes. Figures 19 and 20 show the results of the modelling as the result of dye release at the same station after 70 minutes from the commencement of release. Figure 17 and 19 show the surface dye concentration variations and figures 18 and 20 are profiles across the centre of the plumes. The total length of dye release is 60 minutes. These figures indicate that in general advection dominates in the Broadwater resulting in a narrow plume. Figure 18 shows that the concentration of dye near the source (at the surface) remains substantially higher than that at the bottom. This situation is sustained throughout the 60 minutes dye release indicating that the advection component of transport is substantially stronger than the dispersion element. A short time after the dye release is stopped (figure 20) the concentration of dye becomes uniform in depth indicating strong mixing processes being active in the water body. On this basis, a two dimensional model of the study area could be sufficient in dealing with accidental spillage. For this study (continuous release of wastewater from diffusers) a three-dimensional model seems to be appropriate for assessing the impact of an increased release time.

Figure 18 shows negative concentration within the study area, though their value is very small. The existence of the negative concentration is because of the procedure that has been applied for solving the 3D transport equations. The 3D transport equations applied in the advection dispersion module use simple first order unwinding scheme. To provide stability and to minimize oscillatory effects Essentially Non-Oscillatory (ENO) type procedure is applied to limit gradients (Shu, 1997). This procedure is suitable for sharp concentration gradient situations, such as the scenario that we have in this simulation. The penalty for using such an optimum procedure is that we have to expect under and overshooting in results. This means that we have to allow negative values for mass conservation. However, these negative values do not influence the overall performance and can be ignored.

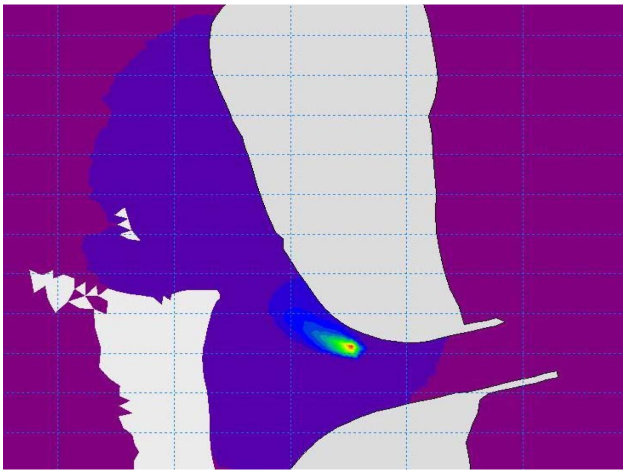


Figure 17. Dye concentration, 10 minutes after commencement of release at station 2 (flood tide).

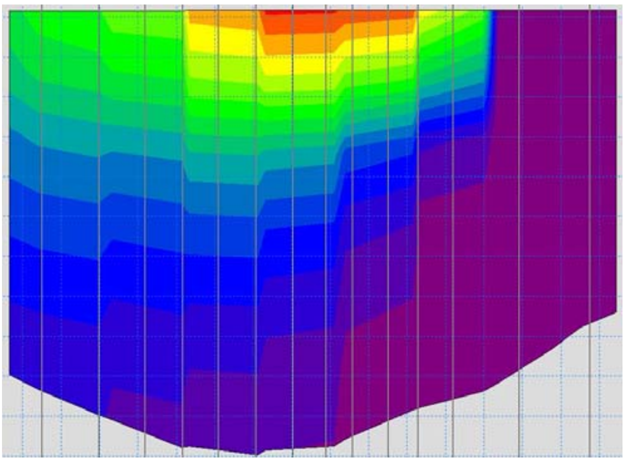
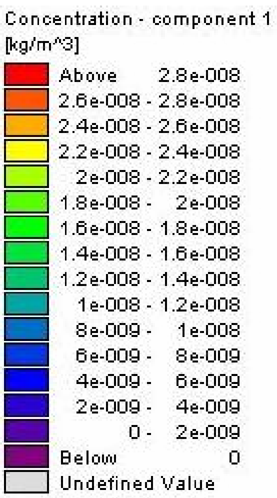


Figure 18. A profile across the centre of plume (shown in figure 17)



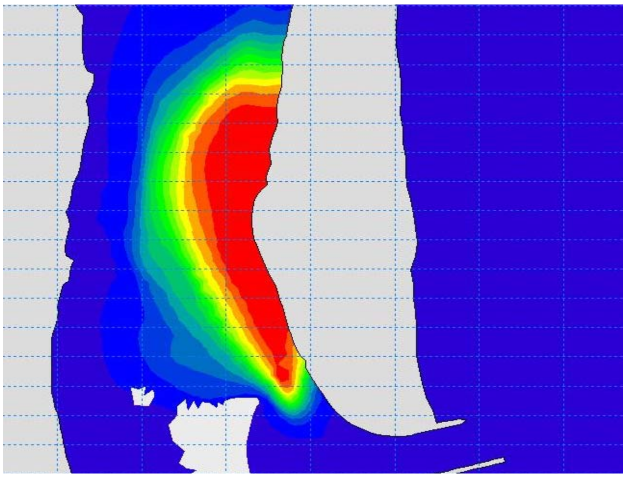


Figure 19. Dye concentration, 70 minutes after commencement of release at station 2 (flood tide).

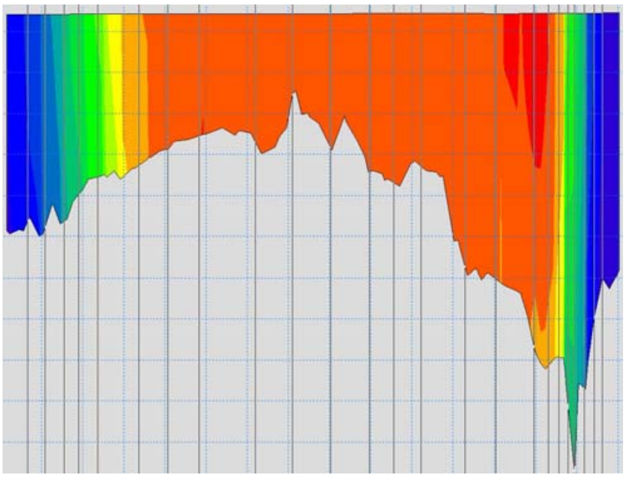
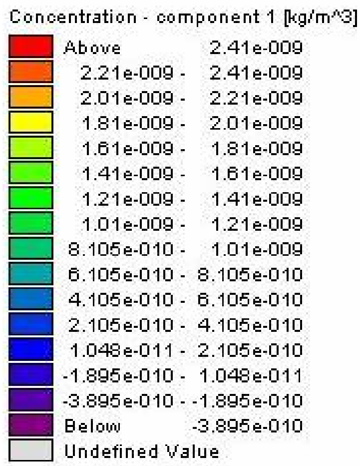


Figure 20. A profile across the centre of plume (shown in figure 19)



An examination of the concentration level, as shown in figures 18 and 19, reveals that its value reduces one order of magnitude over a very short period of time and distance. This indicates strong mixing processes and in particular strong advection forces within the study area. Model results also indicates that the whole plume exits the Broadwater during one ebb tide cycle. Having said that, it should be noted that the fate of the plume outside of the Broadwater in the Pacific Ocean depends on environmental forces. Modelling exercises using typical environmental forces showed that the possibility of the return of wastewater over the next tidal cycle back to the Broadwater was limited to values of the order of 5% [6].

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