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Appraisal of a one-dimensional model, field data and dimensionless parameters in a study of estuarine circulation

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Keywords

Appraisal, one, dimensional, model, field, data, dimensionless, parameters, study, estuarine, circulation, GeoQUEST

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Appraisal of a one-dimensional model, field data and dimensionless parameters in a study of estuarine circulation

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Abstract
Parallel research programs encompassing the hydrodynamics and geochemistry have been undertaken in Oatley Bay, a small urban estuary that is a lower tributary to the Georges River in Southern Sydney Using field data and a simple numerical model, the regimes of flow effecting circulation in Oatley Bay have been determined. The efficiency of flushing and the subsequent fate of conservative pollutants are discussed. The field data comprised bathymetry, tides, drogue tracking and dye tests, the latter enabling the calibration of the model under different environmental conditions. With this model we have performed numerous runs and have characterised temporal and spatial patterns in the estuarine circulation. These results have been collated in terms of a simple dimensionless parameter – the estuary flushing parameter. This will allow generalization of the results for application to other similar estuaries.

1 Introduction

The University of Wollongong, with assistance from Monash University was commissioned by Kogarah Council to undertake studies on the hydrodynamics and sedimentology of Oatley Bay. These studies will comprise the information required to complete Process Studies on Oatley Bay and are part of the NSW Estuary Management Program run with support from the NSW Department of Natural Resources. Following this, and other biological research, Council will be in a position to proceed with a management Plan for Oatley Bay which is underpinned and guided by credible scientific studies.

The present study was designed to document rates of sedimentation, determine pollutant levels in the sediments and provide explanation for their distribution. A vital component was to examine the water movements under both tidal and fresh catchment flows and build and apply a hydrodynamic model to characterise water movements in Oatley Bay. The geochemical and hydrodynamic studies have run in parallel and the final stage in which the model is to be coupled with the geochemical data to provide explanation for the geochemical components of the study is currently in progress.

The major benefit of this research is that it will provide a robust framework for understanding the sediment and chemical dynamics of this urbanised estuarine embayment, allowing Council to assess suitable control and remediation measures to minimise the impacts of current urban uses on the waterway.

In this paper the results of the hydrodynamic data program and modelling are reported.

2 The Oatley Bay Study

2.1 Research strategy

This project aims to provide tools for management and to serve as part of an ongoing research activity on the estuary. While a field study can provide detailed information about flows, concentrations and in-situ sediments, only a limited number of flow situations can be sampled and hence a model study was needed to fill the gaps. In particular, the model study was designed to show the residence times, salinities and sediment concentrations under a prescribed set of stream inflows and to explore the effect of inflow duration on residence time.

Because of the paucity of data on bathymetry, tides and processes in the estuary a detailed field program was required before model schematisation was undertaken.

2.2 Field area: Oatley Bay

Oatley Bay is a small estuarine tributary located some 6 km upstream from the mouth of the Georges River in Botany Bay, southern Sydney. It has a water area of 34 Ha and a catchment area of approximately 407 Ha (KMC, 1995). The estuary has a relatively simple plan form, with the upper estuary divided into two short main arms. The East Arm is partially impounded in its upper reach by a causeway, linked to the estuary by four 1.8 m diameter culverts with their inverts constructed close to MLW. This upper reach of the East Arm is referred to in this paper as the Pondage. The middle estuary is a straight section which expands through the presence of the broad Western Embayment then narrows again before reaching the Georges River, as shown in figure 1.

Depths throughout the estuary were determined as part of the field program. While the average depth of the estuary is 1.5 m below AHD (approximately MWL) this varies from a mid channel depth of about 2 m falling to just over 3 m at the mouth. Dredging for navigation in the 1970s is still evident via the presence of 2 m depths in the upper arms. The thalweg of the Georges River passes directly across the Oatley Bay mouth, and is considerably deeper than Oatley Bay.

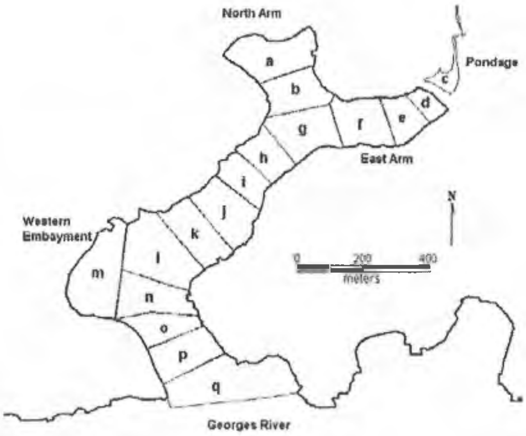

Figure 1 Oatley Bay, showing model segments

There are two main sub-catchments of approximately equal area, both being highly urbanised with constructed storm water drainage which has decreased the runoff concentration time. Urbanisation has been mainly residential but a former refuse disposal site is located within each of the lower catchments. Kogarah Council has a program to rehabilitate these former tip sites and the lower catchment channels, introducing pollutant trapping measures.

The geology of the lower Georges River has produced small but steep tributary gullies which were flooded by the post-glacial sea level rise. This has resulted in narrow foreshores and steep valley sides to the estuary. The bed of the estuary is composed mainly of fine sediments mixed with a varying fraction of fine sand.

The area experiences a moderate eastern maritime climate. Annual average rainfall is approximately 1100 mm (Bureau of Meteorology, 1999). Base flow from the catchments is low and contributes little to estuarine circulation. Catchment flows are generated by storm events and do not display significant seasonality. An important factor in generating estuarine circulation is produced by local winds which funnel through the steep-sided valleys.

Tides are driven by the ocean tide via Botany Bay, modified by the tidal gradient along the Georges River. Input tides at the mouth of Oatley Bay are effectively the same as those at the Como Bridge, recorded by Manly Hydraulics Laboratory. The mean tidal range is 1.038 m, the neap range is 0.803 m and the spring range is 1.277 m.

3 Field Data Program

3.1 Measurement

The early field program for this project was geared towards basic data collection to determine the dimensions (especially depths) of the Bay and to depict the salinity and velocity structure of the Bay under basic tidal conditions.

Echo-sounding traverses within the Bay and adjacent Georges River waters, using a Ceeducer digital echo-sounder with differential GPS for location, provided the geometry of the estuary. All depth information was reduced to Australian Height Datum by reference to the nearby Como Bridge tide gauge.

Salinity and temperature profiling to establish the relationship between Oatley Bay and the Georges River and to map the structure within Oatley Bay under tidal conditions were completed for a range of tides under minimal catchment flow. No significant salinity differences between the Georges River and Oatley Bay were found, except for one occasion when the upper East Arm showed a higher salinity than the remainder of the bay, illustrating incomplete flushing of a previously existing condition. Hence under low catchment run-off conditions, salinities in the estuary are driven by the Georges River salinity.

Current velocity tracking (using specially designed current drogues) was undertaken over both flood and ebb conditions for a range of tides under minimal catchment flows. Flow magnitudes and trajectories were calculated through an Excel spreadsheet macro and mapped into a GIS for spatial display.

Table 1 Current velocities (cm/s) 0.5-1.0 m below surface near mid-channel

Reach	0.8 m tide		1.2 m tide	
	Ebb	Flood	Ebb	Flood
Upper		4-5	3-5	
Middle	6-8	5-6	6-8	2-2[1]
Lower	5-9	5-7	8-12	7-12[2]

[1] Wind suppressed

[2] Wind assisted

Current velocities at mid-channel measured from the drogue trajectories are listed in Table 1. These mid-channel velocities are at least twice as large as the sectionally-averaged velocities generated by the tide. This velocity non-uniformity is reflected in the high values of the longitudinal dispersion coefficients obtained during calibration of the model.

3.2 Dye tracing

Field investigations revealed that under dry weather flows, salinity variations were too small to provide information on circulation. Since catchment flows are transient and their occurrence is unpredictable, the decision was made to conduct a dye experiment to reflect exchange under minimum catchment flow conditions. Thus the main external variables to be considered were tidal flows and wind events.

In the dye test 1.5 litres of a saturated solution of rhodamine-WT dye was first diluted in about 10 litres of water and was then released into the Pondage on the high tide (HT0). The dyed water was initially mixed by releasing it from a moving boat and then running the boat repeatedly through the dye release lines to attempt to obtain a uniform concentration within the Pondage. An extensive surface sampling, supported by limited depth sampling was undertaken over the first ebb tide (LT1) and then on the high and low tides on the following day (HT2, LT3).

For observational purposes 1.1 kg of fluorescein dye was mixed with water and released as a line across the middle of the North Arm shortly after HT0.

Dye concentration was determined from the bottle samples using a spectrophotometer at the University of Wollongong. An average background concentration was subtracted from the observed levels.

During the first ebb tide a frontal wind from the south east impacted on the tidal dispersion of both dyes. Downstream passage of the rhodamine was rapid while the mid-channel part of the fluorescein line was driven upstream against the northern shore of North Arm. Lateral movement and escape of the fluorescein occurred against the bay shores. This was supported by observation of mid-depth drogues which moved upstream with the wind against the expected direction of ebb flow. Return flows appeared to be predominantly lateral under these conditions. That evening and the following day, wind conditions reverted to very light and dye movement followed the tides.

When the dye concentrations were mapped in the GIS, lateral variations in concentration were observed and persisted during the times of observation. For application to the study the data were sectionally averaged, using the segments shown in figure 1. Figure 2 shows the sectionally-averaged data and the smoothed profiles used in the model calibration. The implications of these patterns are discussed under model calibration.

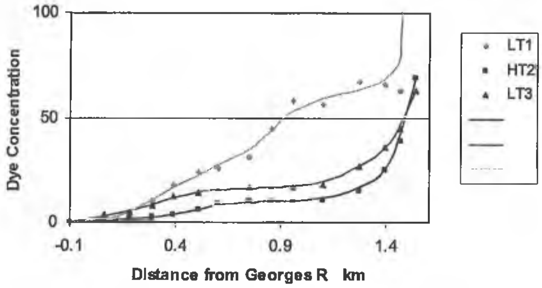

Figure 2 Measured rhodamine dye concentrations and smoothed profiles (East Arm)

4 Model Study

4.1 The model

The numerical model used is a one-dimensional parametric hydrodynamic model, described by Hinwood and McLean (1996). It was developed as a decision support tool for use by a government department in assessing management options, and has since been applied to a number of estuaries. Its simplicity and structure ensure that it is fast to run and robust in use. Since its early uses the model has been extended to simulate sedimentation and pollutants transport and decay over time.

To apply this model, Oatley Bay has been divided into a number of reaches defined by cross sections, see figure 1. The tidal elevations are forced by the Georges River (Como Bridge) tide, using measured tidal planes. The model computes currents at each cross section from these elevations and from the river inflows using the one-dimensional mass conservation equation. The salinity distributions are computed using analytical solutions for the dynamics of a well-mixed or salt-wedge estuary as appropriate, applied piecewise to each small computational reach of the estuary. The depth-averaged salinities at each cross-section and at each time step may be output, but most uses require only tidal maximum or minimum salinities. In the present study, model runs have been made to compute the salinity throughout Oatley Bay for a repeated sequence of tides during which the stream inflows have been varied.

4.2 Model calibration

Calibration of a numerical model is necessary as there are physical parameters which are not accurately known. For this model, the principal parameter to be calibrated was the dispersion coefficient which determines the extent of mixing due to both turbulence and the velocity variations across the Bay and over the depth. Published field measurements on other estuaries have confirmed theoretical predictions (Fischer et al, 1979) for the dispersion coefficient in tidal inlets in which tidal currents are dominant and which are fairly well mixed both vertically and horizontally (Williams and Hinwood, 1976). These conditions do not apply in Oatley Bay and so the dye experiment described above was conducted to provide calibration data. The possibility of using a natural tracer – the salinity - instead of dye was carefully considered but the natural variation of salinity was found to be insufficient to enable the required accuracy to be obtained.

As described above, rhodamine dye was mixed into the Pondage north of the causeway at high tide (HT0). Detailed samplings were conducted at the next low tide (LT1) and both the high and low tides on the next day (HT2, LT3). The conditions changed significantly during the dye test and hence two calibrations were performed: a high wind calibration over the first half-tide cycle (HT0 to LT1) and a low wind calibration over the final two tide cycles (LT1 to LT3).

For calibration 1, the test conditions were: Dry weather flows, taken as 0.03 MLD in each creek, and average measured tidal range of 1.017 m. The initial condition was dye mixed into the Pondage at HT0 with a concentration of 1318 units. The results of this calibration are shown in figure 3.

The initial concentrated release in the Pondage is shown by the spike on the right side of figure 3, but has been truncated so that the later values may be seen easily. The measured dye concentrations at LT1 are shown by the curve, falling from the Pondage on the right to the Georges River near the origin of the graph. The calibrated dispersion coefficients were in the range 2 to 8 m^2/s.

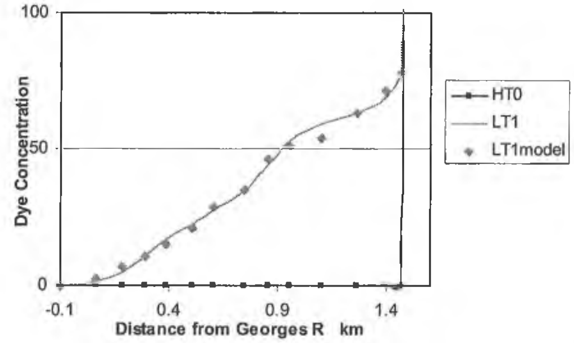

Figure 3 Calibration of model against dye measurements from HT0 to LT1 (East Arm)

For calibration 2, the test conditions were: Dry Weather Flows, taken as 0.03 MLD in each creek, and average measured tidal range of 1.017 m. The initial condition was dye concentration as measured at LT1.

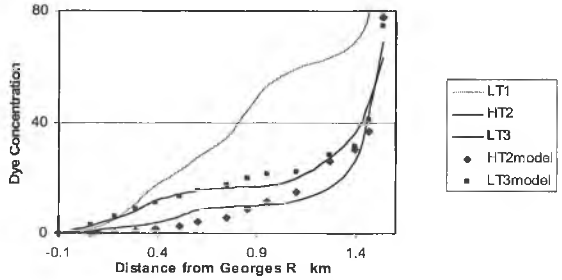

Figure 4 Calibration of model against dye measurements, from LT1 to LT3 (East Arm)

Over the course of the next tide cycle the dye concentration reduced to the curve HT2. The model results scatter around the measured line. There is a local departure from the measured values at about 1.3 km but otherwise the match is good. At the next low tide the concentrations at each section are higher as the water at each section has come from further upstream. The match of measured and modelled results is very good at this time. The dispersion coefficients for this case were generally in the range 0.5 to 6 m^2/s, with lower values at the upstream limits.

The second calibration has been adopted for the remainder of the study as being more typical and, in terms of residence times, more conservative.

4.3 Model test program and results

Two sets of model runs were made, the first using the First Flush (scenarios FF1 and FF2) and the 1, 2 and 5 year ARI catchment flows, using catchment flow data provided by Kogarah Council. The concentration times of the catchments are each only a couple of hours, so flood inflows were simulated as average flows over a tide cycle, commencing at low tide for maximum effect. Floods were modelled superimposed on the dry weather flow (DWF). Only the results of runs made with the mean tide are reported here.

The second set of runs was aimed at improving understanding of the flushing processes and used sequences of flows with the FF1 and 5yr ARI flows spread over an increasing number of tide cycles. Flows used in the second set were the FF1 and 5yr ARI flow volumes each spread over 1, 2, ..6, 8 and 10 tide cycles, with mean, neap and spring tides – 48 cases in all.

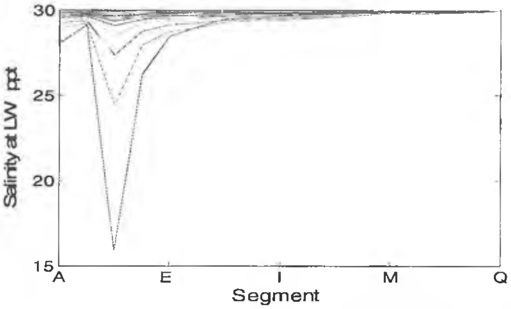

Fig. 5 Recovery of salinity after First Flush (FF1) into model segment C (Pondage)
Curves at successive times of low tide
Note that model segments are shown in name order

Figure 5 shows the salinity at each of the model segments at times of mean water level (MWL), for an inflow to segment C (Pondage), under FF1 inflow in tide 2 followed by DWF, with mean tide. The salinity is initially sharply lowered in Segment C, the Pondage, and to a lesser extent in Segments A and D. The effect is very localised and short lived and has almost disappeared by the 4th curve, corresponding to 3 tides (one and a half days) after the inflow.

The effect of the 5yr ARI flood with mean tide and dry weather flow as base flow are shown in figures 6 and 7, in terms of flushing of a stream-borne conservative pollutant, rather than salinity. The much larger flood volume means that the whole of Oatley Bay is significantly affected for about a dozen tides. The slow flushing under the assumed low wind dispersion is evident.

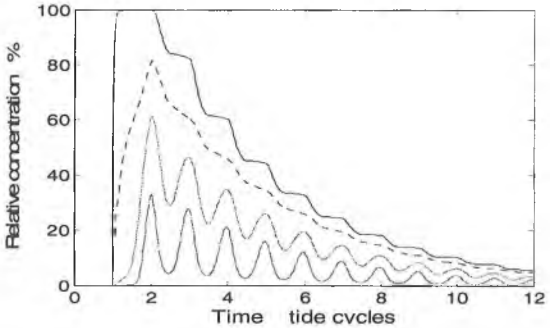

Figure 6 Recovery after pollutant infow:
Inflow to segment C under 5yr flood in tide 2,
Top line: segment C; dashed: A; middle: G; bottom: M

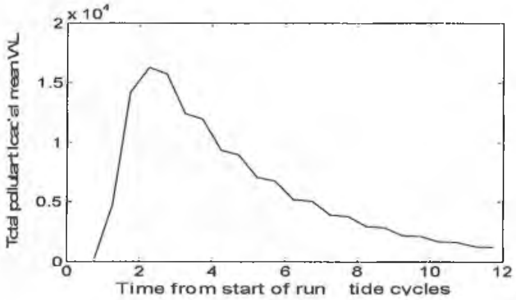

Figure 7 Flushing of pollutant after 5yr flood on tide 2
Lines as in figure 6

5 Discussion

5.1 One-dimensional modelling

The use of a one-dimensional model depends on being able to estimate key parameters with sufficient accuracy, in particular the one-dimensional momentum coefficient and the longitudinal dispersion coefficient. Uncertainties in the momentum coefficient have negligible effect in Oatley Bay, but the model predictions depend sensitively on the longitudinal dispersion coefficient. One-dimensional models have been applied with excellent results for many estuaries world wide, including the Snowy River estuary which we will use for comparison. Table 2 compares these two estuaries.

Table 2 Selected statistics Snowy River estuary and Oatley Bay

Property	Snowy R	Oatley B
Length km	19	1.74
Breadth (excludes entrance and lakes) m	110 (50-250)	210 (150-250)
Average depth m	2.0	1.50
Mean tidal range outside estuary m	0.95	1.04
Dry weather flow MLD	253	0.061
Typical DWF current m/s	0.33	0.023
Vertical mixing time, DWF/mean tide min	3	29
Lateral mixing time, DWF/mean tide d	1.7	120
Residence time DWF/mean tide d	8.6	3.8

For the water to be effectively homogeneous over the depth, the vertical mixing time, given by equation (1) must be short, say very much less than one tide cycle and much less than the residence time in a model segment

Vertical mixing time,

$$t_z = h^2/8K_z \qquad (1)$$

where $K_z = 0.07 u_* h \approx 0.07\, uh/15$ (2)

and h = water depth, K_z = vertical eddy diffusivity, u_* = shear velocity, and u = depth mean velocity.

For Oatley Bay under DWF and mean tidal conditions, a typical value is $t_z = 29$ min which is just compliant but is much longer than the 3 min calculated under the same conditions for the Snowy. Ideally the lateral mixing time, calculated in a similar fashion, will also be much less than 1 tide cycle. For the Snowy it is calculated as 1.7 d but for Oatley Bay it is 120 d! Note that low wind DWF conditions are extremely unlikely to persist for more than a week, let alone 120 days, so this estimate for Oatley Bay mainly serves to indicate that that under low wind conditions, lateral mixing will be negligible and concentrations or salinities will not be uniform over the breadth at any section.

Despite the lack of homogeneity, the one-dimensional model may be applied because the longitudinal dispersion coefficient, D_x, explicitly contains the variations of velocity across the section, as shown in equation (3):

$$D_x = 0.07\, h^2 \langle u_d^2 \rangle / K_y \qquad (3)$$

where u_d = the departure of the velocity at any point from the mean velocity and the brackets indicate the cross-sectional average (Fischer et al, 1979). During the dye tests it was observed that under the strong wind conditions, the velocities departed from the mean to a much larger extent than under the low wind conditions, resulting in a much larger dispersion coefficient under the stronger wind. Through the calibration process, appropriate values were obtained for the dispersion coefficient under two different wind conditions, enabling the one-dimensional model to be used to predict sectional-mean concentrations and mass transports under either of these conditions.

Typical concentrations and residence times could be estimated for both estuaries using a range of model types. As has just been discussed, one-dimensional models can furnish concentrations and residence times for Oatley Bay but, unless calibrated under a range of conditions, may give biased estimates. Because of its very low tidal current speeds, Oatley Bay is relatively much more affected by wind-induced currents and mixing. Hence there is little to be gained by using a two-dimensional model because in these poorly mixed waters the wind-induced flows are strongly three-dimensional. On the other hand, in order to determine flow and deposition patterns on a scale of say 30 m, a three-dimensional model with detailed wind field inputs and salinity modelling would be required.

5.2 Residence times

The mean residence time for the estuary may be defined as

$$T_r = V_f / Q \qquad (4)$$

where V_f = mid-tide volume of fresh water within the estuary, Q = river inflow rate (Officer & Lynch, 1981). Based on equation (4) and model output (eg figure 7) mean residence times have been determined for the selected flood flows superimposed on DWF and mean tide, as shown in figure 8. The larger stream inflows result in a reduced residence time but, surprisingly, it was found that T_r is very little different for the 3 tides.

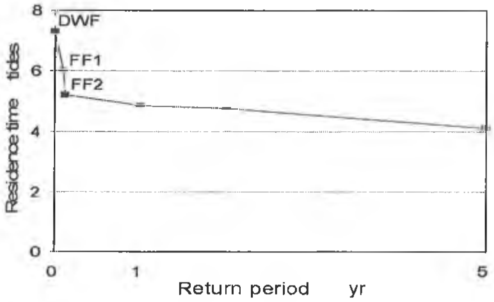

Figure 8 Mean residence time for flows with various ARI and mean tide

5.3 Salinity patterns

Using the second set of runs –with the FF1 and 5yr ARI flow volumes each spread over 1, 2, ..6, 8 and 10 tide cycles, the role of the residence time, tidal range and inflow in determining salinity patterns has been explored. In a major study on the Snowy River, Hinwood & McLean (2006) found that these parameters could be grouped as an "estuary flushing parameter", *E*, which could be used to systematise the observed salinity distributions, where

$$E = W/Q\,T_r \qquad (5)$$

and W = mid-tide volume of water within the estuary. A small value of *E* indicates that river flow is dominant while a large value indicates that tidal exchange is dominant.

The minimum salinity reached during a flood inflow, *Smin,* is an indicator of the stress on ecosystems and is a surrogate for maximum concentration of stream-borne pollutants. Expressing this dimensionlessly in terms of the equilibrium dry weather salinity, *Sb*, *(Sb-Smin)/Sb* has been plotted against *E* for selected sections in figure 9. For all segments, the use of the non-dimensional variables has collapsed the two 1yr flow curves with their very different tides and the 5yr spring tide curves lie close. These are the most strongly tidally dominated cases. The 5yr flood volume with neap tide is the most fluvially dominated set and shows greater relative dilution of salinity. For such cases in the Snowy River it was found that the secondary parameter $W/Q\,T_p$ was required to correlate all tide and flow cases, where T_p is the duration of the flood inflow. This remains to be investigated for Oatley Bay.

All of the curves for Section C, the East Arm Pondage, stand out as different, with the curves reaching *(Sb-Smin)/Sb* = 1 for low *E* values. They closely resemble results obtained for the upper Snowy River estuary, where the fresh inflow may totally expel sea water, even for relatively small floods. All of the other sections are similar and similar to results for the lower Snowy section.

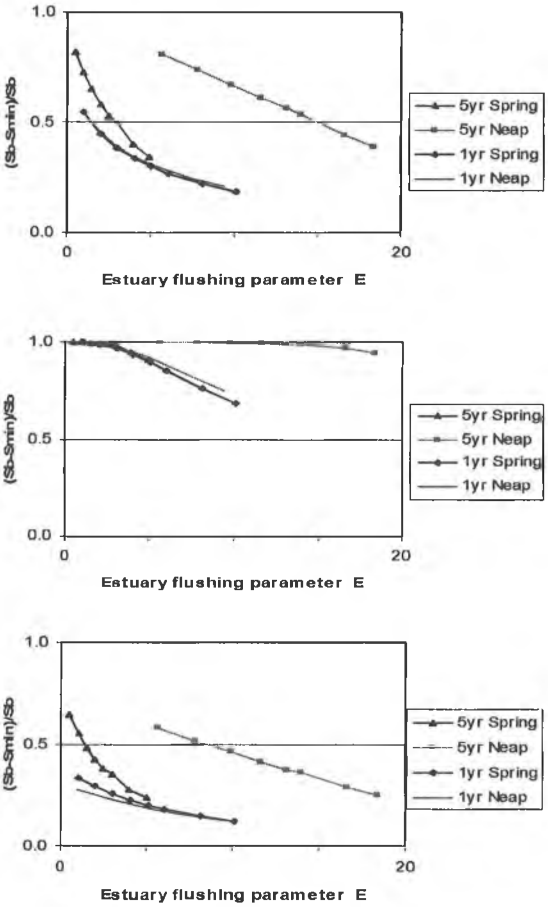

Figure 9 Dimensionless minimum salinity vs *E*
Top line: segment A; middle: C; bottom: G

6 Conclusions

Significant results from this research include:

- Because of its very low tidal current speeds, Oatley Bay is strongly affected by wind-induced currents and mixing.
- Wide sections and low current speeds mean that vertical and lateral mixing in Oatley Bay are very slow and the water is unlikely to be sectionally homogeneous (even with wind mixing). Thus there may be dead zones within Oatley Bay where residence times are much longer than the average. However, the long residence times mean that conditions are likely to vary within a residence time, reducing it below the values for sustained low-wind conditions.
- The strong influence of the wind on circulation and mixing in Oatley Bay and its lack of homogeneity mean that any modelling will be less accurate than modelling of a system which is strongly driven by well defined tides and river flows.
- The longitudinal dispersion coefficient explicitly includes the effects of non-uniform velocity. Thus, with appropriate calibration, as illustrated here, one-dimensional models can furnish sectionally-averaged concentration distributions and residence times for Oatley Bay but, unless calibrated under a range of conditions, may give biased estimates.

- The estuary flushing parameter was shown to be a useful tool in classifying estuarine flow regimes. Further work in this area is in progress to specify the catchment flows and tidal conditions which result in a change of flow regime.

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Disclaimer

Model results presented here have been chosen to illustrate estuarine processes and study methodology and should not be used for management purposes. A report for this purpose will be supplied to Kogarah Municipal Council.