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Preliminary modelling of hydrodynamics of purified recycled water inputs to Lake Wivenhoe

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Abstract: Water security has become a major issue within Australia and particularly within South East Queensland (SEQ). In response to projected limits to conventional water supply systems in SEQ a range of innovative projects have been initiated. A key element of this water security response has been the development of the SEQ Water Grid, which includes the capacity for introducing Purified Recycled Water (PRW) into the region's largest water supply reservoir, Lake Wivenhoe. The highly dendritic and thermally stratified nature of Lake Wivenhoe suggests that three-dimensional (3-D) flows are likely to exert a controlling influence on PRW mixing. In this investigation we present the results of initial 3-D simulation of PRW mixing in Lake Wivenhoe with a focus on the boundary condition used to simulate PRW inflows.

The proposed Lake Wivenhoe PRW scheme involves the introduction of between 10-232 Ml day^{-1} of PRW via a sub-surface diffuser located in a side-branch of the Lake. The configuration of the diffuser is expected to result in relatively high port exit velocities that are likely to exhibit jet-like characteristics with length-scales significantly smaller than the scale of the computational grid used for a typically configured far-field numerical model. Further, the numerical model selected for the far-field simulations (ELCOM) does not include a method for representing sub-grid diffuser inflows or sub-grid jet-like inflows of this type. The effects of these sub-grid processes were investigated using two different numerical approaches to simulate the same idealised near-field model domain. The first approach used the OpenFOAM computational fluid dynamics software to simulate flow from the PRW diffuser ports. The second approach used the ELCOM hydrodynamic code to simulate PRW inflow through the bottom boundary of the domain. The aim of these near-field investigations was to assess differences in flow patterns (if any) when using two different modeling approaches. Simulations revealed two distinct modes of PRW flow in the near-field: i) a predominantly surface outflow away from the diffuser; ii) a complex surface outflow away from the diffuser with subsequent vertical mixing due to re-circulating flow resulting in a seemingly well mixed (vertically) flow away from the diffuser.

The results of the near-field simulations were then used to develop three representative boundary conditions for PRW inputs to the far-field ELCOM model of the entire Lake. These boundary conditions included : i) a simple mass flux into a bottom cell of the model; ii) a uniform (with depth) lateral mass flux; and iii) a lateral mass flux in the surface layer. Keeping all other aspects of the far-field simulations consistent, the results were then used to investigate the influence of these boundary conditions on the distribution of the PRW plume. Simulation results revealed that the choice of PRW inflow boundary condition significantly affects the dynamics of the PRW plume near (≈ 0–3 km) the inflow boundary. Differences in PRW concentration in the order of 10–30 % were predicted depending on the inflow boundary condition. These results suggest that the correct representation of PRW inflow conditions is an important factor for near to mid-field modeling. The influence of the PRW inflow boundary condition on hydrodynamics was found to diminish with distance away from the inflow boundary. This is due to the role of other mixing processes such as wind-driven destabilisation, periodic stratification/de-stratification, catchment inflows and hydro-electric power station flows within the Lake. As such it is more important to accurately simulate the larger scale mixing process when attempting to understand tracer behavior in the far-field (e.g., near downstream offtake points). The model development process has highlighted the value of simulating 3-D processes with the Lake.

Keywords: *3-D hydrodynamic model, limnology, Purified Recycled Water (PRW), Lake Wivenhoe, ELCOM, OpenFOAM.*

1. INTRODUCTION

In many regions of Australia a combination of drought and rapid population growth has lead to concerns over the long-term security of conventional (centralised) water supply systems (Coombes and Barry, 2008). This situation is particularly acute in South East Queensland (SEQ) where a number of innovative projects have been initiated to augment the region's water supply systems. A key element of this water security response has been the development of the SEQ Water Grid, which includes the capacity for introducing Purified Recycled Water (PRW) into the region's largest water supply reservoir, Lake Wivenhoe (Figure 1). This PRW scheme is the first large-scale project of its type in Australia and has the potential to introduce between 10-232 Ml day^{-1} of PRW via a sub-surface diffuser located in a side-branch (Logan's Inlet) of the Lake.

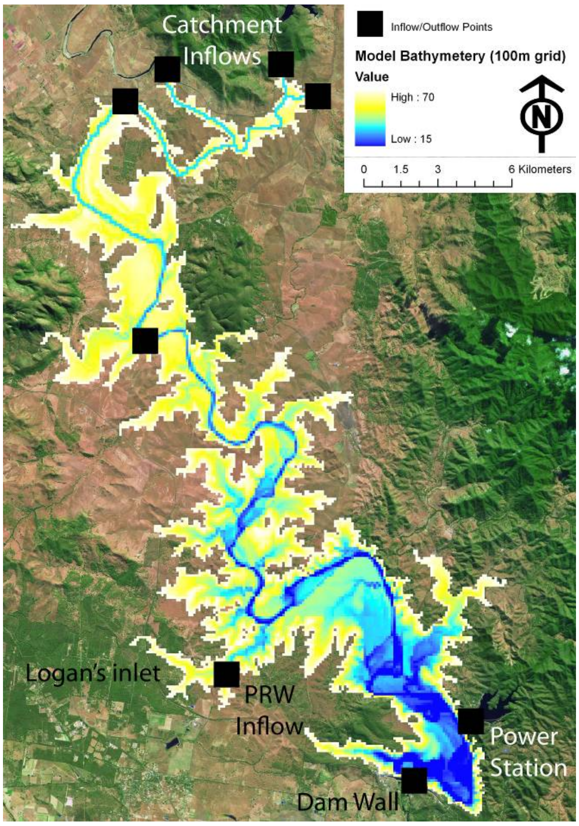

Figure 1. Lake Wivenhoe numerical model domain showing bathymetry (mAHD) and inflow/outflow points.

Of interest to reservoir managers and regulatory authorities are the mixing dynamics of PRW discharges and the potential flow paths and travel times of PRW through the Lake. The highly dendritic and thermally stratified nature of Lake Wivenhoe suggests that three-dimensional (3-D) flows will exert a controlling influence on PRW mixing. To assist reservoir managers and regulators to plan and optimise future monitoring strategies a 3-D numerical model of Lake Wivenhoe was developed using the ELCOM (Hodges and Dallimore, 2008a-b) hydrodynamic model.

This paper presents the findings of a preliminary investigation which aimed to explore and improve our understanding of local PRW mixing processes and their potential implications for far-field or whole-of-lake simulations. To the authors' knowledge the 3-D simulation of PRW inputs to an Australian sub-tropical reservoir has not been reported previously. As such, the aim of this paper is to introduce some of the key issues that were encountered during the first-pass modeling investigation, with a particular focus on the choices of boundary conditions for simulation of PRW discharges. While the simulation results are specific to Lake Wivenhoe, the issues identified are broadly applicable to most reservoirs which might receive PRW inflows in future.

1.1. Background and rationale

The proposed Lake Wivenhoe PRW scheme involves the introduction of PRW via a sub-surface diffuser located in a side-branch (Logan's Inlet) of the Lake. The configuration of the diffuser (11 × 0.15 m diameter ports at 2.0 m spacing, vertically orientated ports) is likely to result in relatively high port exit velocities (theoretical velocity range ≈ 0.5–13.8 m s^{-1}). Such outlet flows are likely to exhibit jet-like characteristics with length-scales significantly smaller than the scale of the computational grid used for the far-field numerical model (100 m × 100 m horizontally, 1 m vertically). The numerical model selected for the far-field simulations (ELCOM) does not currently include a method for representing sub-grid diffuser inflows or sub-grid jet-like inflows of this type. This presents a challenge in terms of specifying a suitable boundary condition to effectively represent the PRW inflows in a far-field whole-of-lake model.

As a first-pass to improving the understanding of these sub-grid effects two different numerical models were developed to simulate the diffuser inputs within an idealised near-field model domain. The first approach used the OpenFOAM (OpenCFD Ltd, 2009) computational fluid dynamics (CFD) software to simulate the PRW diffuser inflows. This approach resolves the turbulent flows associated with the diffuser inputs and considers the full non-hydrostatic solution. The second approach used the ELCOM (Hodges and Dallimore, 2008a-b) hydrodynamic code to simulate PRW inflow through the bottom boundary of the domain. Both of the near-field models used a numerical grid that was sufficiently refined to largely resolve the jet-like inflows around the diffuser, although the CFD approach explicitly resolved the diffuser port openings, a feature that the ELCOM model is not suited for. The aim of these near-field investigations was to assess any differences in flow patterns and discharge characteristics of the two different approaches.

The information developed from the near-field simulations was then used to develop boundary conditions for the far-field ELCOM model. These boundary conditions represent three different, but commonly applied methods of simulating input into the model domain. Simulation results from the far-field model, which incorporated three different boundary condition representations of the PRW inputs, were then used to assess the influence of the choice of boundary condition on the overall distribution of the PRW plume. The comparison of far-field simulation results was concerned with highlighting the effects that the choice of PRW input boundary condition on PRW plume simulations in a dendritic sub-tropical reservoir.

2. APPROACH AND METHODS

The OpenFOAM (OpenCFD Ltd, 2009) and ELCOM (Hodges and Dallimore, 2008a-b) models were used to simulate near-field dynamics of the PRW plume. These models were selected as they are representative of two numerical modeling tools that are commonly available to investigators in this field. OpenFOAM uses a finite volume approach and has been successfully applied to a range of flow regimes. ELCOM has been successfully applied to a range of reservoir systems. The model solves the Reynolds-Averaged Navier-Stokes equations using both hydrostatic and Boussinesq approximations. Details of the ELCOM model are provided elsewhere (i.e., Hodges 2000, Hodges et al. 2000, Laval et al. 2003, Botelho et al. 2009). The ELCOM model was also used for far-field simulations.

2.1. Near-field models

Both the OpenFOAM and ELCOM models were applied to the same stylised model domain. This domain is shown in Figure 2 and consisted of a rectangular prism with a diffuser located near the centre of the domain. The domain was intended to represent a small enclosed inlet (DABC) with an opening CD to the main lake.

The OpenFOAM model used a variable sized finite volume mesh which provided fine detail around the diffuser including the circular shape of the diffuser ports. PRW inflows were set to 0.1 $m^3 s^{-1}$ through all 11 diffuser ports with an inflow water temperature of 25°C. The initial water temperature of the domain was set to a uniform 20°C and water velocities in the model domain were set to zero at the start of the simulation. The model was run using a variable time-step to insure stability.

The near-field ELCOM model used a regular rectangular grid consisting of 2.4 m × 2.0 m horizontal cells at a 0.25 m vertical spacing. PRW inflows were represented by a mass flux into the base of adjacent model cells in the location of the diffuser (Figure 2, EF). The same PRW flow rates, temperature characteristics and initial conditions as specified for the OpenFOAM model were used. The model was run using a 1s time-step to insure stability.

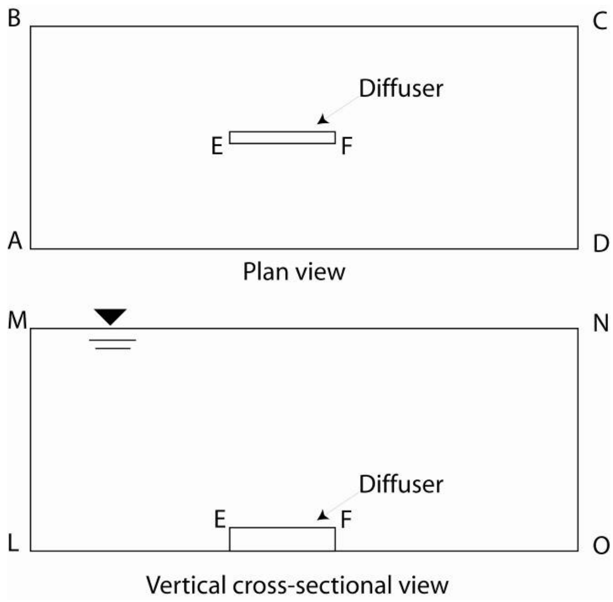

Figure 2. Near-field model domain showing (a) plan view and (b) vertical elevation. Length AB = 60, AD = 170 m, height ML = 12 m. The diffuser length (EF) is 22 m and distance LE is 50 m. The diffuser ports (located along EF) are 1.7 m above the base elevation LO. All boundaries were represented using a "slip" boundary condition with the exception of CD/NO which was represented with an open or symmetry boundary condition. The near-field ELCOM simulation represented MN as a free water surface.

2.2. Far-field model

The far-field model domain included the whole of Lake Wivenhoe and was discretised with uniform 100 m horizontal and 1.0 m vertical grid. Bathymetric data for the model were sourced from a digital elevation model (DEM) that was prepared by BMT WBM for SEQWater using a combination of recently acquired LIDAR and on-water bathymetric surveys. The bathymetric data was sufficiently robust so as to capture areas around key inflow/outflow points and the meandering river-like channel in the northern (upper) parts of the Lake. The model bathymetry is shown in Figure 1.

The model was forced by a combination of meteorological and inflow/outflow data. Meteorological data from an on-lake station and a station located on the Lake's western shore were used to derive parameters for the simulation of a full heat budget. Continuous (gap free) data for key parameters such as solar radiation, air temperature, relative humidity, wind speed and wind direction were available at 2 h intervals for a 6 month period from 1 September 2007 to 1 March 2008. This period was subsequently adopted as the simulation period for the far-field model. Cloud cover data from the nearest available monitoring station (Brisbane Airport) was used to complete the heat budget parameters. These parameters were then applied uniformly across the Lake (i.e., no spatial variation in forcing parameters). Work is underway to improve the model in this regard.

Inflow and outflow data were sourced from a combination of operational records (for outflows) and stream gauging stations (for catchment inflows). Flow data for the Splityard Creek hydro-electric power station was provided by Tarong Energy. This data was not measured directly but instead derived from empirical relationships for the various power-machine settings. The initial conditions used to represent the Lake's vertical density structure were derived from measured water temperature and salinity profiles. Water velocities in the model domain were set to zero at the start of the simulation.

3. MODEL TESTING

3.1. Near-field diffuser models

No data was available for testing, calibration and validation of the near-field models primarily because the diffuser structure has yet to be operated. Furthermore as the aim of these near-field simulations was to assess broad differences in simulation results using two different numerical modeling approaches no formal testing of these models was undertaken (this research has been incorporated into later studies).

Table 1. Thermal structure simulation assessment

Statistic	Euphotic zone	Aphotic zone
Maximum error [°C]	1.86	1.18
Minimum error [°C]	-1.86	-1.61
Error range [°C]	3.72	2.80
Mean error (ME) [°C]	-0.53	-0.03
Standard deviation of error [°C]	0.46	0.52
Mean absolute error (MAE) [°C]	0.61	0.43
Root mean square error (RMSE) [°C]	0.70	0.52
Relative error (RE) [%]	2.50	1.96
Relative range error (RRE) [%]	6.49	5.86
R^2 statistic [0–1 range]	0.95	0.96
Coefficient of efficiency (E) [-∞–1 range]	0.90	0.85

3.2. Far-field model

The far-field model was validated against temperature profile data from a single point in the model domain (where sufficient quality field data was available) over the simulation period. Summary statistics for pair-wise comparison of the observed and simulated temperature data are provided in Table 1. Overall the model was able to simulate the dynamics of the Lake's thermal structure within acceptable error limits. A lack of lake-specific field data prevented an assessment of the model performance against other parameters such as velocity fields and tracer advection-dispersion. Data collection activities are underway to address these issues.

4. RESULTS

4.1. Near-field diffuser models

Both near-field simulations showed (not surprisingly) the PRW plume moving in a predominantly vertical direction to form a surface plume that then migrated laterally away from the diffuser (Figure 3). As expected the OpenFOAM simulation was able to effectively resolve the jet-like behavior of the diffuser inputs (and simulate vertical momentum fluxes) and exhibited more complex mixing than the ELCOM model which predicted the vertical plume behavior as a result of density differences between the ambient and PRW waters. In particular the OpenFOAM simulation showed more pronounced return flows towards the diffuser along the base of the domain. These return flows were found to entrain some of the surface PRW billows causing

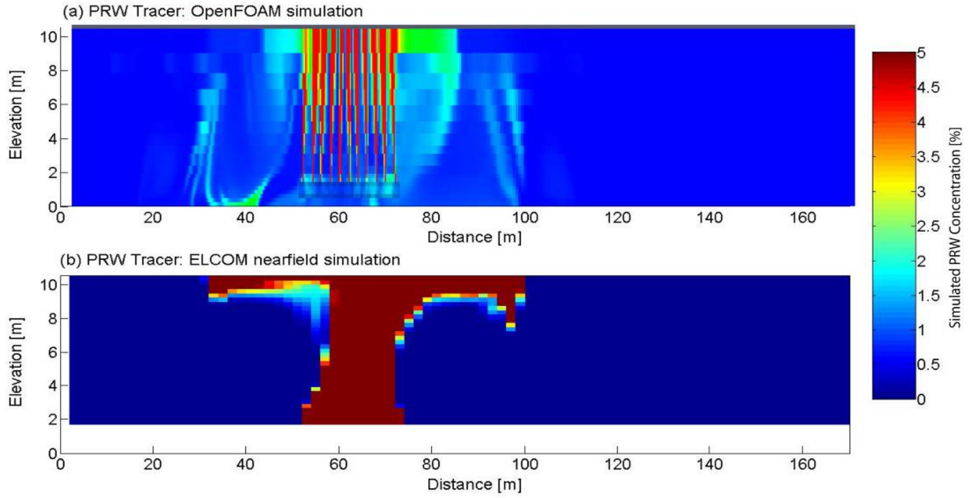

Figure 3. PRW tracer concentrations from (a) OpenFOAM near-field simulation and (b) ELCOM near-field simulation, during the early stages of plume development (t = 8 min).

PRW to mix vertically through the water column as the plume moved towards the open boundary. This vertical mixing of the PRW plume was generally not observed in the ELCOM nearfield model which showed the PRW migrating away from the diffuser predominantly as a surface plume. These results were used to derive the two lateral flow boundary conditions (i.e., uniform lateral flow and surface lateral flow) for the far-field models.

4.2. Far-field Lake Wivenhoe model

Overall, it was found that simulated PRW tracer progressively travelled through the Lake towards the raw water offtake point. Detectable concentrations (> 0.1%) were observed at the raw water offtake point after approximately 1 month (Figure 4). The PRW tracer was shown to mix through the water column by a combination of the periodic formation and breakdown of the thermocline, the influence of catchment inflows and the effects of flows from the Splityard Creek hydro-electric power station.

Variations were observed in the simulated distribution of the PRW tracer between the models with the three different PRW inflow boundary representations. These variations were particularly evident near the PRW inflow boundary (Figures 4 and 5) but progressively reduced with distance away from the boundary (Figures 4-5, Table 2). Within Logan's Inlet the different PRW inflow boundary conditions influenced the vertical distribution of the plume as it moved laterally toward the confluence of the inlet and the main Lake (Figure 5).

A combination of visual comparisons (Figure 6) and basic pair-wise statistics were used to compare

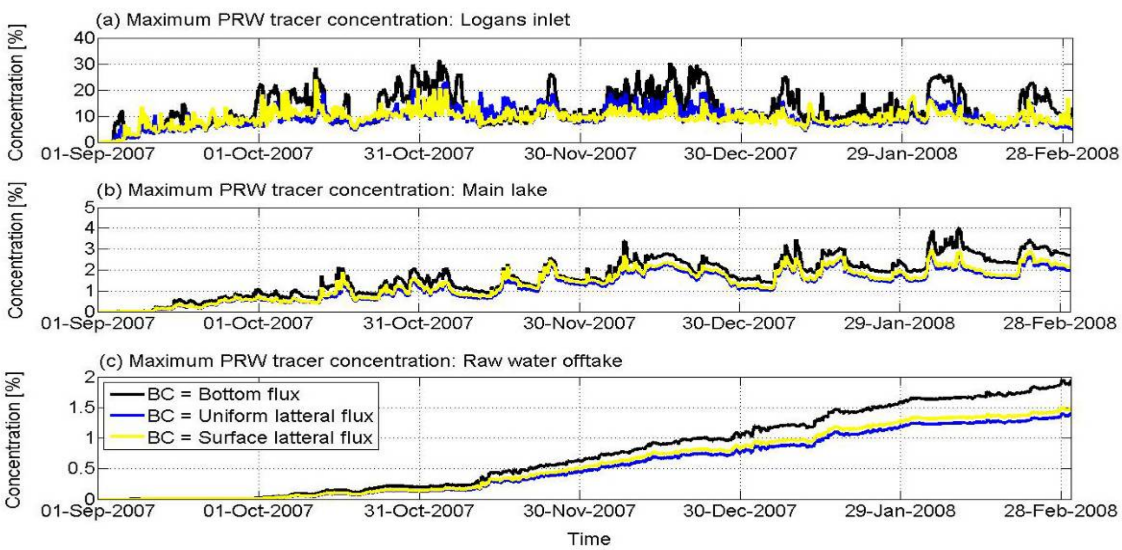

Figure 4. Time-series plots of simulated PRW concentration at three locations within the Lake. Note changes in y-axis scale between sub-figures.

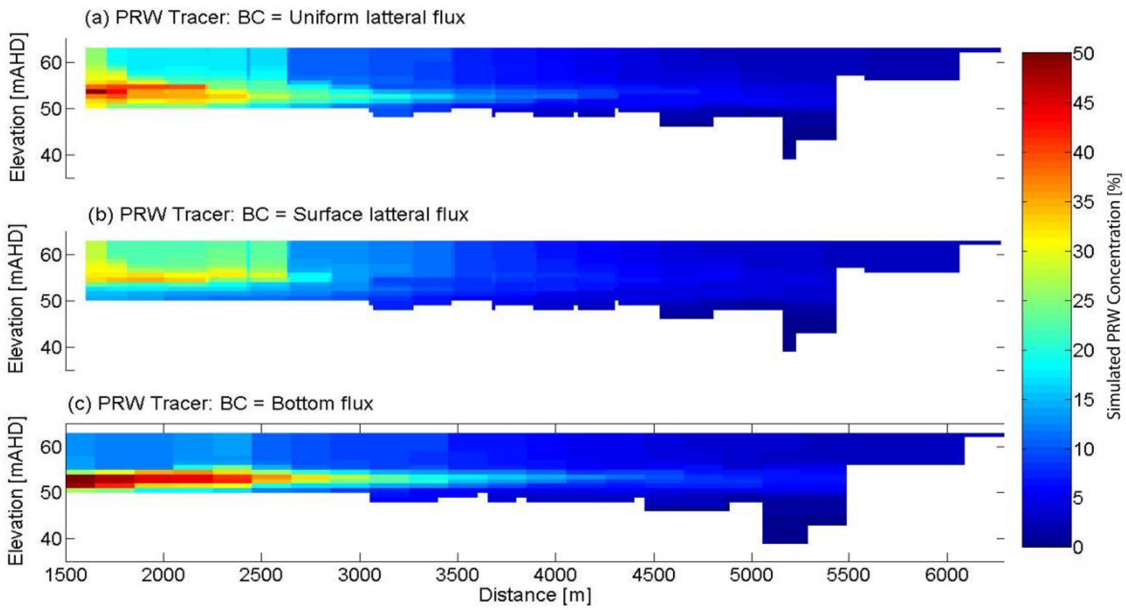

Figure 5. Vertical cross-section view of simulated PRW tracer concentration along the thalwag of Logan's Inlet from the far-field models that introduced PRW as (a) a uniform lateral flux, (b) a surface lateral flux and (c) a bottom flux.

differences in simulated PRW concentrations at three points within the Lake between the models with different PRW inflow boundary conditions (Table 2). Maximum differences in the simulated PRW concentration at a monitoring site within Logan's Inlet were in the range of 23–32 % (Table 2). The maximum concentration differences reduced to < 2% at the main raw water offtake point (Figure 5 and Table 2). The correlation between simulated PRW tracer concentrations resulting from different inflow boundary representations was assessed through the use of basic skill score statistics (i.e., r-squared (r^2), Nash-Sutcliffe coefficient of efficiency (E) and Wilmott Index of agreement (d)) (Table 2). Results generally showed poor agreement between the different PRW inflow boundary representations close to the inflow boundary (i.e., Logan's Inlet) (Figure 6 and Table 2). Correlations improved with distance away from the boundary (Figure 6 and Table 2).

5. DISCUSSION AND IMPLICATIONS

This preliminary investigation into the influence of different representation of the PRW inflow boundary condition suggests that important variations in the simulated distribution of a PRW plume can arise close to (i.e., within 0–3 km) the inflow boundary. This in turn has implications for the use of 3-D numerical models for the simulation of potential chemicals of concern (e.g., nutrients, toxicants) and associated biogeochemical processes in the region near the PRW inflows. Simulation results suggest that the influence of the choice of boundary condition on PRW tracer dynamics diminishes with distance away from the inflow boundary. This is due to the role of other mixing processes such as wind-driven mixing, periodic stratification/de-stratification, catchment inflows and hydro-electric power station flows within the Lake. This suggests it is more important to accurately simulate the larger scale mixing process when attempting to understand tracer behavior in the far-field (e.g., near downstream offtake points) for large scale systems. Furthermore, while a

Table 2. Basic PRW concentration statistics derived from simulation time-series data

Statistic	Logan's Inlet site			Main lake site			Raw water offtake		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
Maximum value	31.6 %	23.2 %	23.8 %	4.0 %	2.8 %	2.9 %	1.9 %	1.3 %	1.4 %
Mean value	12.7 %	9.4 %	9.2 %	1.6 %	1.2 %	1.3 %	0.7 %	0.5 %	0.5 %
Median value	10.5 %	8.9 %	9.1 %	1.6 %	1.3 %	1.4 %	0.6 %	0.4 %	0.5 %
Standard deviation	6.3 %	3.6 %	3.0 %	0.8 %	0.6 %	0.7 %	0.6 %	0.4 %	0.5 %
Comparison pairs	S1-S2	S1-S3	S2-S3	S1-S2	S1-S3	S2-S3	S1-S2	S1-S3	S2-S3
Mean error (ME)	3.3	3.4	0.1	0.4	0.3	-0.09	0.2	0.1	-0.04
Mean absolute error (MAE)	3.9	4.3	1.6	0.4	0.3	0.1	0.2	0.1	0.04
Root mean square error (RMSE)	5.4	6.1	2.1	0.4	0.3	0.1	0.2	0.1	0.06
Relative error (RE)	31.3 %	34.2 %	17.1 %	25.2 %	19.3 %	8.0 %	26.8 %	20.3 %	8.8 %
Relative range error (RRE)	17.1 %	19.6 %	9.4 %	12.1 %	9.6 %	4.0 %	13.3 %	10.2 %	4.3 %
R^2 statistic	0.56	0.35	0.64	0.96	0.96	0.99	0.99	0.99	0.99
Coefficient of efficiency (E)	0.26	0.04	0.64	0.70	0.81	0.97	0.83	0.90	0.98
Index of agreement (d)	0.73	0.62	0.88	0.91	0.94	0.99	0.94	0.97	0.99

Note: S1, S2 and S3 refer to simulation using the bottom flux, uniform lateral flux and surface lateral flux PRW boundary conditions respectively.

sub-grid representation of diffuser inflows might offer a more effective means of simulating these inflows, in the near-field, this investigation has shown that commonly available CFD approaches can also be used. However it is clear that a combination of field measurements and additional modeling investigations are required to develop an improved representation of the PRW inflow boundary condition. In particular, further work is required to explore the implications of variations in the temperature of diffuser inflows (an aspect not addressed in this investigation). Baroclinic flows resulting from temperature differences between the ambient Lake water and PRW inflows are likely to exert a strong influence on PRW mixing dynamics in the near-field and need to be better understood.

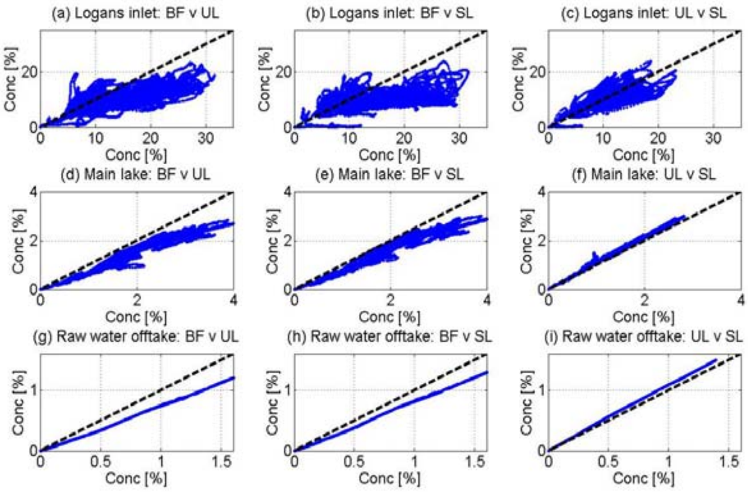

Figure 6. Pair-wise correlation plots of simulated PRW concentration at three different locations within the Lake. BF, UL and SL respectively denote simulations using the “bottom flux”, “uniform lateral flux” and “surface lateral flux” PRW inflow boundary conditions. Blue points are the correlation data and the black dashed line represents a 1:1 correlation.

On a more general note the authors found the use of 3-D models and their subsequent simulation output provided an effective means of engaging regulators and non-specialist stakeholders in discussions regarding the proposed PRW scheme. The ability to visualise the influence of different PRW inflow methods as well as the interaction of tracer plumes with thermal stratification/de-stratification processes and the Lake’s complex bathymetry significantly enhanced stakeholder understanding of key hydrodynamic processes. This in turn has aided in the development of more effective data acquisition programs. Such outcomes would not have been possible with more traditional 1-D and 2-D approaches. As such, the model development process has highlighted the value of simulating the 3-D processes of the Lake in terms of broader system understanding and management.

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REFERENCES

Botelho, D.A., B.R., J. Imberger, C. Dallimore, and B.R. Hodges (2009). A hydrostatic/non-hydrostatic grid-switching strategy for computing high-frequency, high wave number motions embedded in geophysical flows. *Environmental Modelling & Software*, 24, 473-488.

Coombes, P.J. and Barry, M.E. (2008) The Relative Efficiency of Water Supply Catchments and Rainwater Tanks in Cities Subject to Variable Climate and the Potential for Climate Change. *Australian Journal of Water Resources*, 12(2), 85-100.

Hodges, B.R. (2000). *Numerical techniques in CWR-ELCOM*. Technical Report ED 1422. Centre for Water Research, University of Western Australia.

Hodges, B.R. and C. Dallimore (2008a). Estuary, Lake and Coastal Ocean Model: ELCOM, v2.2 Science Manual. Centre for Water Research, University of Western Australia.

Hodges, B.R. and C. Dallimore (2008b). Estuary, Lake and Coastal Ocean Model: ELCOM, v2.2 User Manual, Centre for Water Research, University of Western Australia.

Hodges, B.R., J. Imberger, A.A. Saggio, and K.B. Winters (2000). Modeling basin scale internal waves in a stratified lake. *Limnology and Oceanography*, 45, 1603-1620.

Laval, B.E., J. Imberger, and A.N. Findikakis, (2003). Mass transport between a semi-enclosed basin and the ocean: Maracaibo system. *Journal of Geophysical Research*, 108, 3234.

OpenCFD Ltd (2009). The OpenFOAM® (Open Field Operation and Manipulation) CFD Toolbox, http://www.opencfd.co.uk/openfoam/index.html, accessed February 2009.