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Tamar Lake Destratification - Research on Destratification Systems

Reference: R.B20921.002.00.Destratification_Investigation.docx
Date: February 2016
Confidential

Document Control Sheet

	Document:	R.B20921.002.00.Destratification_Investigation.docx
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Synopsis:		

REVISION/CHECKING HISTORY

Revision Number	Date	Checked by		Issued by	
0	26th February 2016	MEB	[signature]	AS	[signature]

DISTRIBUTION

Destination	Revision										
	0	1	2	3	4	5	6	7	8	9	10
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1 Background

BMT WBM has prepared a three dimensional hydrodynamic, sediment transport and water quality model of the Tamar estuary. Tamar Lake Inc has subsequently commissioned the execution of several scenarios using this model. Model predictions to date have suggested that if a lake was to be constructed that it would experience considerable thermal stratification, and that this in turn would have a significant detrimental impact on ambient and downstream water quality. As a result, Tamar Lake Inc had requested that BMT WBM undertake works that will examine this stratification in more detail, and present potential mitigation measures.

This document presents a summary of the various measures adopted by a selection of similar projects around the world, including some suggested by Tamar Lake, to control water quality. A demonstration numerical simulation is also set up and executed so as to provide some indication of potential destratification options for the scenarios Tamar Lake is considering.

2 Stratification and its Implications

2.1 General

Stratification in water bodies occurs due to the differential penetration of the heat fraction of incoming radiation with depth. This differential penetration causes surface layers to heat more than bottom (benthic) layers. The resulting temperature difference causes density differences leading to accumulation of heavier, colder water at depth and the lighter, warmer water at the surface.

Stratification restricts vertical exchange processes within the water column, and one consequence of this is that replenishment of deeper waters with atmospheric oxygen is suppressed. This oxygen depletion at depth results in increased release of nutrients from the sediment to the benthic layers (Hipsey, Bruce, & Hamilton, 2013).

For surface water quality of fresh water systems, 80% oxygen saturation is considered to be sufficient to support ecosystem function (ANZECC & ARMCANZ, 2000). Thermal stratification often leads to significant deviations at depth below this guideline, with anoxic conditions (0% oxygen saturation) commonly occurring.

2.2 Stratification in the Tamar model predictions

Model predictions of barrage scenarios run to date suggest that areas with depths greater than approximately 10m show sustained thermal stratification and de-oxygenation in the benthic layers. Figure 2-1 and Figure 2-2 (following) indicate how water at depth upstream of the barrage becomes depleted in oxygen as the overlying thermal stratification strengthens over the summer months (October to March). The depleted benthic layer of oxygen originates near the barrage and slowly spreads upstream as the summer season progresses. The hypoxia (lack of oxygen) of benthic waters is most severe in the deeper parts of the river upstream of the barrage where depths are in the range of 30 m. T7 is the site furthest from the barrage that is still influenced by this process. It is approximately 20 km from the barrage.

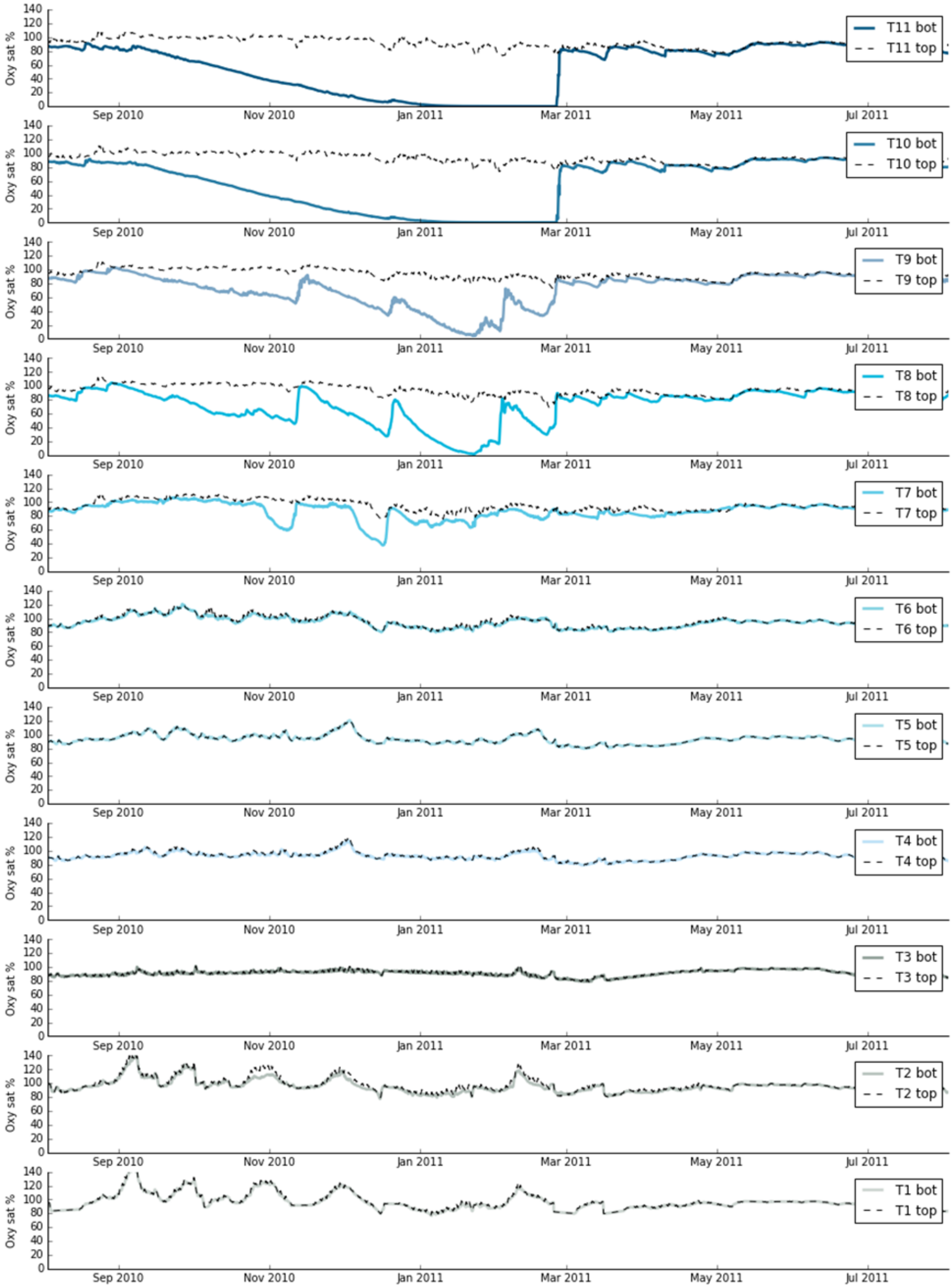


Figure 2-1 Time series evolution of bottom and top layer oxygen saturation

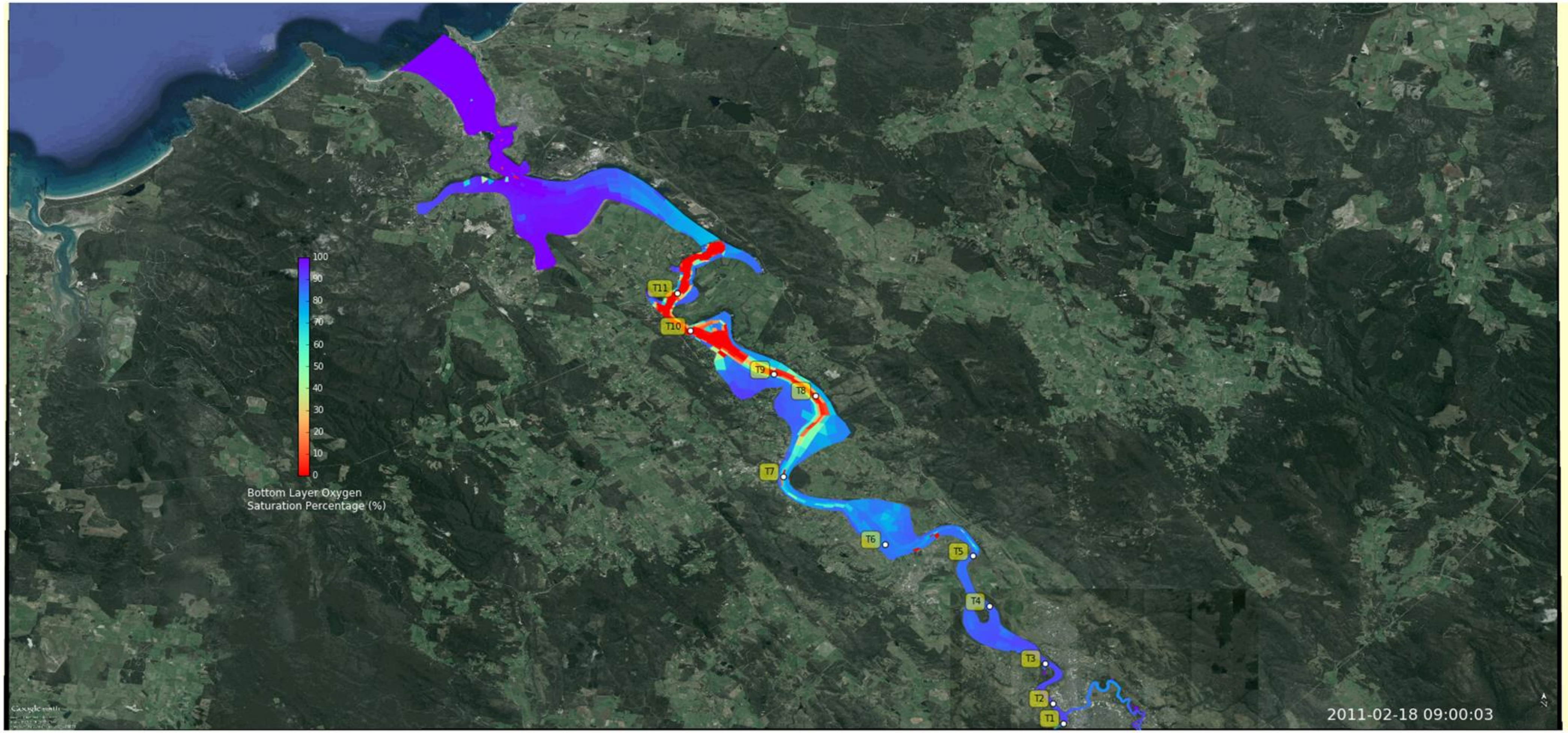


Figure 2-2 Spatial distribution of benthic layer oxygen saturation

3 Comparison with Similar Projects

3.1 Marina Barrage, Singapore

The Marina Bay Barrage was commissioned in November 2008, primarily with the aim of securing Singapore's fresh water supply, of which historically a large proportion was imported. The Marina Bay started out as an inter-tidal estuary being fed by the Kallang and the Singapore Rivers until the barrage turned the estuary into a large fresh water reservoir. The barrage acts as a barrier against the tidal influence and protects low lying areas of Singapore against flooding during high rainfall events (Figure 3-1).

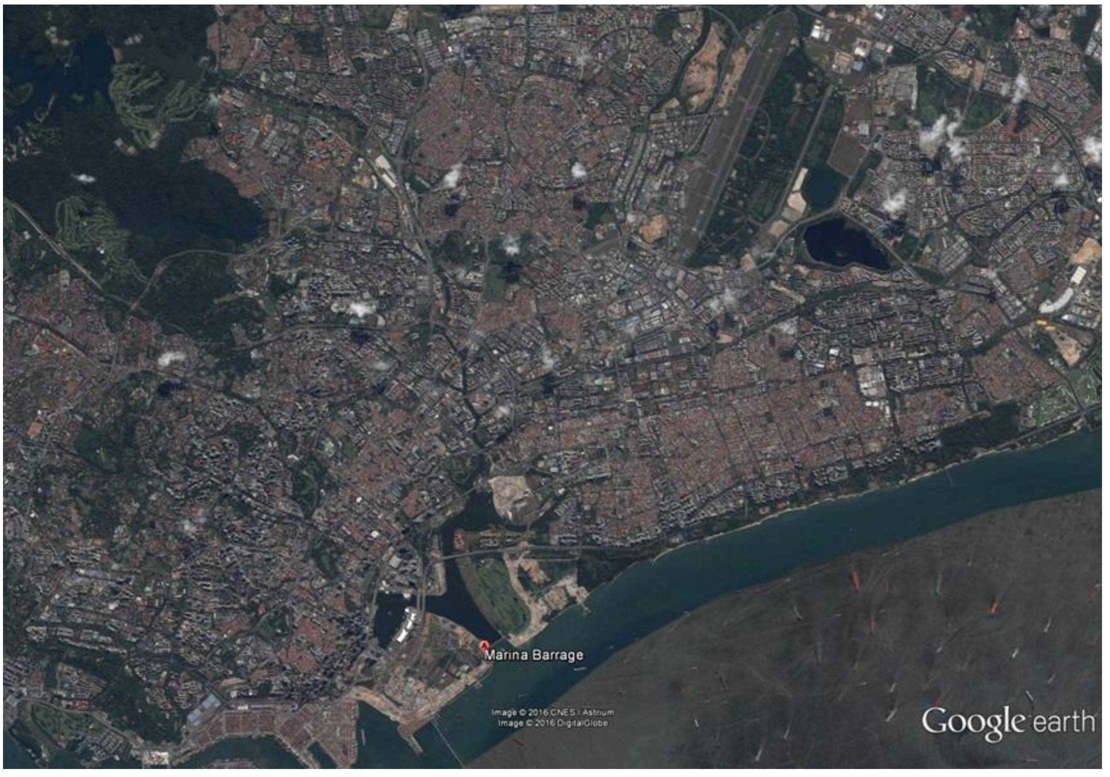


Figure 3-1 Location of the Marina Bay barrage

An important aspect of this project is the catchment scale improvement plans undertaken as early as 1977 to relocate polluting industries, dredging to restore sediment characteristics and phasing out of various activities causing release of nutrients into the river. Various improvements at the catchment scale coupled by the well flushed tidal nature of the estuary meant that there were no major water quality issues following commissioning of the freshwater system (Galelli, Caietti Marin, Castelletti, & Eikaas, 2012).

When the barrage was constructed, the system was found to be more prone to water quality degradation as a result of catchment loading than processes associated with thermal stratification (Galelli et al., 2012). This is due in part to the relatively shallow bathymetry of the Marina Bay (at approximately 11 m deep), and these depths generally not being conducive to strong stratification (Lewis Jr., 1983). , In contrast, the Tamar is approximately 30 metres deep near the barrage.

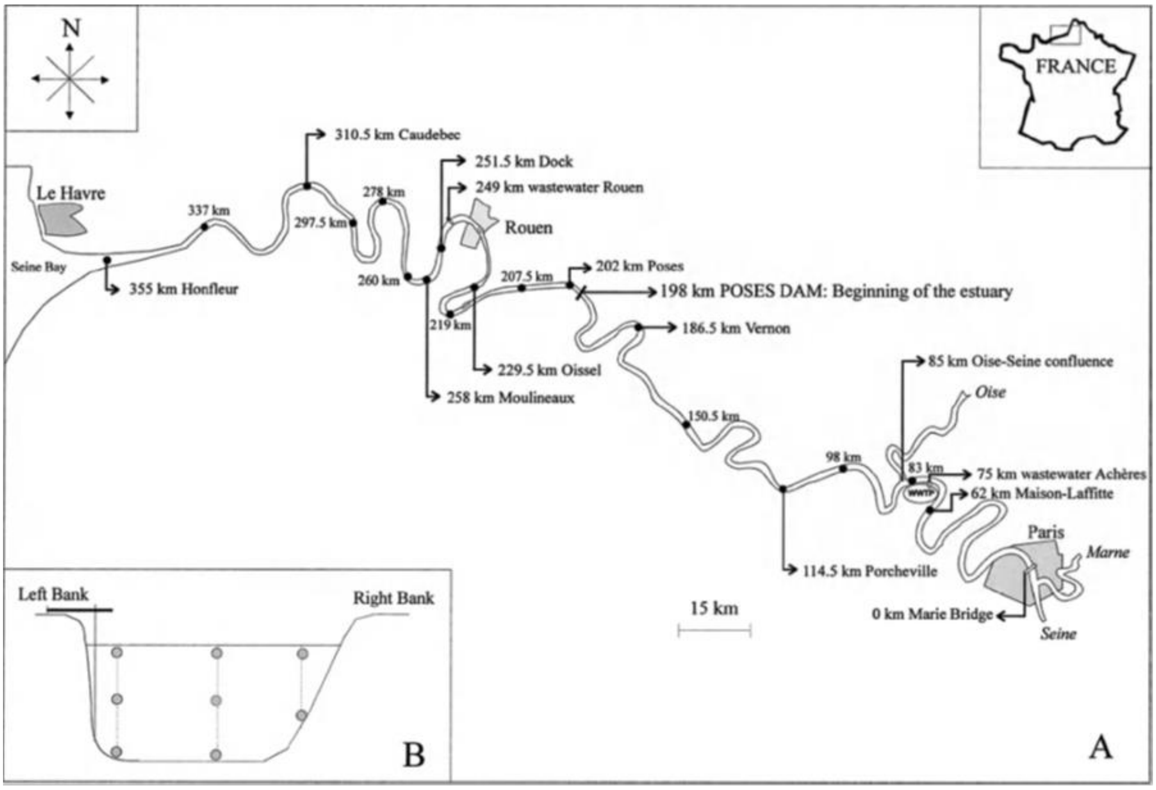
Since commissioning, authorities have put in place various action programmes to ensure that the water quality in Marina Reservoir will meet aesthetic, recreational and drinking water standards. There have been cases of algal blooms, with the last one reported in 2015, mainly due to the flux of nutrients after a storm event and strong sunshine just after. Some of the steps taken to control such events involve sewer rehabilitation, silt control at construction sites, catchment surveillance and litter control. Finally, a o a recirculation system has been built that circulates up to 5 m3/s of water from the Marina Reservoir through a treatment plant to remove pollutants, before returning cleaned water to the lake. (Nauta, Wui, Smits, & Lee, 2008).

3.2 Seine River

Commissioned in July 1887, the Poses Barrage on the Seine in France is a historical site. The site had severe issues with mobile sediments and small islands that restricted the movement of shipping transport along the Seine. With the construction of the barrage, the river system was insulated from the influence of tidal forcing. Flooding due to high tides and/or high flows was mitigated and the depth of the Seine increased by 1.2 m. There were parts of the Seine with calcareous outcrops which were only 0.5 to 0.6 m deep during low tides, and the increased depth improved navigation around these areas (Foussard et al., 2010).

The Seine around Paris is shallow. Before the barrage was put in, depths of about 3-4 m were documented and after the barrage this increased to 4-5 m. These depths are generally not enough to support significant thermal stratification. The depths in the Seine rise to a maximum of about 12 m near the barrage. This region has had a history of hypoxia (oxygen concentrations below 2 mg/l) and this has been attributed to the treatment plant outlets, especially the Achères outlet 75 km downstream from Paris, catering to 10 million residents (Guillaud, Andrieux, & Menesguen, 2000). The river system is able to handle the load because of the addition of fresh water inputs from the River Oise and the oxygenation in waterfalls at some of the navigation dams (Brion et al., 2000).

The Seine River system with the barrage at Poses is different to the proposed system on the Tamar River in terms of length and size. The barrage at Poses is approximately 200 km from the centre of Paris and the mouth of the Seine is about 150 km downstream of the weir (Garnier, Servais, Billen, Akopian, & Brion, 2001) (Figure 3-2). The Seine Estuary, which roughly starts at the Poses Barrage, is fresh for the first, approximately 100 km and the next 50 km is its tidal exchange zone. Salinities in the tidal range have values from oligohaline (0-10%) to euhaline (greater than 33%). Due to the barrage being built upstream of the tidal limit, there was no transition from saline water to fresh water like the case was in Singapore or is going to be in the proposed Tamar project. With depths of 3-4 m around Paris, thermal stratification ceases to be a factor influencing water quality.



(Brion et al., 2000)

Figure 3-2 Layout of relative positions of important sites on the Seine

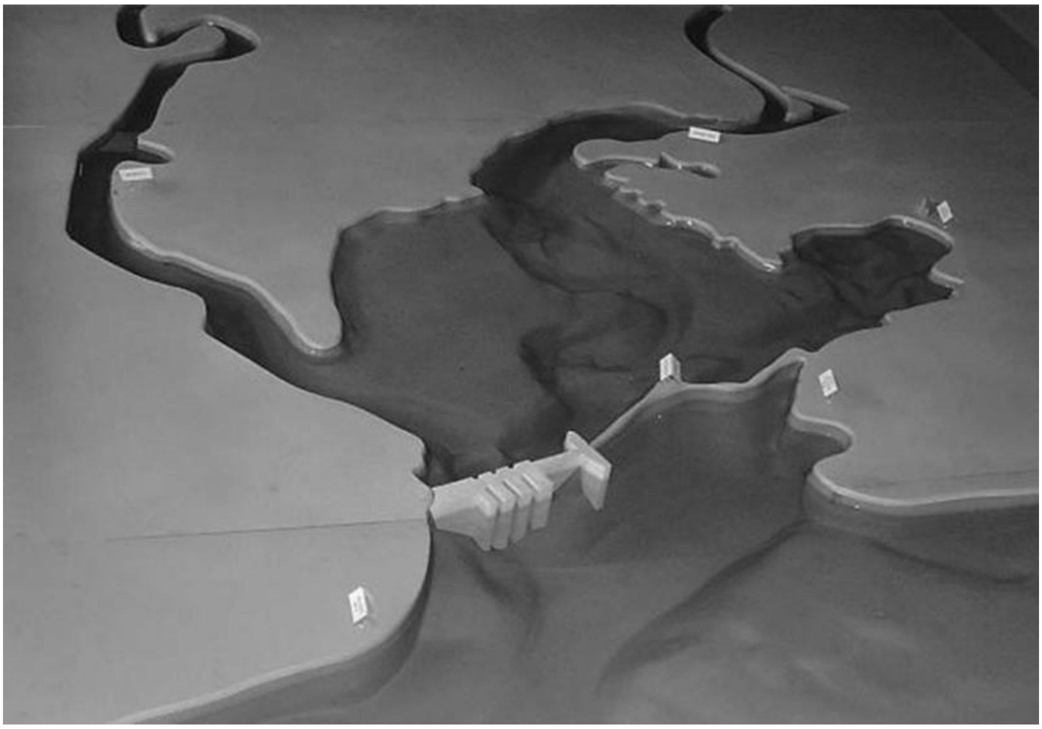
3.3 Cardiff Bay Barrage

The main objective of the Cardiff Bay Barrage was to cover the extensive mud flats that are exposed over much of the tidal cycle and improve the overall aesthetics of the Rivers Taff and Ely. The tidal variations at Cardiff are amongst the highest in the world and range up to 14 m causing cyclic flooding of significant area in the tidal zone. The barrage was considered a major redevelopment project aimed at creating value from reclaimed land and adding to the aesthetics of the general area. The Cardiff Bay Development Corporation (CBDC) was set up to build and operate the barrage. The project was envisaged in 1987, with most of the review completed in 1991. The final commissioning took place in 1999 (Falconer & Lin, 2004).

Depletion of oxygen in the Bay was considered as a potential problem during the decision making process in 1991. Mathematical models were used to model the dissolved oxygen concentrations and year-long field measurements of the Taff and Ely were used to inform the model. The legislation that set up the CBDC in 1993 explicitly stated that 5 mg/l of oxygen had to be maintained in the impounded water at all times (Environmental Advisory Unit Ltd., 1991).

The results of the mathematical modelling showed that at about half the riverine inflows and without the effects of wind, the dissolved oxygen would fall below 5 mg/l. The Act mandated that diffusers be put in to improve the water quality and suitable steps were taken including opening up of the barrages to maintain water quality.

Just after construction, major water-quality problems ensued which required the bay to be drained dry overnight and re-filled each day. Eventually oxygenation systems (Figure 3-4) were installed in the deeper sections (Figure 3-3) which improved water quality and allowed the composition of the bay to become entirely fresh with the only salt ingress happening from the locks being opened to let boats pass (Falconer & Lin, 2004).



(Falconer & Lin, 2004)

Figure 3-3 Scaled physical model of the Cardiff Bay system

The Cardiff Bay is approximately 5 m deep and unlike the Tamar River, the main reason for stratification is the ingress of heavier salt water from the locks, especially during high tides and this water would settle down, leading to a strongly stratified, salt wedge system.

(Falconer & Lin, 2004)

Figure 3-4 Air-bubble diffuser used at Cardiff Bay

3.4 Charles River, Boston

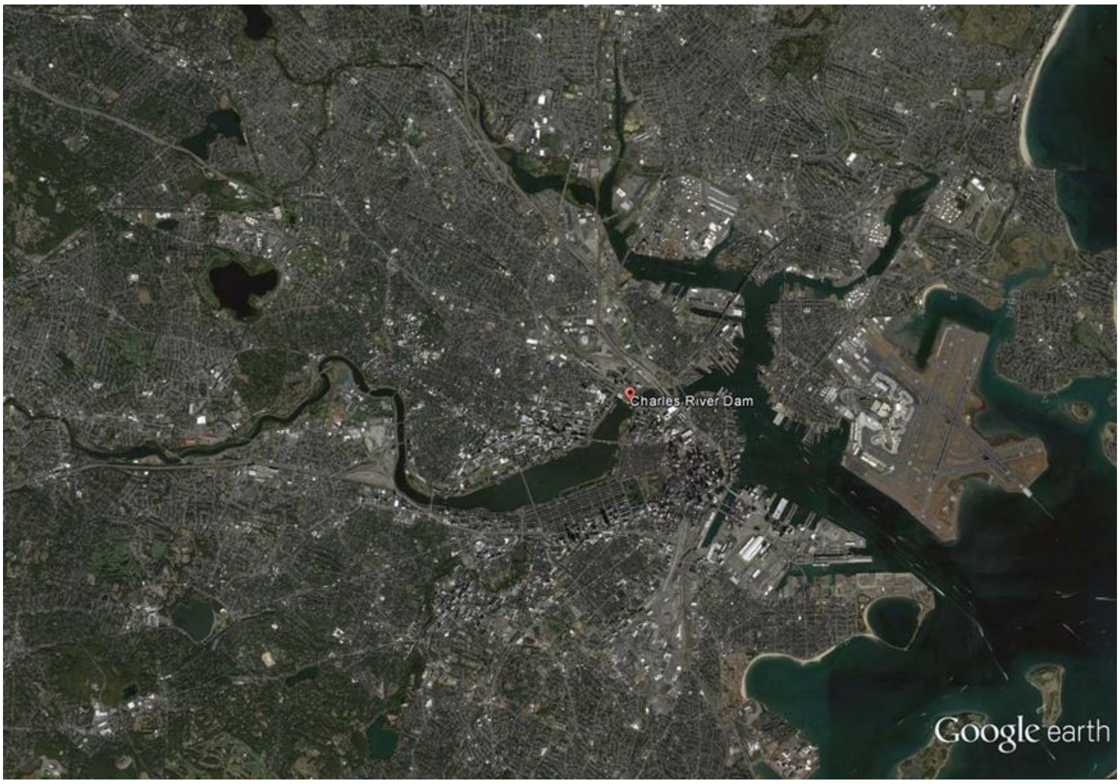


Figure 3-5 Location of the Charles River dam

Before the construction of the Charles River dam (Figure 3-5), the Lower Charles River Basin was a tidal region. Water and materials were washed in and out of the river with the movement of the tides. The result was a mixing region with high levels of dissolved oxygen in the water and a relatively stable salinity concentration. Tidal flats, a characteristic of the region, were submerged by water during high tide and exposed during low tide, making them unusable for building. The raw sewage in the river made the flats unsightly and foul smelling, so in 1910, the Charles River Dam was built to correct the problem (Thompson, 2001).

The creation of the Charles River Dam made a number of changes to the Lower Charles River Basin. The depth of the river was increased, making it more navigable for ships. Land reclaimed from the tidal flats became available for buildings.

The addition of the dam created a slew of environmental problems. The salt water was able to enter the basin either by seeping through the dam or by entering with the passage of ships through the locks. Because the tides were no longer able to flush the basin, the salt water was trapped, sinking to the bottom of the river and forming a salt wedge (layer of salt water lying below fresh water). Due to the salt wedge, the dissolved oxygen levels in the river were reduced. The tides could no longer induce mixing in the water. This left photosynthesis as the only way for dissolved oxygen to enter the water column. The high biochemical oxygen demand of the river depleted the DO levels in the deeper parts of the river and left no way for those oxygen levels to be replenished. In many areas, the DO levels were near 0 mg/L, leaving the water unable to support aerobic life.

In 1970, a plan was formulated to build a new dam downstream of the existing dam and install bubblers to oxygenate the water and de-stratify the water column. The operation of the bubblers was found to be expensive, costing US$ 24,000 per annum in 1978 (Thompson, 2001). While the diffusers solved the issues around stratification and the hypoxia, they were discontinued because they also brought up Hydrogen Sulphide which was produced because of the anoxic conditions (Thompson, 2001). The odour problems made the diffusers unpopular and they were discontinued.

Similar to the Cardiff Bay barrage, the mechanism for deoxygenation in the Charles River is ingress of salt water. This mechanism could be relevant to the use of navigational gates on the Tamar River. The ingress of salt water can potentially deteriorate the oxygen levels further in the Tamar River.

3.5 Summary of studied sites and comparisons

The following table (Table 3-1) captures the key characteristics of each site and the key differences with respect to the proposed Tamar project:

Table 3-1 Summary of the studied sites

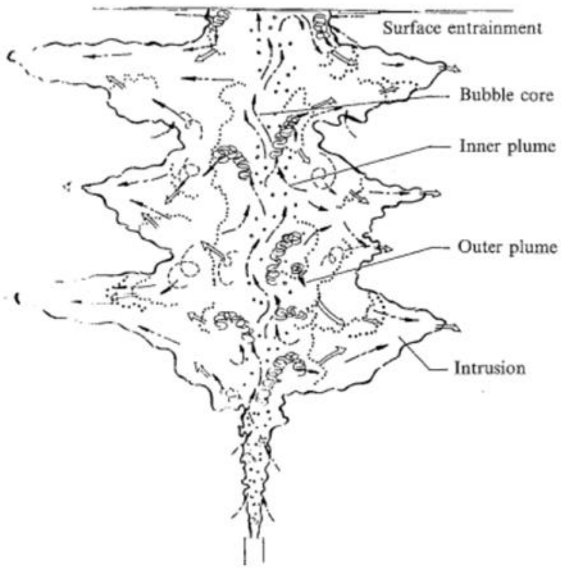
Project Site	Nominal Depth	Mechanism affecting Water Quality
Marina Bay, Singapore	11m	Inflow of contaminants from the catchment
Seine River, France	3-4m (near Paris) 12m (near Poses)	STP inflows into the river and polluted rainwater from urban runoff
Cardiff Bay, UK	5m	Saline water ingress from navigational gates and creation of salt wedge
Charles River, USA	6m	Saline water ingress from navigational gates and creation of salt wedge
Tamar River, Australia	30m (near barrage)	Onset of thermal stratification during summers in the deeper parts and inflow of contaminants from the catchment

4 Destratification Options

Thermal stratification has been identified as the key reason behind the predicted depletion of benthic oxygen. This section reviews various destratification options that are available for deployment and their strengths and weaknesses.

4.1 Air Bubble Diffusers

Bubble plume devices consist of an air supply connected to a pipeline that generally sits at the bottom of the lake, where several diffusers at appropriate spacing and flow rates inject air in the water column. The rising air bubbles produce a shear layer that entrains surrounding water (Figure 4-1). As the water rises, denser fluid at the bottom of the lake is carried within the plume whilst mixing with less dense overlying fluid. As the water within the plume reaches a level of neutral buoyancy, it is detrained and spreads horizontally increasing the circulation at intermediate levels of the water column whilst reducing vertical temperature gradients. With a reduced stratification, other natural mixing mechanisms such as wind and convective cooling become more likely to destabilise the stratified water column.



(Asaeda & Imberger, 1993)

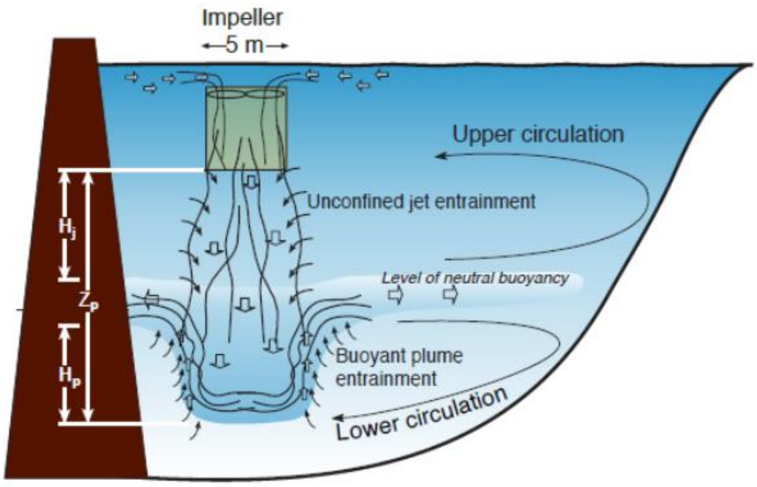
Figure 4-1 Structure of a bubble plume

Air bubble diffusers were installed in Lake Samsonvale in October 1995 (Louise & Bappsci, 2004). The system was found to reduce the surface to bottom thermal gradient and increase dissolved oxygen concentrations at depth. While the diffusers did not result in the lake becoming completely mixed during the summer season, the resistance to mixing during meteorological events was reduced (Louise & Bappsci, 2004).

4.2 Draft Tube Mixers

Surface pumps and draft tube mixers reduce stratification by producing a downwards vertical jet and/or plume that entrains water from the adjacent water column as it descends and produces an intrusive flow and large scale circulation similar to that produced by bubble plumes. These plumes are produced by a pump at the surface that is oriented downwards either as an unconfined jet (surface pump) beginning at the level of the impeller or as a jet emanating from the bottom of a draft tube (Figure 4-2).

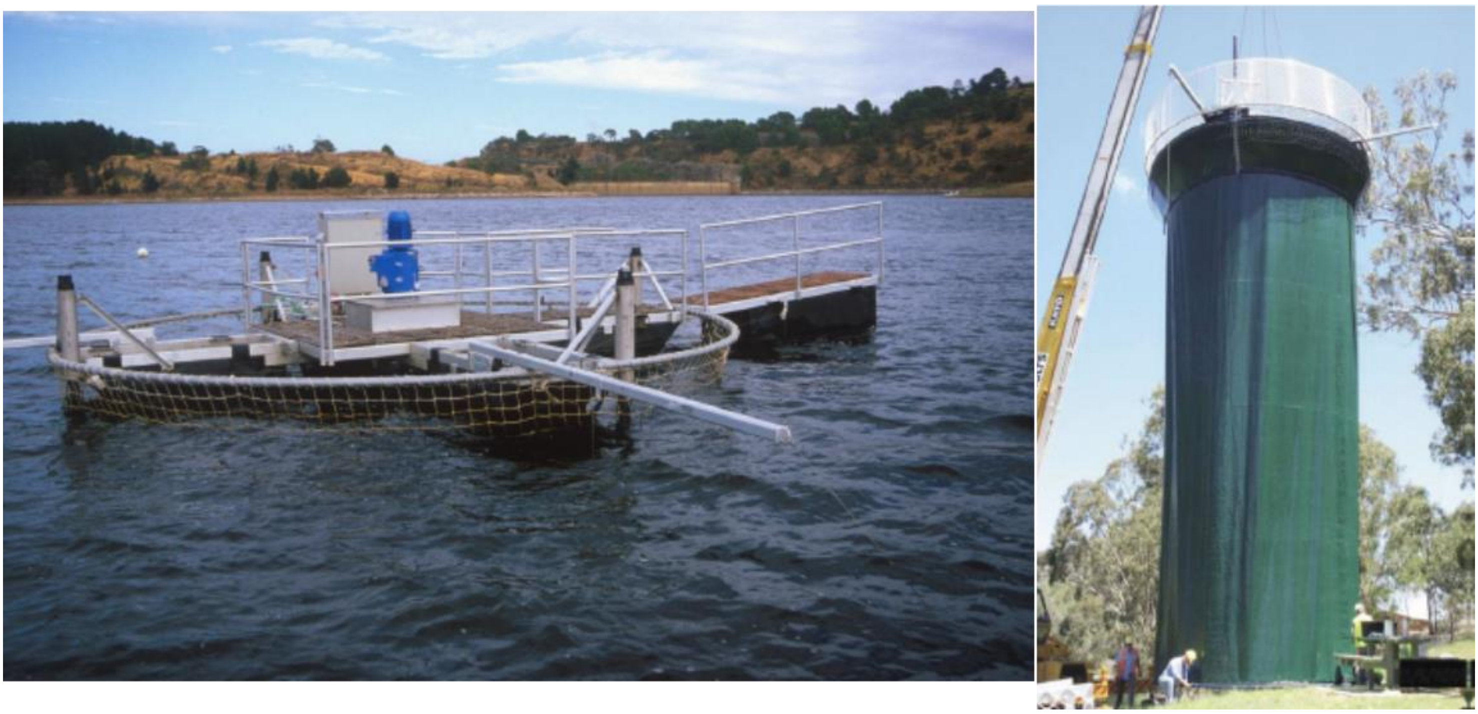
Impeller systems can be used as a replacement for bubble plume systems by locating the pump at the bottom of the water column and pumping the water vertically upwards. Stevens & Imberger, 1994 conducted laboratory experiments on an upwards-facing pump-type system and observed efficiencies of 6-12 % when de-stratifying a two-layer fluid.



(Sherman, Lemckert, & Zhang, 2010)

Figure 4-2 Operating mechanism of Draft Tube Mixers

Draft tube mixers have the ability to inhibit algal blooms, by causing algae to be pumped into the bethic layers which in turn have reduced access to light and the organisms are unable to photosynthesize. Draft tube mixers have been deployed at the Googong Reservoir (Figure 4-3) and Myponga Reservoir in ACT and South Australia respectively.



(Sherman et al., 2010)

Figure 4-3 Draft Tube Mixer unit at Googong

4.3 Super-oxygenation of Hypoxic Water using Liquid Oxygen

Liquid Oxygen ("LOX") is used extensively at an industrial scale in a variety of applications and is commercially available. Hypoxic water from bottom layers can be drawn out and mixed turbulently with LOX at pressure to deliver water supersaturated with dissolved oxygen in the range of 50-100 mg/l. This oxygenated water can then be pumped back to the bottom layers and allowed to spread. Impellers can be added to spread the oxygenated plume. This scheme is suited for applications where target DO concentrations are 5 mg/l and above (MACTEC & Authority, 2009).

Estimates of energy consumed per Ton of LOX range from 200-500 kWh and in general the cost of energy consumed is about 10% of the cost of LOX (MACTEC & Authority, 2009). The pressurised nature of the incoming oxygen reduces the overall oxygen consumption.

There are different configurations of the system suited to different applications and are described below.

4.3.1 Speece Cone

This device incorporates an inverted conical gas transfer vessel in which the water is introduced at the top of the cone, flowing in a downward direction. As the water flows downward its velocity decreases in proportion to the cross-section of the cone. Pure oxygen is also injected into the cone and the resulting hydraulic turbulence creates a bubble swarm which has an exceptionally high oxygen/water interfacial area, and the oxygen transfer is greatly enhanced. This system (Figure 4-4) has been deployed at the Savannah Harbor in Georgia, USA.

(www.savannahnow.com)

Figure 4-4 Speece Cone installation at Savannah Harbor

4.3.2 U-Tube Oxygenation

This process involves the passage of a gas water mixture vertically down a shaft underneath a baffle and back up to the surface, providing prolonged contact of the bubbles with the water and pressurization of the bubbles by the hydrostatic head. Water is pumped down the centre of this shaft to the bottom and then flows back through an annular space to the surface. A vertical shaft of considerable depth is required for this type of oxygen transfer technology.

This system has been tested successfully at the Swan River in Western Australia (Figure 4-5), where two oxygenation plants have been working for more than a decade now. Model studies and field observations show that the plants are effective in mitigating the deoxygenation caused by the upstream migration of the salt wedge during summer. The running costs for both plants (only including electricity and oxygen) are of the order of $200,000 per annum with a total service area of 0.5 km^2 (pers. Comm. Matt Hipsey, 2016).

(www.water.wa.gov.au)

Figure 4-5 Oxygenation plant on the Swan river

4.3.3 Mobile Oxygenation Barge

A self-contained mobile oxygenation system includes on-board oxygen generation by pulsed swing adsorption or vacuum swing adsorption. This feature avoids the safety concern of needing to store oxygen. Diesel or propane driven engines can directly drive the oxygen generation system and pumps to move water through the oxygen transfer system and also generate electricity.

The mobile oxygenation system operates with the oxygen absorption reactors lowered to the bottom of the river to take advantage of the hydrostatic head enhancement of oxygen transfer and raised during transport.

Such barges have been used at Thames River (Figure 4-6), Cardiff Bay and Shanghai.

(www.shipspotting.com)

Figure 4-6 Oxygenation barge on the Thames River

5 Modelling of Destratification Scenarios

5.1 Qualitative Diffuser Design

Qualitative assessment of the potential size of a bubble plume diffuser system required to destratify a small portion of the water volume that stratifies in summer (i.e. not the entire stratified volume) was undertaken. This provides a broad overview of the likely order of magnitude scale of destratification line length and compressor size required. This preliminary design approach was based on the step procedure developed by (Helfer, 2012). These calculations are indicative only and **should not be relied on in any way for subsequent analysis (technical or investment) or similar**. If Tamar Lake Inc does require this level of assistance then a detailed analysis can be undertaken – the calculations that follow are not suitable for any other purpose.

The qualitative diffuser design takes into consideration mechanical and energetic efficiencies (Schladow, 1992, Asaeda & Imberger, 1993). As a starting point, data predicted by the model at T11 (Figure 5-1) was used to provide the input stratification characteristics. It was assumed that there was a static lake extending from the barrage to approximately midway between T11 and T10 (which is a small portion of the volume that actually stratifies).

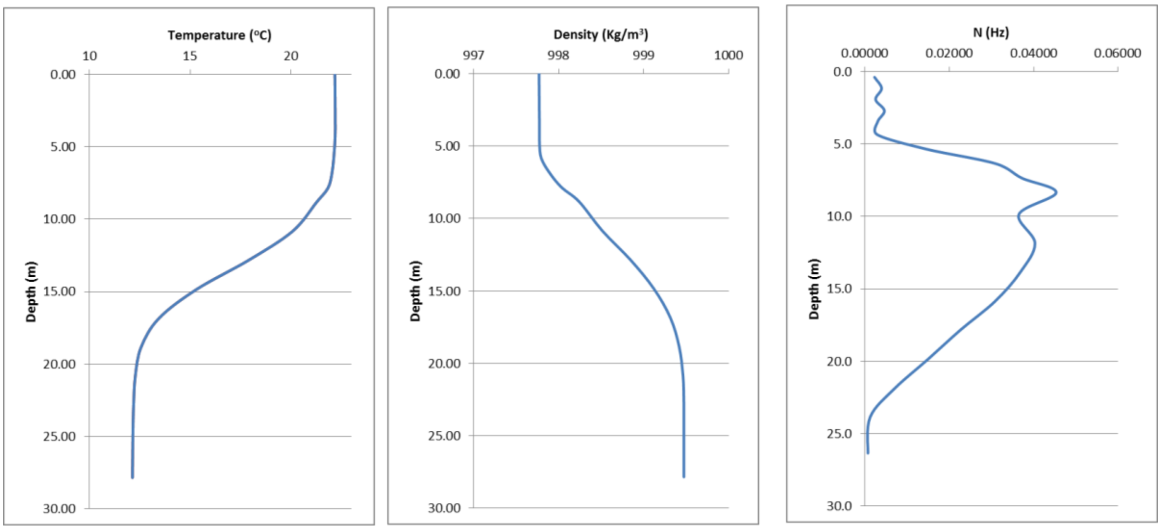


Figure 5-1 Variation of Temperature, Density and Buoyancy Flux with depth

The non-dimensional entrainment rate Q_R and head ratio H_R is given by:

$$\boldsymbol{Q_R} = \frac{\boldsymbol{N^3 h^3}}{\boldsymbol{4\pi\alpha^2 u_s^3}}$$

$$N = \frac{g}{\rho_o}\frac{\Delta\rho}{\Delta z}$$

$$H_R = \frac{h}{H}$$

where *N* is the buoyancy frequency, *g* is the acceleration due to gravity, ρ and ρ_o are respectively the density and a reference density taken as 1000 kg/m^3, z is the vertical level, *h* is the lake depth, *H* is the total pressure head, including the atmospheric pressure, u_s is the slip velocity of the bubbles taken as 0.3 m/s and α is an entrainment coefficient. These parameters are required to calculate the plume number for maximum efficiency P_N^* , given by:

$$\log_{10} P_N^* = 0.16 \log_{10} Q_R + 2.1 + 1.2H_R - 0.55H_R^2$$

The air flow rate per port can then be calculated as:

$$Q_B^* = \frac{N^3 h^4}{P_N^* g}$$

The air flow rate per port allows the calculation of the source strength M_H^* and total entrained water flux per plumeQ_I^*, given by:

$$M_H^* = \frac{Q_B^* g}{4\pi\alpha^2 h u_s^3}$$

$$Q_I^* = 0.56 \left(\frac{Q_B^* g}{N^5}\right)^{1/4} M_H^{*\,0.11}$$

In order to overturn the lake, the required number of ports is calculated from:

$$m = \frac{V}{T Q_I^*}$$

where *V* is the lake volume and *T* is the time desired for lake Destratification. Helfer (2012) recommended adopting a 21 day destratification time (Lemckert & Imberger, 1993). In the present study, a shorter duration of 7 days was adopted, considering the polymictic lake mixing characteristics. Is can be adjusted if needed. The total flow rate for the bubble plume system is the given by:

$$Q_T^* = m Q_B^*$$

To avoid interactions between adjacent bubble plumes, a port separation distance is specified by (Lemckert 1992):

$$l_s = 3.88 \left(\frac{Q_o^* g}{N^3}\right)^{1/4}$$

where

$$Q_o^* = Q_B^* \frac{H}{h_a}$$

and h_a is the atmospheric pressure head. Finally, the total length of the diffuser can be given by:

$$L_P = m * l_s$$

These design parameters were calculated for mixing of only the area from the barrage to midway between T10 and T11, which is a small portion of the volume to be destratified. The preliminary design parameters are tabulated in Table 5-1.

Table 5-1 Preliminary Bubble Plume Diffuser Design

Location	N (Hz)	Q_R	H_R	P_N^*	Q_B^* (10^{-5} m^3/s)	Q_I^* (m^3/s)	V (ML)	T (d)	Q_T^* (L/s)	m	l_s (m)	L_P (m)
Barrage to midpoint T11&T10	0.04	1773	0.73	1594	0.0073	2.788	9018	7	394	54	23.6	1266

As shown by the preliminary calculations, pumping approximately 400 l/s of air over a 1.2 km diffuser line (to only destratify a small portion of the required volume) would entail a large, setup that has never been implemented at the scale envisaged, as far as BMT WBM is aware. This suggests that destratifying the required volume using a bubble plume (or array thereof) will be difficult.

5.2 Scenario Run with Draft Tube Mixers

Given the above result, a model scenario run with draft tube mixers (not a bubble plume) was set up to explore the feasibility of implementing them as destratification devices.

To model the effect of a draft tube mixer, water with quality parameters set to the surface water quality was pumped at 0.5 m above the bed and an equal amount of water was withdrawn from the top surface to maintain water levels and retain the original water balance.

The proposed system was assumed Include 36 mixers with each pumping about 11 ML per day (Figure 5-2). The total pumping rate of these devices has been set up to be twice that of the recirculation system at Marina Bay, Singapore (Nauta et al., 2008). This is a very large number of devices.

Figure 5-2 Locations of destratification devices

The following is a comparison of the areal extent (Figure 5-3) of dissolved oxygen at depth with and without the destratification devices operating. The model predicted that the proposed system would have little impact on bottom DO. Whilst there are some minor improvements in this regard, these are not significant and the destratified system would still experience depleted oxygen concentrations at depth, with consequent environmental harm likely. More broadly, the model predicts that bottom layers become anoxic at approximately the same time of year depth with and without the destratification devices operating.

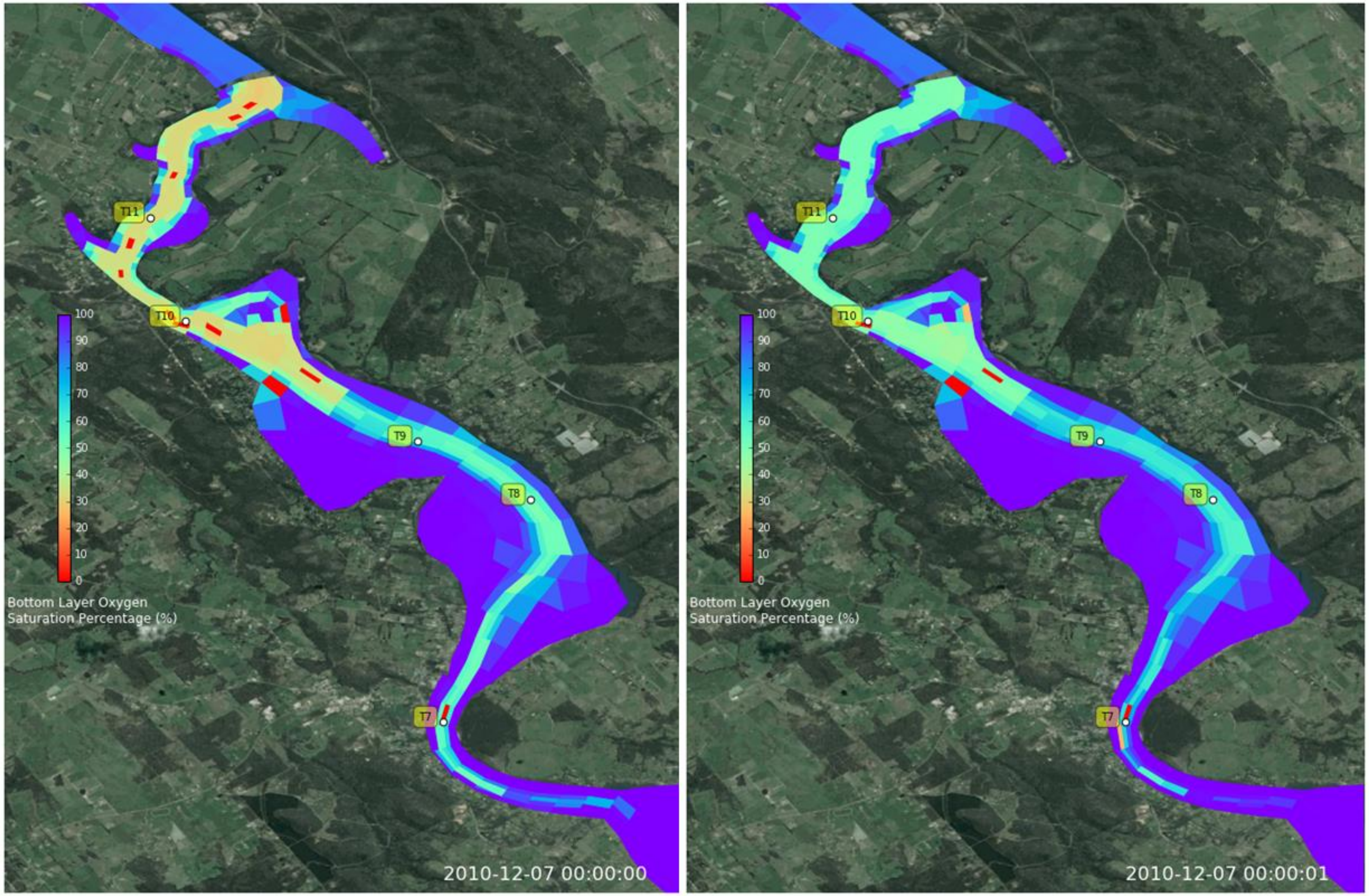


Figure 5-3 Comparison of scenarios without (left) and with Draft Tube Mixers (right)

6 Conclusion

Extensive thermal stratification is likely to be experienced in the lake if the proposed project were to go ahead. Destratification efforts are likely to require significant (and as far as BMT WBM understands unprecedented) infrastructure (capex and maintenance) and power (ongoing) investment. Some high level calculations in this regard have been provided in this report, for illustrative purposes only. Whilst useful for indicative purposes, these calculations should not be relied on for any other purpose whatsoever, especially not for any subsequent design or investment analyses.

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