Transactions on Ecology and the Environment vol 49, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

Measurements of dissolved oxygen in an impounded stratified estuary

D. S. Speers[1], P.A. Mackinnon[1], D.M. Moore[2] & J.R. MacDonald[3]
[1]*School of Civil Engineering, The Queen's University of Belfast, Northern Ireland.*
[2]*White Young Green plc., Belfast, Northern Ireland*
[3]*Laganside Corporation, Belfast, Northern Ireland*

Abstract

Like many impounded stratified estuaries, the Lagan (in Belfast, Northern Ireland) suffers water quality problems from time to time. These problems date back to 1937, when the first weir was constructed to allow navigation within the estuary. With the replacement of the original weir in 1994 by the Lagan Weir, a half tide-barrage, water quality issues were addressed. Provision was made for flushing of saline water that would otherwise become trapped at the base of the barrage, and artificial aeration facilities were installed with the intention of improving dissolved oxygen in the upper reaches. Despite these measures, the semi-tidal nature of this impounded estuary continues to allow the formation of a highly stratified flow regime. This prevails during the summer months when the weather is warm and the freshwater flow in the river is very low. Low dissolved oxygen levels in the lower dense seawater layer result, due to a high sediment oxygen demand within the estuary and reduced tidal mixing.

This paper outlines the effects of an artificial hydraulic regime on dissolved oxygen levels and density stratification in the impounded estuarine waters of the River Lagan. Measurements of dissolved oxygen and salinity are presented for a number of different aerator operating regimes under low freshwater flow conditions. The results suggest that the aerators serve to improve water quality by mixing of the fresh and saline waters, but uptake of oxygen by dissolution remains unproven. The discussion is confined to the nature of the different aerator regimes and their influence on the distribution of dissolved oxygen and salinity within the estuarine waters.

Transactions on Ecology and the Environment vol 49, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

Introduction

A fundamental characteristic of any estuary is the interaction between fresh and salt water. When the river flow is high, the salt and fresh water tend to mix. When flows are low, stratification forms as the less dense freshwater from the river overrides the saltwater [1]. When an estuary is impounded, stratification upstream of the impounding barrage tends to become more pronounced; the reduction in tidal flushing is often associated with a decrease in mixing and reduced dissolved oxygen in the water. This deterioration in water quality may affect fisheries, industry, recreation and river aesthetics.

In recent years, the impoundment of estuaries has been a central feature of several urban regeneration schemes in the United Kingdom. However, the success of these schemes depends, amongst other things, on the ability to create an attractive riverside environment. Without mitigating measures, the problem of depleted dissolved oxygen has the potential to detract from such schemes, particularly when obvious signs such as death of aquatic species or offensive odours arise. With this in mind, the designers of recently constructed barrages, such as those in Cardiff Bay and the River Tawe (both in Wales), and the River Lagan (in Belfast, Northern Ireland) have incorporated facilities to counteract these problems [2].

The River Lagan, shown in Figure 1, has been impounded since 1937. In 1994, the original fixed-crest McConnell Weir was replaced by the Lagan Weir, a half-tide barrage designed to ensure coverage of unsightly mudflats throughout the tides. The aim was to encourage redevelopment along the riverside and to promote greater recreational use of the estuary. The installation consists of five hydraulically operated fish belly gates. These are lowered to bed level for a few hours either side of high tide to allow free flow, and are then raised to retain water. As a result of its density, the incoming seawater tends to sink underneath the river water, so that it is isolated from the atmosphere but in contact with oxygen-demanding sediments. On the ebb tide, low-level sluice gates allow the selective removal of oxygen-depleted seawater trapped behind the barrage [3].

The sluice gates are thought to be relatively successful in counteracting dissolved oxygen problems near the Lagan Weir. However, it was anticipated that, during periods of low freshwater flow, insufficient mixing of the water upstream of the tidal excursion limit would allow saline stratification to occur, with two distinct layers forming. Due to the high sediment oxygen demand and the inability of oxygen to be transferred across the halocline, surface aeration alone was unlikely to maintain satisfactory dissolved oxygen concentrations close to the riverbed [4].

Artificial aeration was therefore provided in the impoundment in an attempt to satisfy the oxygen demand [4]. In 1994, seven aerator stations were installed in the upper reaches of the impoundment. Rising columns of air have often been used to destratify freshwater reservoirs but their performance in saline stratified waters, impounded or otherwise, is less well understood [5]. The aim of the research reported here was to quantify the impact of the aerators on the impounded stratified waters of the Lagan and to obtain information to optimise their mode of operation. The research was carried out using full-scale tests within the Lagan estuary.

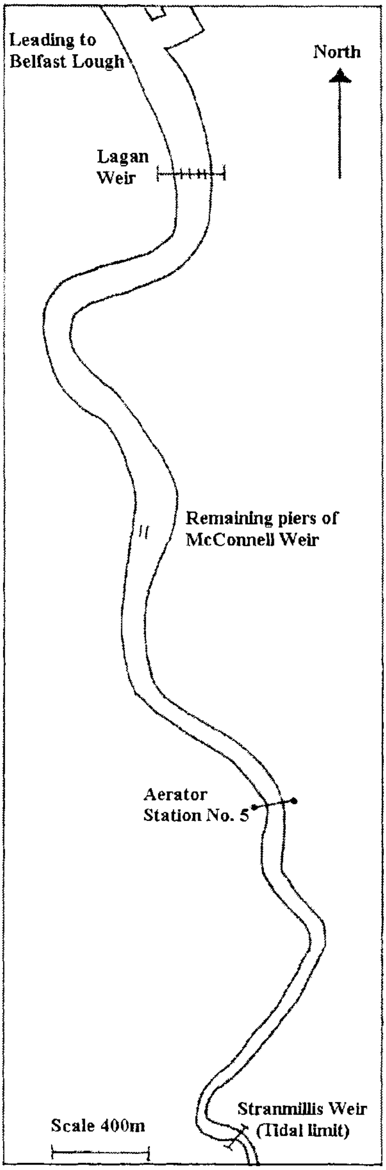

Figure 1: The impounded section of the River Lagan

Transactions on Ecology and the Environment vol 49, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

Methodology for field tests

The work was carried out using a series of tests during the summer period (June – August 2000) when the dissolved oxygen levels within the impoundment are most seriously depleted. Data were recorded in the area around aerator station number 5 (see Figure 1). Previous investigations had been carried out in this area following recommendations by Wood [6]. Intensive measurements of dissolved oxygen (DO), conductivity, temperature, pH and velocity were carried out at 0.25m intervals from the water surface to the riverbed. Monitoring of water quality was conducted at least hourly. Where possible, it extended over the full tidal cycle so that tidally induced variations were observed. However, on some occasions, shorter monitoring periods were inevitable for practical reasons.

Data were recorded using a calibrated Grant 3800 water quality logger which was attached to a marked rope. This was lowered into the water and the output was allowed to stabilise. Current speed and direction were recorded using a Valeport direct reading current meter, in order to establish the effects of the tides and freshwater flow on the water quality. The data were processed and plotted using the spreadsheet package Microsoft Excel. Conductivity readings were used to calculate the salinity. Dissolved oxygen and salinity values were plotted against depth and time to provide an insight into the effects of the aeration process on stratification.

The time frame used in all the tests was British Summer Time. When discussing tides, the terms 'high water' and 'low water' refer to the predicted conditions in Belfast Harbour 5km downstream of the survey site.

Data obtained under different aerator operations

Barrage operations

Throughout all the monitoring periods, normal barrage operations were maintained, with the barrage gates lowered on an incoming (flood) tide and then raised to 0.3m Ordnance Datum on the outgoing (ebb) tide to maintain a minimum impoundment water level [7].

Aerator tests

Under the normal mode of operation, the aeration system runs from 5pm in the evening to 9am in the morning during the summer period of late May to early September when river flows are low [7]. Initial tests on normal aerator operations were carried out to gain an understanding of how they affect dissolved oxygen and saline stratification.

The results of these tests (presented in Figures 2, 3, and 4) indicate that, once aeration ceases, the slack period around low tide allows the water to revert to a stratified state. Poor dissolved oxygen concentrations were observed, especially in the lower part of the water column near the riverbed.

Transactions on Ecology and the Environment vol 49, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

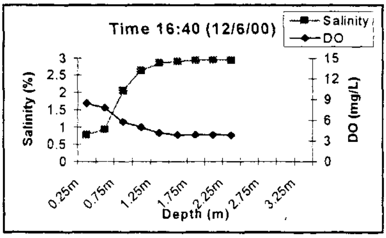

Figure 2: 5 hours before high water

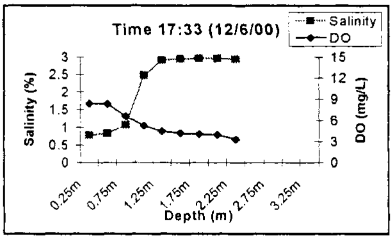

Figure 3: 4 hours before high water

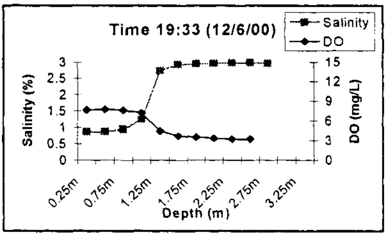

Figure 4: 2 hours before high water

Key:
High water at 08:33hrs & 21:18hrs
Tidal range = 2.5m
Aerators off 11:15hrs, 12/6/00
Fresh water flow = 4.2 m^3/sec

During the period around high water the amount of stratification in the water column was reduced due to the movement and mixing effect of the tidal currents. Examples of this, recorded under similar conditions three days later, are shown in Figures 5, 6, and 7.

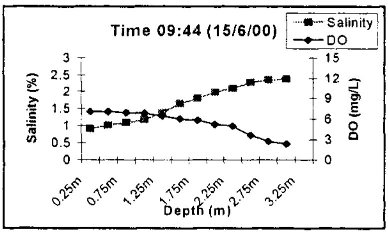

Figure 5: 1 hour before high water

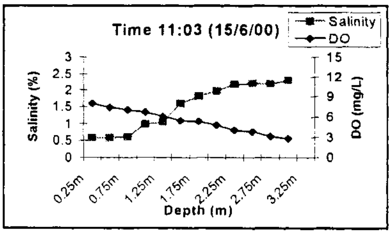

Figure 6: High water

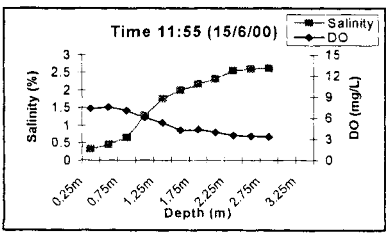

Figure 7: 1 hour after high water

Key:
High water at 11:04hrs & 23:30hrs
Tidal range = 2.6m
Aerators off 9:35am, 15/6/00
Fresh water flow = 3.2 m^3/sec

Transactions on Ecology and the Environment vol 49, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

The break down of stratification also appeared to improve the dissolved oxygen profile, though dissolved oxygen levels near the riverbed still remain below 4mg/l, the value often cited as the minimum required to support a range of aquatic life.

These sets of results suggest that, in the period following normal (continuous night-time) aeration, stratification tends to form during the prolonged period of slack water around low tide. The data suggest that it is counteracted naturally to some extent during the period of maximum water movement i.e. on the flood and ebb tide. Dissolved oxygen profiles become more gradual from the river surface to the riverbed but still remain poor at lower depths.

Following these tests a number of scenarios were identified for further study, namely:

- the effects of the aerators not being operational;
- impacts of aerators alternating on an hourly basis;
- impacts of the aeration system only being operational during flood and ebb tides.

Aerators not operational

A baseline test was carried out to establish the water quality when the aerators were not operational. This allowed an assessment to be made of the effects of the artificial hydraulic regime on the impounded water quality in the absence of aeration. This test was carried out over a two day period. On the second day of the test, pronounced stratification and an associated reduction in dissolved oxygen levels were observed.

Figures 8 and 9 show salinity and dissolved oxygen profiles on the flood tide. The artificial aeration had been operational until 08:00hrs, just several hours prior to taking these measurements.

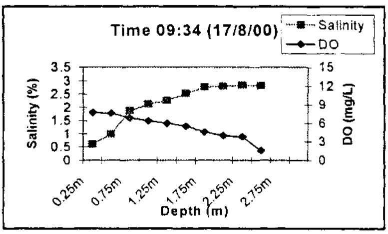

Figure 8: 4 hours before high water

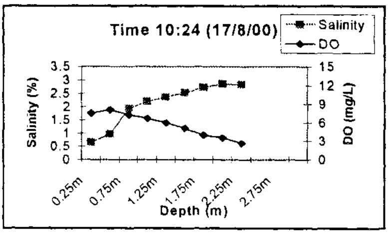

Figure 9: 3 hours before high water

Key:

High water at 00:55hrs & 13:16hrs
Tidal range = 2.4m
Aerators off at 08:00hrs, 17/8/00
Fresh water flow = 2.4 m^3/sec

Transactions on Ecology and the Environment vol 49, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

The relatively smooth profiles shown in Figures 8 and 9 suggest that the aerators had provided mixing of the water column, which was then sustained for some time after aeration ceased. The profile of dissolved oxygen shows a gradual decrease with depth, as opposed to the more sudden decrease associated with stratification. However, there is no indication of improved levels of dissolved oxygen near the riverbed.

Comparing the same period of the tidal cycle approximately 24 hours later (see Figures 10 and 11) shows that, in the absence of artificial aeration over this extended period of time, stratification prevails along with poor dissolved oxygen profiles especially near the riverbed.

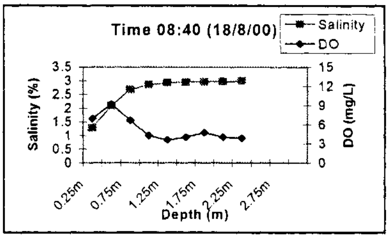

Figure 10: 5 hours before high water

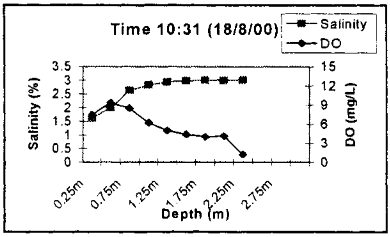

Figure11: 3 hours before high water

Key:
High water at 01:22hrs & 13:48hrs
Tidal range = 2.1m
Aerators off 08:00hrs, 17/8/00
Fresh water flow = 2.4 m^3/sec

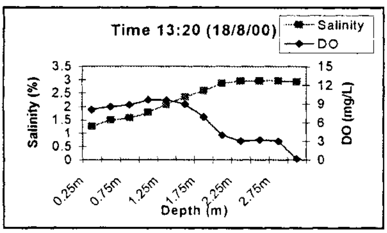

Figure 12: 0.5 hours before high water

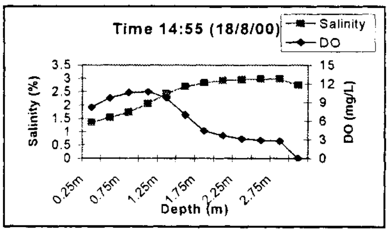

Figure13: 1 hour after high water

Key:
High water at 01:22hrs & 13:48hrs
Tidal range = 2.1m
Aerators off 08:00hrs, 17/8/00
Fresh water flow = 2.4 m^3/sec

This confirms that, without mitigating measures, the artificial hydraulic regime would result in pronounced stratification. Figures 12 and 13 show similar profiles of salinity and dissolved oxygen later in the tidal cycle, indicating that the stratification could persist at various states of the tide.

Aerators alternating on an hourly basis

Preliminary tests indicated that the effects of the aerators on stratification were limited with respect to time. Although effective while operational, their impact reduced rapidly after operation ceased. In order to determine if maintaining good mixing would result in further improvements in dissolved oxygen levels, aerators were switched on and off on an hourly basis (i.e. off at 9:00hrs, on at 10:00hrs etc.). As with all the other tests, the period of investigation was preceded by a period of normal (i.e. continuous night time) aerator operation.

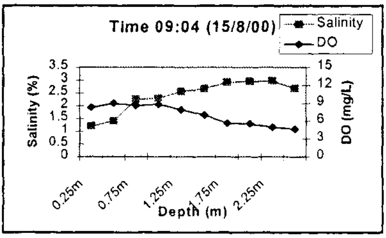

Figure 14: 3 hours before high water

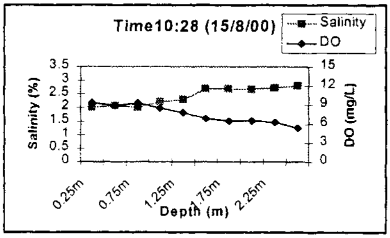

Figure15: 2 hours before high water

Key:

High water at 12:21hrs

Tidal range = 2.4m

Aerators on 08:00hrs, off 09:00hrs, on 10:00hrs etc.

Fresh water flow = 1.8 m^3/sec

The results shown in Figures 14 and 15 and those recorded later in the test suggest that, while operating in this mode, the aerators are effective in providing mixing, giving smooth dissolved oxygen and salinity profiles. The dissolved oxygen levels near the riverbed are not as low as the values recorded in the previous tests, reported earlier. Ignoring the potential for some other influencing factor, there are two possible explanations for this observation. The first is that the aerators increase dissolved oxygen in the water column by direct dissolution. The second is that the bubble plume causes increased circulation of water and hence boosts the mixing of de-oxygenated saline water and freshwater, which is oxygenated by contact with the atmosphere. The exact mechanism of transfer of dissolved oxygen across a density-stratified medium remains unproven.

Aerator operations according to tides

When the aeration system was originally installed, it was recommended that the aerators operate for 100 minutes on the flood tide and 150 minutes on the ebb tide in order to take advantage of the increased water movement in the estuary at this time, thereby aiding dissolution of the oxygen [4]. However, without facilities for automatic switching (now present), this regime was abandoned in favour of overnight operation. As the results obtained in the early tests showed a clear tidal influence, it seemed logical to investigate the option further. The aerators were operated for several hours on the flood and ebb tides with a period of no aeration around high water.

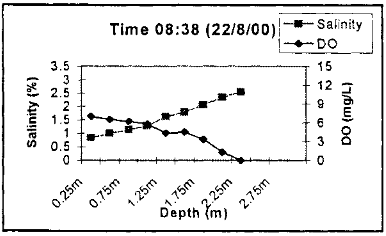

Figure 16: 4.5 hours after high water

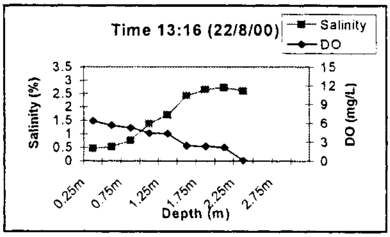

Figure 17: 4 hours before high water

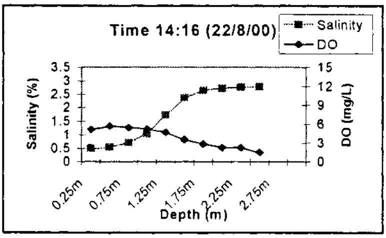

Figure 18: 3 hours before high water

Key:
High water at 04:10hrs & 16:51hrs
Tidal range = 2.4m
Aerators off 07:00hrs; on 14:00hrs
Fresh water flow = 2.4 m^3/sec

Figure 16 shows the results four and a half hours after high water; the aerators had been switched off one hour before the measurements. It appears that, after the period of ebb tide movement, the aerators are able to sustain a mixed water column, counteracting any tendency to stratify. The dissolved oxygen profile is smooth but, near the riverbed, reaches critical levels necessary to sustain a range of aquatic life. As the period of low water (minimum impoundment level) progresses, the lack of aeration at this stage allows stratification in the water column to re-establish, as shown in Figures 17 and 18. Dissolved oxygen levels in the upper part of the water column also steadily declined.

Conclusions

It is clear that the aerators play an important role with twice daily tidal movements in the mixing of the water column and reducing stratification. Their role in improving dissolved oxygen is, however, less obvious. Further tests are required to clarify their exact mechanism of improving water quality. The results suggest that the use of the aerators at periods of little water movement within the impoundment is most beneficial in keeping the water column mixed and maintaining a consistent dissolved oxygen profile. Further research on different aerator regimes is under way to ascertain how artificial aerators can be best used to minimise stratification and dissolved oxygen deficiency in a stratified impounded estuary.

Acknowledgements

The authors would like to acknowledge the Department of Higher & Further Education, Training & Employment (DHFETE) in Northern Ireland and Laganside Corporation who have provided funding for this research project. Thanks also go to the Queen's University of Belfast technical staff who assisted in equipment preparation and water quality surveys throughout summer 2000.

References

[1] Walker, S.A. *The effect of time on interfacial mixing in density stratified flows*, PhD Thesis, The Queen's University of Belfast, 1996.

[2] Maskell, J.M. & Barraclough, A.K. The impact of barrages on water quality: predictions and reality. *Proc. of the International Conference on Barrages: Engineering Design & Environmental Impacts*, Cardiff, UK, Burt, N. & Watts, J. (eds). John Wiley & Sons Ltd, pp.295-300, 1996.

[3] Cochrane, S.R. & Weir, D. *The Development and Operational Control of the Lagan Weir and its Impoundment, 1987-1997.* Laganside Corporation, Belfast, 1997.

[4] Cochrane, S.R. *Lagan Weir Impoundment – Development of Aeration System.* Laganside Corporation, Belfast, 1993.

[5] Baines, W.D. & Leitch, A.M. Destruction of stratification by bubble plume. *Journal of Hydraulic Engineering*, **118(4)**, pp. 559-577, 1992.

[6] Wood, S. *A study into the effectiveness of the Lagan's artificial aeration system.* MSc Thesis, University of Ulster, Coleraine, 1997.

[7] Byrne, J. Pers. comm. – River Warden, Laganside Corporation, Belfast, 2000.