Mixing studies in an Orbal activated sludge system

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Abstract

Orbal multi-channel oxidation ditches have received relatively little attention and thus knowledge of their characteristics is not as highly advanced as for other oxidation ditch systems. Dye tracer and dissolved oxygen measurements have been undertaken to elucidate the mixing characteristics of a three-channel Orbal system treating 80 Ml/d. The dissolved oxygen concentrations showed a complex variation in space due to the input, approximating a continuous line source, non-uniform distribution of turbulence and secondary flows caused by channel configuration. Consideration of the DO measurements and the dye tracing results suggest that the flow could be treated as 2 CSTRs in the outer channel and a single CSTR in each of the two inner channels.

Nomenclature

BOD_5	=	5 d biochemical oxygen demand (mg/l)
COD	=	chemical oxygen demand (mg/l)
DO	=	dissolved oxygen (mg/l)
S_{NH}	=	concentration of ammoniacal-nitrogen (NH_4-N)(mg/l)
S_{BOD5}	=	concentration of soluble BOD_5 (mg/l)
RAS	=	return activated sludge (mg/l)
TBOD	=	total BOD (mg/l)
TSS	=	total suspended solids (mg/l)
X_{BOD5}	=	concentration particulate BOD (mg/l)
X_{NVSS}	=	concentration of non-volatile solids (mg/l)
X_{VSS}	=	concentration of volatile solids (mg/l)

Introduction

Since its introduction in 1959, the oxidation ditch has been used very widely throughout the world for the treatment of both domestic and industrial wastewaters. Its original design has been modified to accommodate greater loads, thus creating the Carrousel and the Mammoth systems (Koot and Zeper, 1972; Von der Emde, 1971), and the design expectations have changed so that, as well as removing carbonaceous BOD, an oxidation ditch can be configured to nitrify, denitrify and to even remove phosphorus (Rachwal et al., 1983; Sen et al., 1992). As such, their design and performance characteristics have received considerable attention. One mode of operation which has not been subjected to very much scrutiny is the multi-channel Orbal system. Two decades ago it was reported as being able to provide a reliable form of treatment, both for the removal of carbonaceous and nitrogenous pollutants (Drews and Greeff, 1973; Applegate et al., 1980) and a recent study (Daigger and Littleton, 1999) of six Orbal processes has confirmed this. Nevertheless, the knowledge about its overall characteristics for a wide range of operating conditions is not highly advanced.

The behaviour of wastewater treatment systems is increasingly being examined by mathematical models. These range over a wide variety of sophistication with a comparable range of data requirements. Most of the models which are in use need the mixing characteristics within the aeration tank to be specified, usually in terms of the equivalent number of continuously stirred tank reactors (CSTR) in series. In a traditional activated sludge plant a reasonable estimate of this can be made. In a traditional oxidation ditch a similar philosophy could prevail, and certainly one modeller has assumed that 20 tanks in series would be reasonable to describe an oxidation ditch 100 m long and 10 m wide (Stamou, 1994). What is not known is whether a similar approach would apply to an Orbal configuration. It is known that the mixing characteristics in a single-channel ditch, a Carrousel system, may be viewed in two ways. Over the time scale of one or two hours there is a high degree of plug flow but, viewed over a mean hydraulic retention time, the tank must be considered as being completely mixed (Koot and Zeper, 1972). Recently, four Orbal systems have been built for United Utilities plc, UK and mathematical modelling studies of these systems were required for performance predictions. There are no reported examples of Orbal tracer studies in the literature. It is known that one such study was carried out on the Orbal plant in Paris, Texas, USA in 1974, and this showed that the system could be considered as three completely mixed tanks operating in series (Envirex, personal communication). However, the Orbals at the Paris plant were designed with a depth of 1.5 m compared with 3.65 m for the UK plants.

This paper reports the results of tracer studies carried out at one of the plants operated by North West Water Ltd., UK and discusses the implications of the data for future studies.

Materials and methods

The Orbal treatment plant

The treatment plant, which treats a dry weather flow of 80 Ml/d, consists of conventional preliminary and primary treatment followed by two Orbal units. Each one consists of three concentric oval ditches. The mixed liquor flows around the outer channel, then through one of two ports into the central channel and finally into the inner channel, before passing into the final settlement tank. (Fig. 1). Aeration is achieved by four banks of disks which rotate around horizontal shafts. The number of disks on each section of the shaft may be altered to adjust the oxygen transfer, which can also be changed by varying the depth of submergence. The DO concentrations in the three channels are controlled by DO electrodes

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Received 3 December 1999; accepted in revised form 18 September 2000.

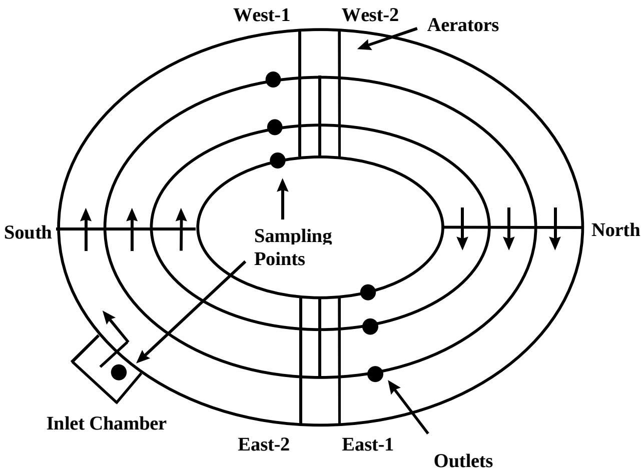

Figure 1
Schematic diagram of the Orbal system showing the sampling points

linked to a Scada system. The discs serve two functions: to aerate and to circulate the contents of the ditch. The feed is settled sewage which has been mixed with the RAS in an anoxic selector which has a mean hydraulic retention time of 40 min at dry weather flow.

Tracer studies

The tracer used in the studies into longitudinal mixing within the Orbal channels was Rhodamine WT. This was chosen for its ease of analysis on site, and the fact that it does not have the adsorption and toxicity problems associated with Rhodamine B. It was supplied as a solution with a concentration of 210 g/l and was dosed (2 l) into the inlet chamber. The consent for using Rhodamine B in the works final effluent was set by the Environment Agency at 10 µg/l but, as only one Orbal was dosed, the permissible concentration at the outlet of the dosed Orbal could be 20 µg/l.

Two separate studies were carried out on 16 and 18 June 1997. Samples were taken from the inlet chamber to account for tracer in the RAS, the first of the two outlets on the outer and middle channels and the final outlet chamber (Fig. 1). Samples at the outlet of the outer channel were taken at 2 min intervals for the first 48 min to provide a better resolution of any short-circuiting flow and thereafter at 10 min intervals. Samples from the middle and inner channel outlets were taken every 10 min for the first 8h and then at half hourly intervals. The study was stopped when the concentration of tracer in the final outlet samples was <1 µg/l (25 to 28 h).

Dissolved oxygen survey

Surveys around the Orbal outer channel at 10 m intervals, on the surface by the outer wall, in May 1998 used a fast response DO probe with a digital meter to examine the change in residual DO concentration with distance from the aerators. Two fast response probes were used, attached to a 13.6 kg lead weight, in October 1998 to examine the concentration of DO with depth and distance from an aerator by the outer wall of the outer channel to enable an estimation of the anoxic volume of this channel.

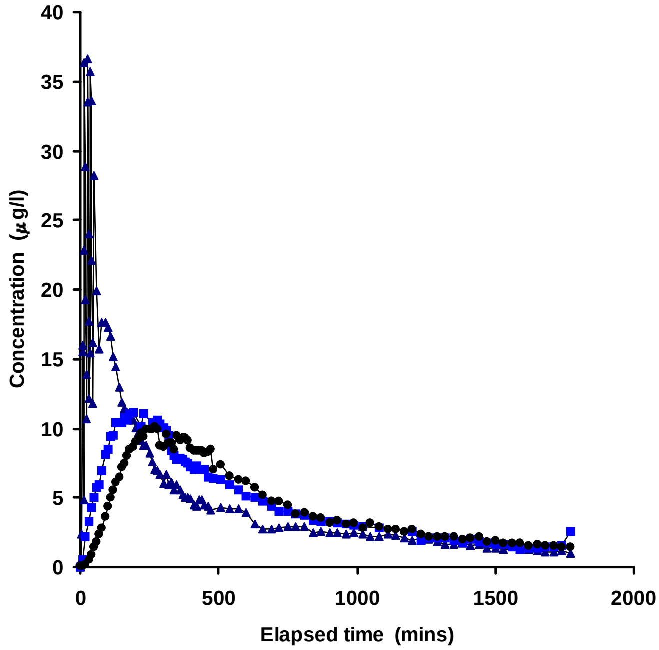

Figure 2
Residence distribution curves from the tracer study on 16 June 1997
▲ *Outer channel*
■ *Middle channel*
● *Inner channel*

Analytical methods

Rhodamine WT was measured with a fluorimeter (Jenway 6200) which had been calibrated with solutions of the tracer in final effluent. The highest standard used was 52 µg/l. DO was measured using a fast response WTW Oxi 330 meter and A325 probe calibrated at 0% saturation using a Na_2SO_3 solution and 100% saturation in air before use. At the end of the surveys, the probe was checked for accuracy by leaving it in air and reading the final measurement.

All other determinands were measured at the Lingley Mere Laboratory operated by North West Water Ltd., UK.

Results and discussion

Tracer studies

The raw data for one of the tracer studies of Orbal 1 are shown in Fig. 2. It can be seen that the outer channel outlet has a well-defined set of peaks and troughs for the first 2 h of the studies. A similar pattern has been observed in a Carrousel plant (Rachwal et al., 1983). This may be attributed to the flow patterns within the Orbal channel. Although no plume of dye was visible, it is likely that the feed fluid made approximately 1.33 laps of the channel before becoming sufficiently laterally dispersed to be detected at the outlet. This readily explains the absence of a peak in the concentration/time curve or **C**-curve before 15 min. Thereafter, a decaying set of peaks was observed with a period of between 7 and 12 min. This range of periodicity is consistent with a mean period of approximately 10 min and the shifting of the relative position of the peak occurs as a consequence of axial dispersion, the through flow of the channel being responsible for the decay. This pattern of flow is in line with published data about the hydraulic characteristics of oxidation ditches (Johnstone et al., 1983).

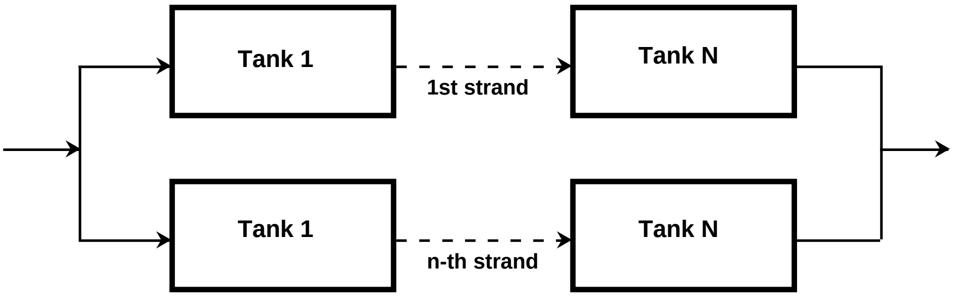

Figure 3
Schematic diagram showing the mult-strand concept of the Martin method

It can be seen from Fig. 2 that the middle and inner channel sampling points did not exhibit the same fluctuating outputs as the outer channel. This is a consequence of the dispersion of the dye as it passed through the outer channel. A tightly defined input pulse is required to discriminate the periodic behaviour of a channel and since the dye entering the inner channels had already partially dispersed during its passage through the upstream channels, such a tightly defined pulse was unavailable.

The method developed by Martin and described previously by Burrows et al. (1999), was used to analyse the tracer results. The method is an extension of the Levenspiel "tanks in series" model for the residence time distribution in a reactor (Levenspiel, 1972), such that the flow can be thought of as entering one of a number of parallel strands of flow through the reactor (Fig. 3). The method uses a special case of the Gamma distribution to allow non-integer numbers of tanks in series to be modelled. The Gamma distribution has three parameters; time, the variance of the RTD curve and the inverse of the RTD variance. The advantage of using more than one strand is that the model can simulate short-circuiting as well as the main flow.

The model shows reasonably close concordance with the eddy diffusion model under closed boundary conditions described by Levenspiel (1972). This model assumes that axial mixing occurs by way of diffusion and that the diffusion is caused by eddies rather than by Brownian movement. It also assumes that there is no diffusion before the inlet to the tank or downstream of the outlet. This condition is satisfied by the Orbal overall and by the channels individually. The degree of agreement between the two types of model has been discussed by Levenspiel and Bischoff (1963). In view of the process modelling objective, it was decided to employ a two-strand approach to describe the flow through the outer channel rather than a comprehensive analysis of the gradually decaying periodicity of the tracer. The principle peak in the experimental **C**-curve was modelled as a bypass around a CSTR body.

Figure 4 shows an example of the Martin method results plotted with the measured 10 min data and it can be seen that the fit is extremely good. The middle and inner channels are modelled using the output curve from the previous channel as the input curve for the present channel. The results from the Martin method are also summarised in Table 1. They show that the outer channel had two distinct streams of flow, a short-circuiting stream and a main flow stream. These are identified as strands 1 and 2 in Table 1. On 16 June, the short-circuiting flow was characterised as 21.8 CSTR in series, indicating a high degree of plug flow as shown by the raw tracer data's peaks and troughs (Fig. 2). On 18 June, the short-circuiting stream was 5 CSTR in series. This was a flow more dispersed than plug flow, but it was not completely mixed like the main body of the flow which was characterised by 1 CSTR for both studies. The reason for these differences is probably flow-related. On 16 June, the mean total flow (settled sewage plus RAS) into the unit was 71.2 Ml/d whereas, on 18 June it was 87.2 Ml/d. The

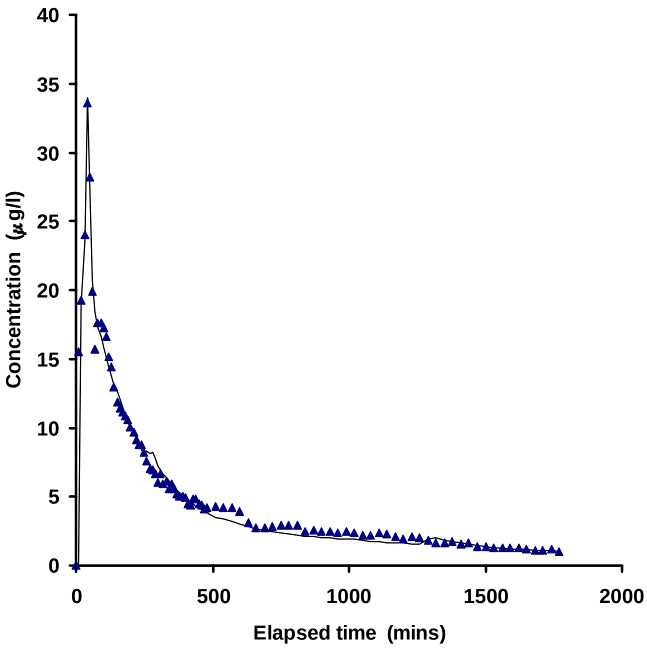

Figure 4
A comparison of the modelled tracer concentrations and the actual values obtained in the study on 16 June 1997

TABLE 1
Results from the Martin Method of analysing the tracer study results

Study	No of CSTR in series	Residence time (min)	
		Modelled	Theoretical
16 June 1997			
Outer - Strand 1	21.8	32	-
Outer - Strand 2	1.0	217	237
Middle	1.1	160	160
Inner	1.6	70	83.5
18 June 1997			
Outer - Strand 1	5.0	18	-
Outer - Strand 2	1.0	311	193
Middle	1.0	148	131
Inner	2.3	73	68

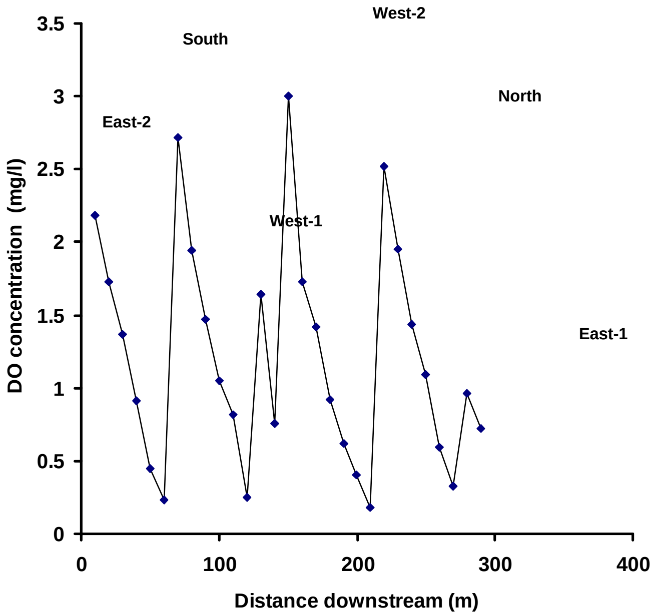

Figure 5
Dissolved oxygen survey in May 1998

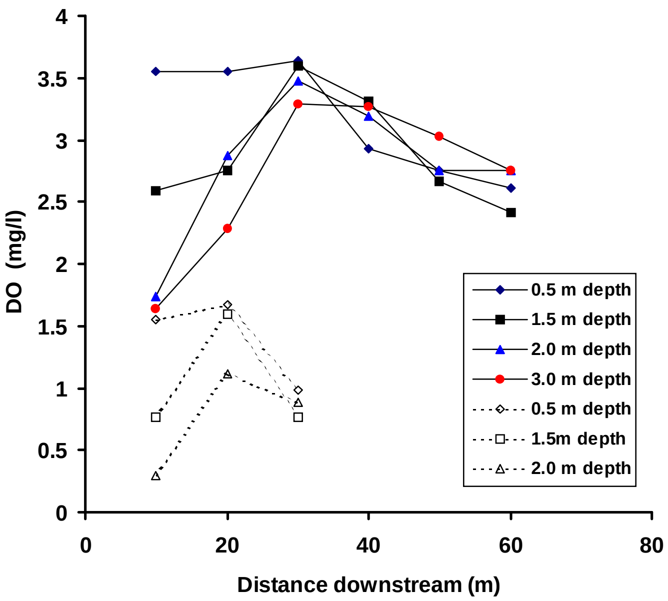

Figure 6
Dissolved oxygen concentrations downstream of aerator East-2 in May 1998 (dotted line) and downstream of aerator North in October 1998 (full line)

middle channel was characterised as a single CSTR whilst the inner channel could be averaged as 2 CSTR in series. This still indicated that the flow was fairly well-mixed and that the contents were dispersed. A comparison of the modelled retention times with the theoretical values based on mean daily flow and channel volume showed (Table 1) that, apart from the data for the outer channel on 18 June, there was a reasonable agreement between the two figures.

The results of these tracer studies may be compared with the way in which Daigger and Littleton (1999) configured an Orbal system for use with the IAWQ ASM1 model. They simulated the outer channel as 6 CSTR in series and both the middle and the inner channels as individual completely mixed cells.

Dissolved oxygen survey

The results from one of the DO surveys in May 1998 are shown in Fig. 5. DO was measured approximately 100 mm below the surface every 10 m downstream of the centreline of one of the aerators (East-2). The peak concentrations, seen after each of the aerators, died away to below 0.5 mg/l immediately upstream of the next aerator where the flow was well mixed. This would have led to anoxic zones where denitrification could have occurred.

The DO concentration with depth was examined at 10, 20 and 30 m downstream of the aerator East-2. The results (Fig. 6) showed that the DO concentration 10m downstream of the aerator decreased quite appreciably with depth, so that the lower part of the channel at this point was verging on being anoxic. At the point 20 m downstream, this decrease with depth was much less marked, and at 30 m downstream, there was little or no variation. It is suggested, therefore, that the majority of the DO added by the aerators is in the first 1 m depth, due to the maximum depth of immersion for the aerators being 0.525 m. Some of this flow will be deflected downwards by the baffles downstream of the aerators, and the DO concentration gradient formed will lead to a downward movement of DO which will stabilise the oxygen concentration beyond the 10 m sampling point.

The results from the October 1998 survey (Fig. 6) show a similar pattern but without any anoxic zones along the outer wall of the the outer channel. However, the flow in October was approximately twice that of May and, therefore, it could be expected that the pollutant load would be more dilute and have a lower DO requirement. However, denitrification did occur at this time and, although no anoxic zones were detected along the outer wall, it is possible that there were such zones elsewhere in the channel, which had a width of 12.45m, due to the complex flow patterns. There are also likely to have been anoxic parts within the centre of the activated sludge flocs.

Taken overall, it is suggested that there are three types of flow within the Orbal channels, all of which contribute to the complex DO patterns observed. The longitudinal flow creates a DO gradient on the surface of 0.2 to 0.3 mg/l.m just downstream of an aerator, and 0.02 mg/l.m just upstream of an aerator, as seen from the data collected in May 1998. The flow has a vertical component near to the aerators, associated with the velocity baffles, and there is likely to be a transverse flow caused by the shape of the Orbal channels. The results of the tracer studies also provide evidence of the transverse and vertical mixing. As stated earlier, there was no tracer peak at the outlet from the outer channel for the first 15 min of the study and it was suggested that this was due to a plume of tracer flowing initially along the outside wall of the channel, and not being mixed immediately with the main body of liquid in the channel.

Studies at other Orbal plants, however, have shown that the DO distribution was generally quite uniform throughout a channel with regard to vertical, horizontal and transverse planes. Elevated concentrations were found immediately downstream of aerators, but these were quickly dispersed by the mixing characteristics of the channel (Envirex, personal communication). Applegate *et al.* (1980) also reported that the DO concentration in each channel was, essentially, uniform except in the zones at the surface immediately downstream of aerators. Without detailed knowledge of the hydraulic configuration of these Orbal channels, it is not possible to understand why the DO distributions are different from those at Preston.

Conclusions

From the point of view of modelling and the data presented above, it can be seen that the complexity of the DO concentrations in the outer channel of the Orbal systems is not easily reconciled with the results of the tracer studies. The latter show that there is a minor, plug flow, short-circuiting stream and a large completely mixed flow. The DO measurements show that there was an appreciable stratification along the outer wall. It was decided that the best way of reconciling these was to simulate the outer channel as two tanks in series, the first being anoxic with no DO input and the other with a residual DO concentration of 0.5 mg/l. The other two channels were each configured as a single completely mixed tank.

Acknowledgements

This work has been supported by an EPSRC studentship (LJB). The authors would also like to acknowledge the financial help and encouragement given by the Technology Development Team of North West Water Ltd., UK.

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