UNDERSTANDING OXIDATION PONDS. IS DISSOLVED OXYGEN PROFILING THE KEY?

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ABSTRACT

Three-dimensional dissolved oxygen (DO) profiling was undertaken at several Oxidation Pond-based wastewater treatment plants (WwTPs) throughout New Zealand. This profiling identified that significant variations in DO can occur within an Oxidation Pond. These variations are not limited to the diurnal variations commonly reported, but can also include significant variations through both the vertical and horizontal profiles. In some ponds profiled, the aerobic layer was restricted to the surface layers, while other ponds remained aerobic throughout the vertical profile. These findings have implications for Oxidation Pond efficacy, with the rate of removal of both BOD and ammonia being influenced by oxygen availability.

The results of three-dimensional profiling undertaken at two of these WwTPs are presented in this paper. This paper also discusses the implications of these measured vertical and horizontal variations in DO, not only with respect to performance, but also as a potential tool to understand when sludge accumulation may be impacting on pond performance.

KEYWORDS

Waste Stabilisation Pond, WSP, Oxidation Pond, dissolved oxygen, DO, profiling, oxypause

1 INTRODUCTION

Oxidation Ponds, or Waste Stabilisation Ponds (WSPs) in todayôs parlance, are widespread, both in New Zealand and overseas, well-researched, but in many ways still poorly understood. Archer (2015) estimated there are approximately 200 WSPôs in use in New Zealand. As the industry and ratepayers place increased focus on environmental sustainability, we are demanding that our wastewater treatment plants (WwTPs) treat wastewater to a higher quality prior to reintegration back into the environment. This has led to a plethora of different upgrade options for WSPs in New Zealand, as described in Ratsey (2016), with variable success.

Engineers have long puzzled over the performance of WSPs, in particular with regard to the removal of ammonia. The most accepted method of predicting ammonia removal through WSPs is that developed by Pano and Middlebrooks (1982). However, as discussed by Archer & OôBrien (2004), Pano and Middlebrooksô models donôt explain the significant ammonia removal achieved in some WSPs in New Zealand, particularly in summer and autumn, suggesting that nitrification and denitrification are major mechanisms for ammonia removal at some WSP-based WwTPs. Undoubtedly factors such as temperature and overall hydraulic retention time (HRT) will influence nitrification, but these donôt appear to fully explain the observed variation in performance.

The most common type of WSP is the facultative pond. In a facultative pond, the upper layers are aerobic, while the bottom sludge layer is anaerobic. In between the aerobic and anaerobic layers is a facultative zone. Facultative bacteria can function under either aerobic or anaerobic conditions.

Many texts refer to diurnal and seasonal variations in dissolved oxygen (DO) in WSPs (e.g. Spellman & Drinan, 2014; USEPA, 2011; Mara, 2003), but little consideration is generally given to horizontal and vertical variations in DO, and how this might impact on WSP performance. Given the majority of dissolved contaminant removal is achieved in the aerobic portion of a WSP, the effective volume and HRT of the aerobic fraction of the pond may be instrumental in determining treatment efficacy.

DO concentrations in WSPs are typically measured at the surface in the same locations, irrespective of whether measurements are taken using portable hand-held probes or on-line instruments. This effectively makes an assumption that the DO measured in these locations is representative of DO in other parts of the ponds. This paper explores this assumption, and the relevance with respect to treatment efficacy.

2 OXIDATION PONDS

2.1 TREATMENT FUNDAMENTALS

There are a variety of treatment mechanisms in play in a conventional WSP, as shown in Figure 1. Heavy suspended solids settle out to form a sludge layer, with a portion of the organic sludge broken down through anaerobic digestion. Dissolved contaminants are mainly broken down by aerobic bacteria, converting substances such as biochemical oxygen demand (BOD) to carbon dioxide (CO_2) and water (H_2O), and potentially ammonia (NH_3) to nitrite (NO_2), nitrate (NO_3) and nitrogen gas (N_2) if conditions allow.

Oxygen for the aerobic bacteria is provided through a variety of mechanisms, with the most significant being the symbiotic relationship between algae and bacteria. During daylight hours, algae photosynthesise, releasing oxygen to the extent that super-saturation can occur. This provides an oxygen-rich environment in the upper layers of a WSP. Aerobic organisms consume oxygen, both to break down contaminants in the wastewater and for normal cell maintenance, releasing CO_2 which, in turn, algae use during photosynthesis. This photosynthesis results in diurnal variations in both DO and pH, with higher concentrations of both during the day, and lower concentrations overnight. Longer sunlight hours and warmer temperatures during summer mean daytime DO concentrations may rise higher, and stay high for longer, than they would during winter. This increases the treatment capacity of WSPs during warmer temperatures, which is the basis for the temperature-based design loadings suggested by Mara (2003).

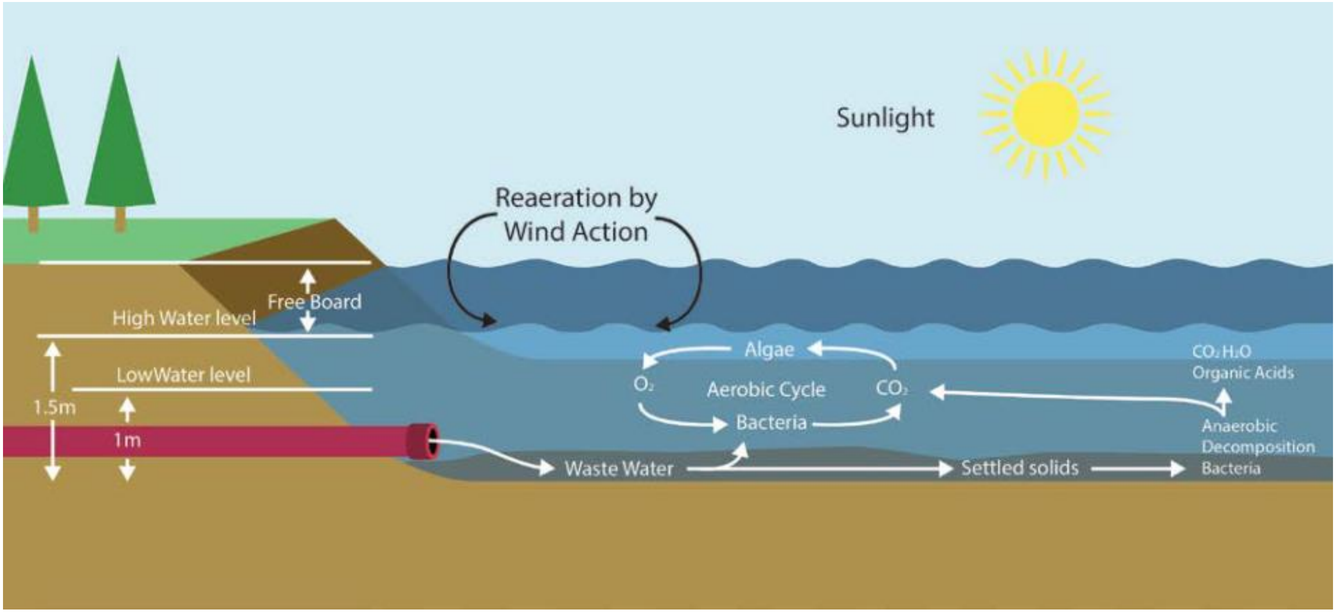

Figure 1: Treatment Processes in a WSP (WaterNZ, 2017)

2.2 VARIATIONS IN DO

The diurnal variation in DO in WSPs, shown in Figure 2, is well documented. During daylight hours, algae photosynthesise, releasing DO. During the night, aerobic organisms consume oxygen, resulting in a marked reduction in DO concentrations.

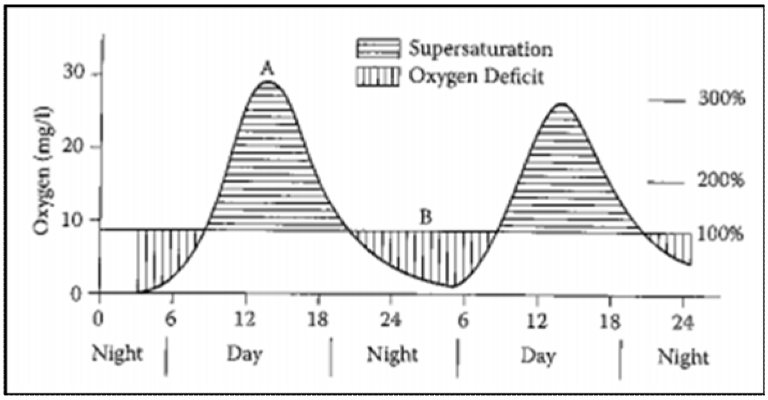

Figure 2: Diurnal DO curve (From Spellman & Drinan, 2014)

However, while most texts relating to WSPs refer to this typical diurnal variation in DO, few comment on whereabouts in the pond this DO relates to, what DO may be in other parts of the pond, or how variations in DO may impact on WSP performance. Both Mara (2003) and von Sperling (2007) do briefly discuss the subject, suggesting the typical diurnal variation relates to DO concentrations in the surface layers, with less DO variation at depth. An example of this is shown in Figure 3.

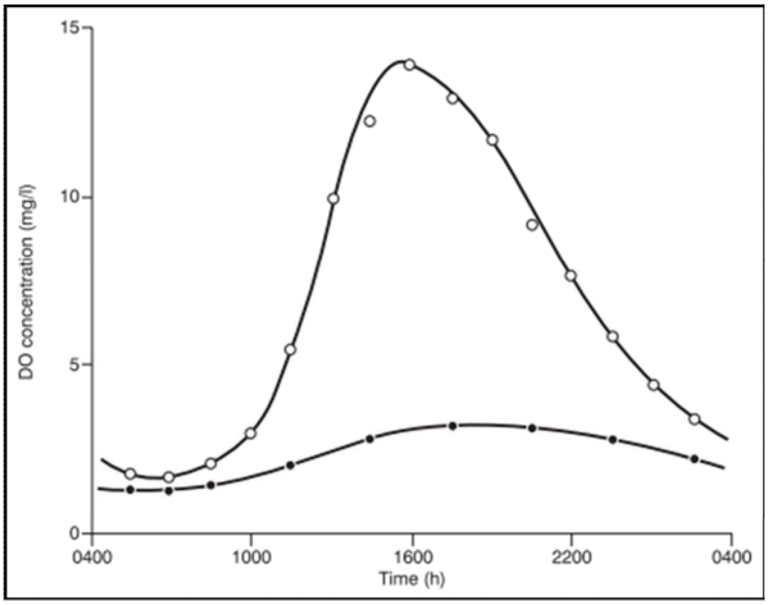

Figure 3: Diurnal variation of DO in a WSP; ○ top 200mm and ● 800mm below surface (From Mara, 2003)

Close to the surface where photosynthetic activity is highest, the amount of oxygen supplied exceeds the oxygen demand. Moving down through the profile, oxygen demand increases due to the release of dissolved contaminants from the anaerobic sludge layer, while oxygen supply falls. The point at which oxygen supply equals oxygen consumption, shown in Figure 4, is referred to as the oxypause.

The location of the oxypause in the vertical profile will vary diurnally and seasonally due to fluctuations in the rate of both oxygen production and consumption. Spellman & Drinan (2014) comment that a WSP may be aerobic through the entire depth if lightly loaded, therefore an oxypause may not be present in all WSPs.

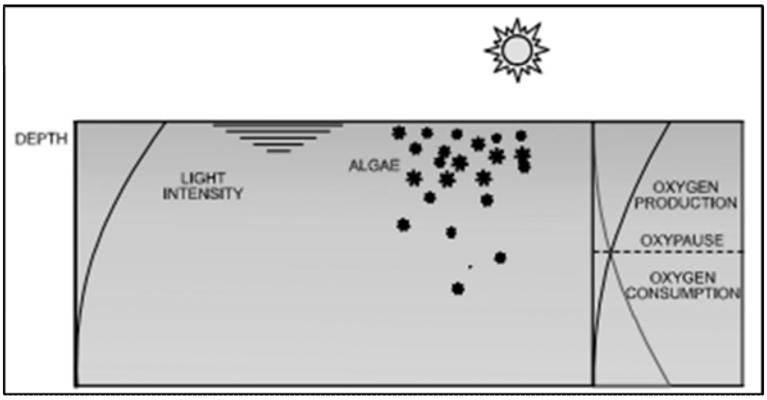

Figure 4: Algae, light energy and oxygen as a function of depth (From von Sperling, 2007)

Authoritative texts on WSPs generally do not discuss how the depth of the oxypause may impact on WwTP performance. However, given the primary mechanism for removal of soluble BOD is breakdown by aerobic heterotrophic bacteria, the location of the oxypause, and DO concentrations both above and below the oxypause, will undoubtedly have some impact on treatment efficacy.

2.3 BOD REMOVAL

The primary design intention of WSPs is usually for the removal of BOD, total suspended solids (TSS) and indicator organisms such as faecal coliforms (FC) and *Escherichia coli* (*E. coli*). The removal of BOD through WSPs follows first-order kinetics, and is therefore a function of temperature and HRT. According to von Sperling (2007), the soluble BOD (sBOD) concentration in WSP effluent can be predicted using Equations 1 (for plug flow) and 2 (for complete mix).

Equation 1:
$$S = S_0 e^{-K_T.t}$$

Equation 2:
$$S = \frac{S_0}{1 + K_T.t}$$

Where:

S_0 = total influent BOD concentration, g/m^3

S = effluent sBOD concentration, g/m^3

K_T = BOD removal coefficient at Temperature T, d^{-1}

t = HRT, d

K_T can be adjusted for temperature from Equation 3:

Equation 3:
$$K_T = K_{20}.\theta^{(T-20)}$$

Where:

K_{20} = BOD removal coefficient at 20°C, d^{-1}, with Mara (2003) suggesting 0.3 d^{-1} for primary facultative ponds, and 0.1 d^{-1} for maturation ponds.

θ = temperature coefficient, typically between 1.05 and 1.085.

Using von Sperlingés equations, the predicted sBOD concentration in effluent from a single facultative WSP operating under both plug flow and complete mix is shown in Figure 5, indicating that more rapid sBOD removal can be achieved by following a plug flow regime. It should be noted, however, that operating under a plug flow regime may cause operational issues such as odour due to the effective high loading at the pond inlet, unless this is effectively mitigated.

The effective BOD removal coefficient, K_T, will be influenced by conditions in the pond. Aerobic treatment processes occur more rapidly than anaerobic processes, therefore if a WSP is aerobic through the majority of its depth, it can be expected that K_T would be higher than in a pond containing low DO at depth. Therefore, while the total HRT will influence performance, it is likely to be the HRT through the aerobic portion of the pond which is of greater importance with regard to treatment efficacy.

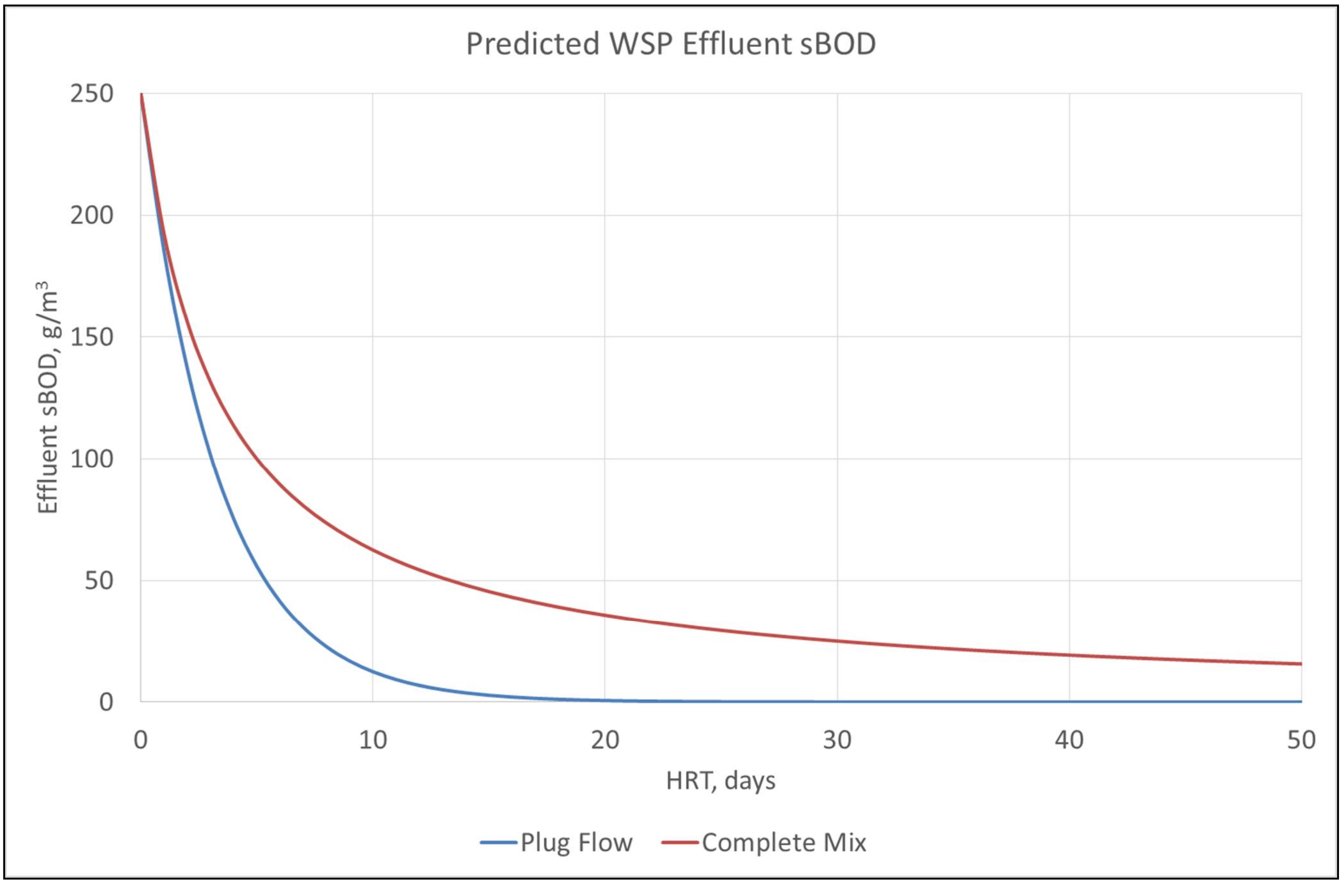

Figure 5: Predicted WSP Effluent sBOD (Temperature 20°C, K_{20} 0.3 d^{-1})

2.4 NITROGEN REMOVAL

The mechanisms for removal of nitrogen through oxidation ponds are poorly understood. Crites *et al*. (2014) suggest that removal mechanisms may include algae uptake, sludge deposition, adsorption to bottom solids, nitrification, denitrification, and volatilisation. Internationally recognised literature generally suggest that volatilisation may be the most important removal mechanism, with models to predict nitrogen removal including that suggested by Pano & Middlebrooks (1982). However, an evaluation of nitrogen removal through oxidation ponds in New Zealand suggests that these volatilisation-based models provide a poor estimate of the performance of ponds under NZ conditions, with Archer & O'Brien (2004) suggesting that nitrification and denitrification are the main nitrogen removal mechanisms in oxidation ponds in NZ.

Nitrogen removal through algae uptake and volatilisation is insufficient to achieve the lower effluent total nitrogen (TN) concentrations required by many newer resource consents in New Zealand. Incorporating nitrogen into algal biomass does not remove the nitrogen from the treated effluent, unless the algae is removed prior to discharge. Removal of algae from WSP effluent through processes such as membrane filtration, sand filtration and dissolved air flotation (DAF) is possible, but effluent generally still contains appreciable concentrations of soluble nitrogen. In addition, handling of the algae-rich waste stream poses its own challenges. At typical pond temperature and pH, ammonia removal through volatilisation is limited.

Therefore, to achieve low (<5 g/m^3) concentrations of ammonia in effluent from WSPs, nitrification is required. Heterotrophic bacteria, which break down BOD under aerobic conditions, utilise oxygen more rapidly, and grow more quickly, than nitrifying bacteria. Therefore, the majority of sBOD must be broken down before nitrification will occur. For fixed film processes, nitrification rates are inhibited at sBOD concentrations >10 g/m^3 (Metcalf & Eddy, 2003). It is also known that nitrification rates increase up to DO concentrations of 3 or 4 g/m^3 (Metcalf & Eddy, 2003). Therefore, minimising sBOD concentrations, and maximising DO concentrations, will increase the nitrification potential of a WSP. Okan & Nagels (2017) reported increased nitrification resulting from installation of mechanical aeration in a two-pond WSP.

If nitrification is achieved in a facultative WSP, denitrification is usually rapid. The typically low DO concentrations in the lower depths of a WSP encourage denitrification. As a result, effluent from a conventional facultative WSP generally contains minimal nitrate and nitrite, irrespective of whether nitrification occurs. It should, however, be noted that effluent from WSPs modified to encourage nitrification, for example using processes such as AquaMats and Bio-shells, may contain elevated nitrate concentrations due to more consistent DO concentrations through the vertical profile.

As well as providing environmental conditions which are suitable for nitrification (low sBOD, high DO, appropriate pH), it is also necessary to maintain a population of nitrifying bacteria to achieve nitrification. Nitrifying bacteria are relatively slow growing, and their reproductive rates reduce further in cold temperatures. Below a temperature of about 5 ^{o}C, the activity of nitrifying bacteria stops (Metcalf & Eddy, 2003). In suspended growth processes such as activated sludge, biomass from the end of the treatment process is returned to the front as return activated sludge (RAS). As a result the ñsludge ageò is greater than the HRT, which allows a population of nitrifying bacteria to be developed and maintained. In fixed growth processes such as trickling filters, a nitrifying bacteria can establish on the filter media if the BOD loading is low. In effect, these fixed-film processes allow a long-sludge age biomass to develop on the media. Similarly, modifications to WSPs, such as AquaMats and Bio-shells, provide a surface for nitrifying bacteria to grow on, and can increase nitrification potential providing favourable conditions are maintained.

In a conventional facultative WSP, there is no clear differentiation between HRT and sludge age. In general, a WSP is a flow through process, therefore the sludge age and HRT are the same. In reality, if high DO concentrations can be maintained in areas of the pond where biomass could grow either in suspension or on a surface, for example on pond embankments, baffle curtains, or even on the surface of the sludge layer, it may be possible for a WSP to operate at a ñsludge ageò which is greater than the HRT, therefore increasing nitrification potential.

2.5 SLUDGE ACCUMULATION

The anaerobic breakdown of sludge at the bottom of a WSP releases contaminants back into solution, including BOD, nitrogen in the form of ammonia, and phosphorous in the form of dissolved reactive phosphorous (DRP). This release of contaminants increases the demand for oxygen above the sludge layer and, along with oxygen supply, will influence at what depth the oxypause occurs in any WSP. Therefore, the greater the rate of sludge breakdown from accumulated sludge, the smaller the volume of the pond available for aerobic treatment is likely to be. This will impact on potential treatment capacity.

There is little guidance in the literature regarding how much sludge is too much in a WSP, and when ponds should be desludged. Where guidelines on sludge removal are provided, they tend to be vague, inconsistent, and not based on any clear rationale. For example:

> ñeventually the digested solids (the ósludgeô) have to be removed, but this is necessary only infrequentlyé ò (Mara, 2003)
>
> ñultimately, removal of sludge from the bottom of the pond cells will be necessaryò (Spellman & Drinan, 2014)
>
> ñthere should be at least 0.9m of aerobic water depth above any sludge layeré ò (WaterNZ, 2017),

ñthe sludge should be removed when the layer reaches a thickness that can be affected by the aerators, or when the net pond volume is substantially reduced (usually when the sludge reaches 1/3 of the pond depthò (von Sperling, 2007).

The reality is sludge accumulation can have a large impact on WSP performance, particularly if nitrification is desired. This will be due to the impact of sludge on HRT, and the increased oxygen demand exerted by contaminants released from the sludge layer by anaerobic digestion. An example of this is the Waihi WwTP, which comprises two facultative WSPs in series. Historically, the Waihi WwTP achieved excellent ammonia removal, both during summer and winter, as shown in Figure 6. In 2006, a DAF was installed to remove algal solids from the effluent prior to discharge to the Ohinemuri River, with the resulting algal sludge returned to the primary facultative pond. Over time, this sludge accumulation has impacted on ammonia removal through the WwTP to the point that full ammonia removal is not now achieved even in summer. This is shown in Figure 6.

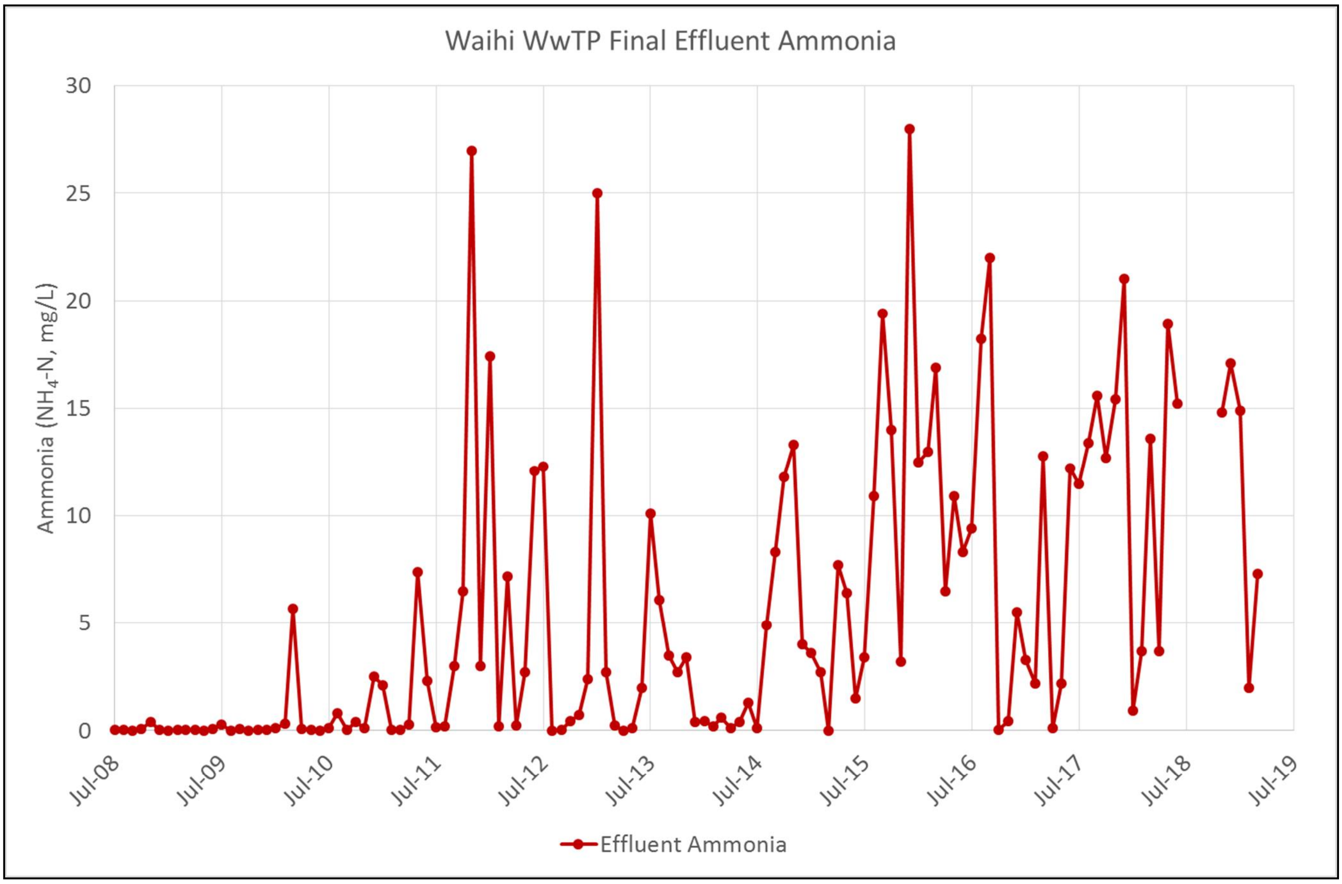

Figure 6: Waihi WwTP Effluent Ammonia

3 INVESTIGATIONS

3.1 METHODS

Three-dimensional DO surveys were undertaken at several WSP-based WwTPs in 2018 and 2019. The majority of these profiles were undertaken in the morning, typically between 08:00 and 10:00. Hand-held DO probes were lowered from the side of a boat, with DO measurements taken at three depths; upper, mid-depth, and lower.

3.2 TREATMENT PLANTS

The results of DO profiling undertaken at two WwTPs, Matamata and Huntly, are presented in this paper. The results of DO surveys undertaken at these two WwTPs are compared due to the following similarities:

- Both WwTPs treat primarily domestic wastewater, with a similar connected population.
- Both are large WSP systems (for New Zealand), each with a total surface area of approximately 10 hectares across primary and secondary ponds.
- Both have mechanical aeration in the primary facultative pond to supply additional DO and aid mixing.
- Both have baffle curtains installed in the primary facultative pond to reduce short-circuiting, each stretching approximately three-quarters of the way along the length of the ponds. The location of these baffle curtains can be seen in Figures 7 and 9.

While there are similarities between the two WwTPs, there are also some key differences, including:

- AquaMats in Pond 2 at the Matamata WwTP, with diffused aeration, designed to enhance ammonia removal during winter.
- Tertiary treatment in the form of membrane filtration at the Matamata WwTP, with the reject flow from the membrane filtration unit (MFU) returned to the primary facultative pond. This accelerates sludge accumulation at this WwTP.

3.3 RESULTS

The results of two DO profilings undertaken at the Matamata and Huntly WwTPs are summarised graphically in Figures 7 and 9 respectively, along with the results of a sludge survey undertaken at Matamata WwTP (Figure 8; Parklink, 2018). These results show:

- At Matamata WwTP, aerobic conditions were limited to the top layer of the primary facultative pond. Below the surface layer, conditions were anoxic or even anaerobic. This shows the oxypause was close to the surface of this pond.
- At Huntly WwTP, high DO concentrations were achieved at both upper and mid-depths, and aerobic conditions were even maintained at depth. This indicates the oxypause was close to the bottom of the pond.
- In the second, AquaMats, pond at Matamata WwTP, DO was distributed relatively evenly through the vertical profile of the portion of the pond containing diffused aeration, as would be expected given the mixing provided by this diffused aeration.

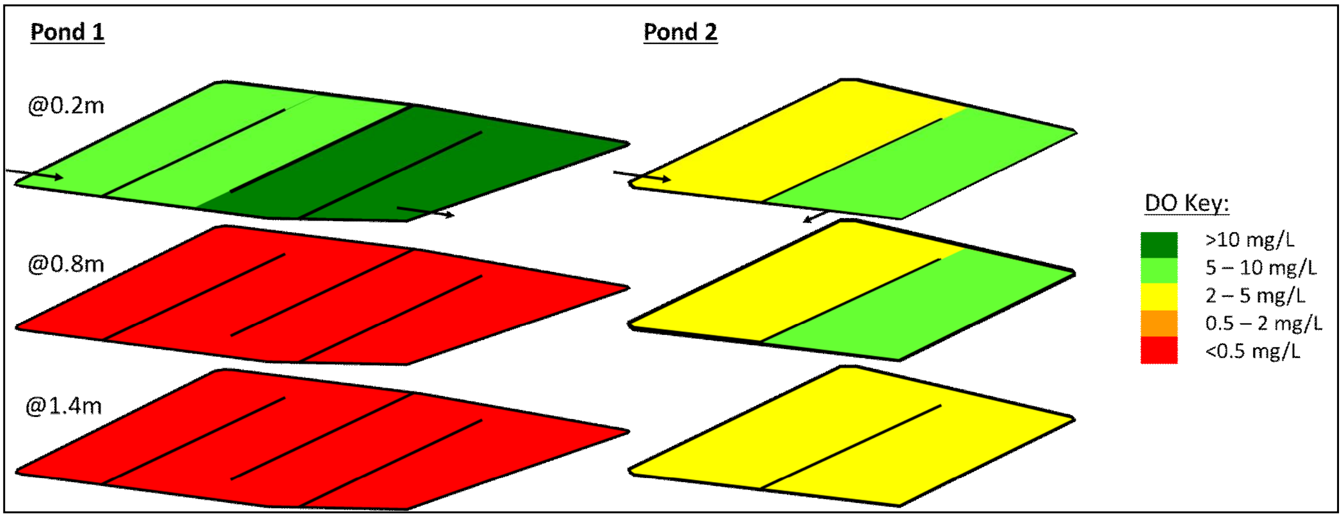

Figure 7: DO profiling at Matamata WwTP, December 2018

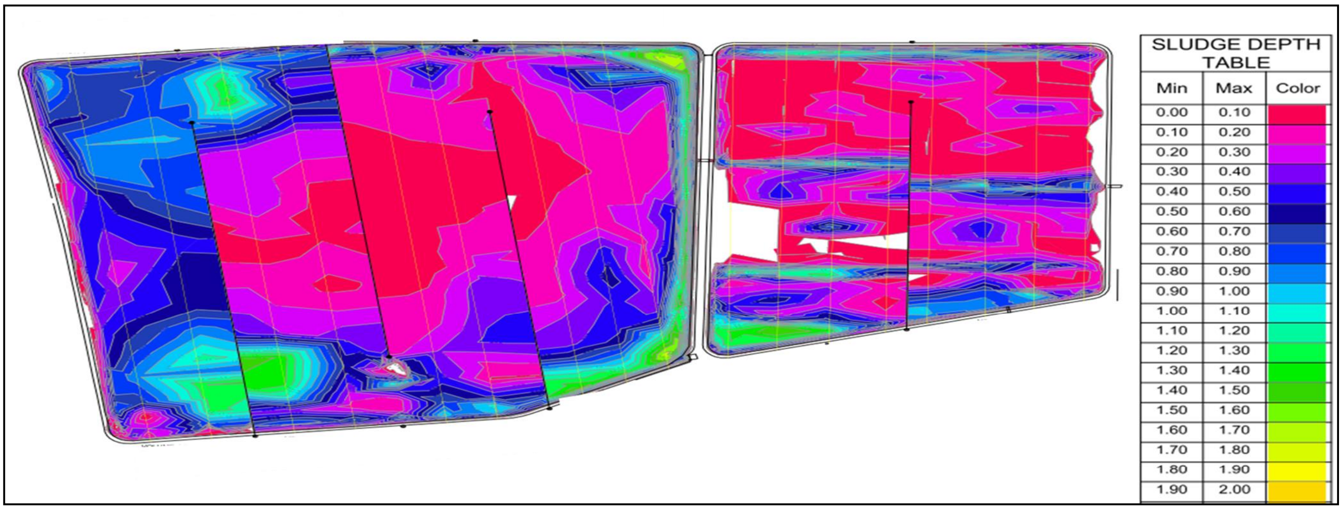

Figure 8: Sludge Survey at Matamata WwTP, November 2018

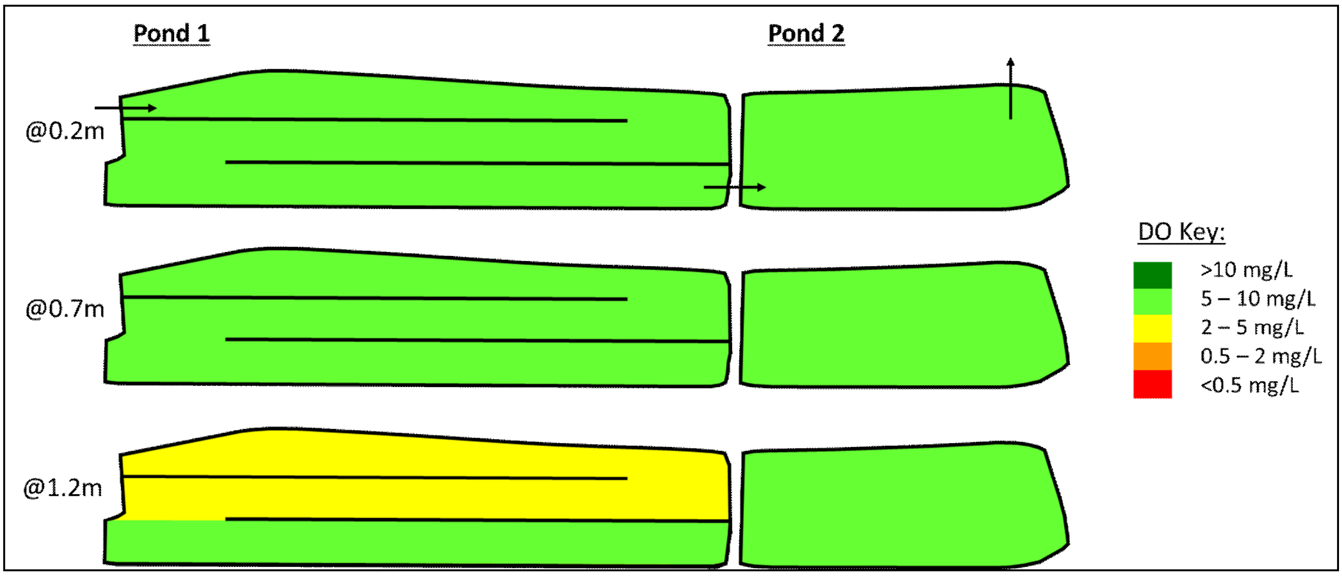

Figure 9: DO profiling at Huntly WwTP, June 2018

However, localised variations in surface DO concentrations in the AquaMats pond at Matamata WwTP are evident when the data is evaluated more closely, as shown in Figure 10. While lower oxygen demand at the end of the pond may contribute to this horizontal variation, increased algal photosynthesis in quiescent zones is considered likely to be the dominant factor because similar variations were also measured at other locations.

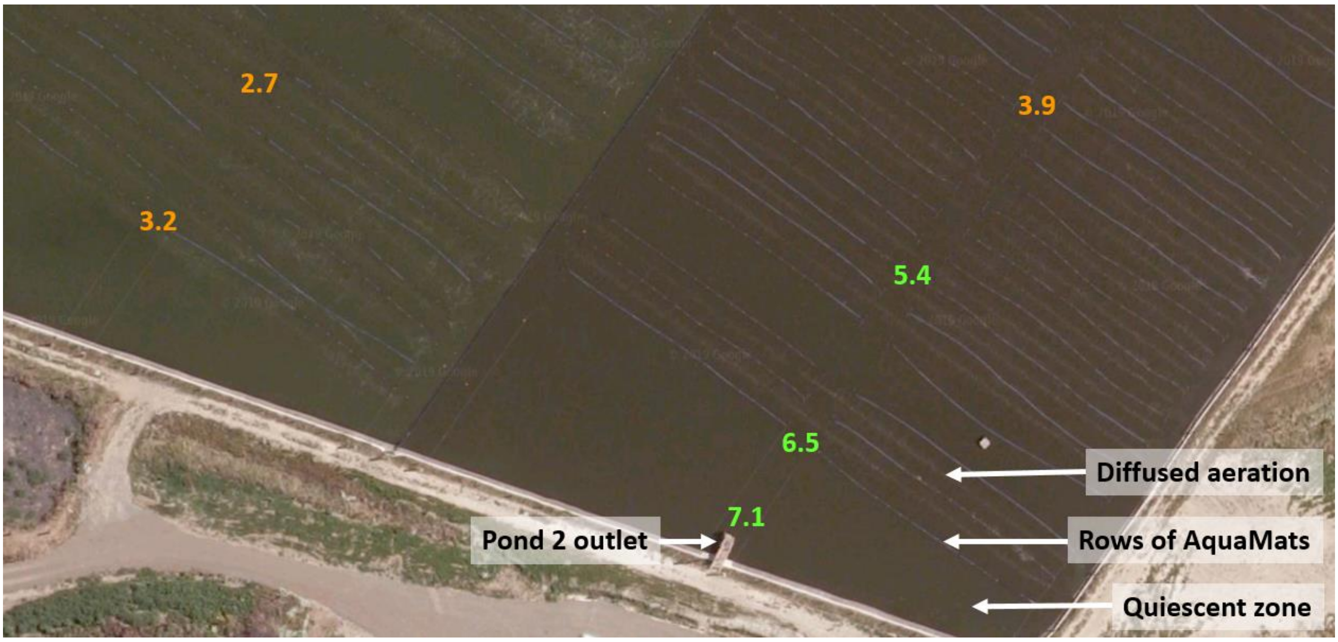

Figure 10: Surface DO (mg/L) at Matamata WwTP, April 2019

4 DISCUSSION

The results of DO profiling undertaken on several WSP-based WwTPs throughout New Zealand has confirmed that DO concentrations in WSPs vary, not only diurnally, but also vertically through the pond depth. Furthermore, horizontal variations in surface DO were also measured in some of the ponds profiled. This has significant implications with regard to understanding WSP health, and, potentially, also on WSP performance.

At a very simplistic level, vertical and horizontal variations in DO mean that measured DO concentrations are not necessarily representative of actual DO concentrations through the bulk of a pond. Measuring DO at, or close to, the surface of a facultative pond will often provide a ñfalse highò DO concentration. This is due to algal photosynthesis being at its most intense close to the surface. Therefore, manual or on-line DO measurements showing a normal diurnal DO trend at the surface may mask underlying issues. Similarly, where manual or on-line DO measurements are taken in areas unrepresentative of the bulk of the pond, for example in a quiescent area of a pond that is otherwise well mixed, the results can be misleading. This could adversely affect pond performance if on-line DO results are used for control of supplementary mechanical aeration. At the Matamata WwTP, DO concentrations measured by the DO probe located in the quiescent zone of the modified pond, shown in Figure 11, are heavily influenced by algal photosynthesis, whereas DO concentrations in the AquaMats zone are not. The more consistent DO concentrations in the AquaMats zone are due to the vertical mixing provided by the diffused aeration.

With the information currently available, it is not possible to understand the full effects of these vertical and horizontal variations in DO concentration on WSP performance, and this is an area that requires further research. However, when considering the mechanisms for removal of BOD and ammonia through a WSP, it is evident that such variations in DO will almost certainly have some impact on treatment performance.

BOD removal through a WSP follows first-order kinetics. This means that the higher the initial BOD concentration, the more rapidly the concentration of BOD will fall in absolute terms. It also means that the higher the first-order rate constant is, the quicker BOD removal will occur. Therefore, if the first-order rate constant can be increased, so the removal of BOD can be expected to occur more rapidly. It is well understood that biodegradation of BOD occurs much more rapidly under aerobic conditions than anaerobic conditions, so it stands to reason that a WSP with good DO through the whole of the pond depth would remove BOD more rapidly than a

WSP in which aerobic conditions are limited to the surface layers. i.e. the first-order rate constant, K, will be higher in a fully aerobic WSP compared to a WSP with low DO at depth.

Figure 11: Location of DO Probe in Quiescent Zone at Matamata WwTP

It is well known that, for biological nitrification to occur, the majority of soluble BOD must be consumed first. This is because heterotrophic bacteria grow faster, and consume oxygen more quickly, than the autotrophic bacteria responsible for nitrification. Therefore, the more quickly BOD removal can be achieved, i.e. by maximising the first-order rate constant, K, the greater the potential for also achieving nitrification in a WSP.

It is also well known that nitrification can occur more rapidly at higher DO concentrations, all other things being equal. Therefore, the further the oxypause is from the surface of a WSP, the greater the nitrification potential in the pond will be. Whether this nitrification potential can be realised will, of course, depend on whether an active population of nitrifying bacteria can be maintained. This will be dependent on other factors, such as the HRT in relation to temperature, the resulting growth rate of nitrifying bacteria, and other environmental conditions, such as pH, which can also impact on nitrification.

Results from DO profiling undertaken as part of these investigations suggest that the depth at which the oxypause occurs in a WSP may be influenced by the depth of sludge and/or the level of anaerobic activity in the sludge layer. This is to be expected given the oxypause is the depth at which the rate of oxygen supply, mainly by algal activity in a traditional facultative WSP, equals the rate of oxygen uptake. Therefore, the faster contaminants are released into solution from anaerobic breakdown of the sludge layer, the lower the first-order rate constant for BOD removal is likely to be, and the less the nitrification potential will be as a result. At the Matamata WwTP, where there is a significant accumulation of sludge in the primary facultative pond, the oxypause is close to the surface, therefore a relatively small part of the available treatment volume is aerobic. The primary facultative pond at Huntly WwTP contains much less sludge, and the oxypause is located close to the sludge. As a result, a much greater proportion of pond volume is available for aerobic wastewater treatment.

5 CONCLUSIONS

This research has determined that measurements of DO on the surface of WSPs may not be representative of oxygen availability in the pond. Surface layers of WSPs normally contain elevated DO concentrations due to algal activity, and measurement of DO at the surface could mask underlying oxygen deficiency. In addition, the position in a WSP at which DO is monitored also needs careful consideration. The surface DO concentration in quiescent zones is more heavily influenced by algal activity than in areas with good mixing.

The location of the oxypause through the vertical profile can vary significantly. This variation appears to be influenced not only by diurnal and seasonal factors, but also by sludge accumulation. If the impact of sludge on the oxypause can be better understood, this may provide a valuable tool for determining when a WSP requires desludging.

This paper has identified areas in which further research may provide invaluable results. We believe these areas of research should include:

- Determining how the first-order rate constant for BOD removal in a primary facultative pond may vary depending on the bulk DO concentration in the pond.

- Investigating the impact of the sludge layer on the first-order rate constant for BOD removal.

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