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# Oxygen Mass Balance Analysis in an Intermittently Aerated Wetland Receiving Stormwater from Livestock Farms

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# 축산유역 강우유출수 처리를 위한 간헐 포기식 인공습지에서 산소수지분석

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## Abstract

In order to assess the role of aeration in stormwater wetlands, oxygen supply and consumption in a wetland treating runoff from livestock farms were estimated and analyzed. Furthermore, oxygen mass balance was conducted during day time and night time. Internal production by algal photosynthesis dominated the oxygen production particularly in the shallow marsh due to the large amount of algae. Consequently, algal respiration was also the major oxygen depletion element with nitrification and biodegradation estimated as 5.35% and 6.43% of the total oxygen consumption. This excessive portion of oxygen consumption by algae was associated to the highly turbid water caused by the resuspension of sediment particles in the aeration pond, which also affected the subsequent wetland. Moreover, an abundance of oxygen was estimated during the day indicating that oxygen produced by algal activity is sufficient to meet the oxygen demand in the wetland. Thus, supplemental aeration was deemed not necessary at daytime. In contrast, oxygen was greatly depleted at night when algal photosynthesis stopped which induced denitrification. Therefore, it was suggested that supplemental aeration may be operated continuously instead of intermittently to avoid oxygen deficit in the wetland at night or it may be stopped entirely to further enhance denitrification.

Key words : algae, aeration, oxygen balance, stormwater wetlands

## 요 약

축산지역 강우유출수 처리를 위한 간헐 포기식 인공습지에서 산소공급 및 소비량을 산출하여 낮과 밤 동안의 산소수지(oxygen balance)를 분석하였다. 조류의 광합성 활동이 활발한 얕은 습지에서 주간에는 내부 생산되는 산소가 지배적이었다. 또한 조류에 의한 내호흡이 가장 큰 소비원인 것으로 분석되었으며 질산화와 탈질에 의한 소비량은 각각 전체의 약 5.35%와 6.43%인 것으로 분석되었다. 조류에 의한 과도한 양의 산소소비는 포기조작에 의한 침전조류의 재부상에 의해 초래된 것으로 후속 공정에도 지속적으로 영향을 미쳤다. 더욱이 주간에 조류의 광합성 활동에 의해 생산된 풍부한산소량은 습지에서 발생하는 산소요구량을 충족시키기에 충분한 것으로 분석되었다. 따라서 주간에 실시되는 인위적인 포기활동은 불필요한 조작으로 판명되었다. 이와 반면에 광합성 활동이 중단되는 야간에는 조류의 내호흡작용으로 습지내부의 산소농도가 크게 저하하였으며 이는 습지에서 탈질반응을 촉진하는 것으로 추정된다. 따라서 인위적인 포기를 중단해도 유기물질 제거나 질소제거에 큰 영향을 미치지 않을 것으로 판단되며, 야간에 혐기성 상태의 지속으로 악취와 같은 문제가 발생될 수 있으므로 간헐적인 모드로 운전하는 것이 타당할 것으로 판단된다.

핵심용어 : 조류, 포기, 산소수지, 강우유출수 습지

## 1. Introduction

Due to their efficient treatment, low maintenance cost and environment-friendly nature, constructed wetlands been used worldwide to treat various types of wastewater (Werker et al., 2002; Kadlec and Wallace, 2009; Hong et al., 2016). Consequently, various studies have been conducted regarding wetland parameters and their affecting factors to be able to understand the treatment processes and mechanisms and one of these parameters is oxygen. In wetlands, sufficient amount of oxygen is important

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because it plays a very important role in the removal of vital pollutants such as nitrogen and organic matter. In addition, it is essential in maintaining a healthy aquatic environment for the survival and growth of plants, animals and microorganisms.

Oxygen is supplied to treatment wetlands through mechanisms such as phytoplankton(algae) photosynthesis, re-aeration through the interface between water bodies and the atmosphere, wind-driven turbulence and plant-mediated oxygen transfer (Kemp and Boynton, 1980; Cosby et al., 1984; Yao et al., 2011). On the other hand, it is consumed to meet requirements for aerobic biodegradation of organic matters, nitrification, and algal respiration and also for sediment oxygen demand (SOD) which comes from decomposing detritus generated by carbon fixation in the wetland.

Aside from the various pathways for oxygen production and consumption, of equal importance are the factors affecting these mechanisms. These include the limiting factors for wetland processes such as temperature, carbon source, etc. existence of open water zones for oxygen transfer through the air-water interface, and emergent macrophytes to name a few. Kadlec and Wallace (2009) reported that the oxygen transfercoefficienthas considerable uncertainty because this process is slow and based on preliminary estimations for treatment wetlands, oxygen transfer coefficient ranges from 0.1 to 0.4 m/day. Furthermore, photosynthesis in a wetland is influenced easily by sunlight, algal concentration and the shade provided by emergent macrophytes. Hence, the oxygen transferred from the air and produced by photosynthesis can be limited.

Furthermore, stormwater runoff from livestock farms tends to carry high concentrations of nitrogen and organic matter which will require high amounts of oxygen for removal. For example, (Sievers, 1997; Sartoris et al., 2000) reported that nitrification was limited in surface flow constructed wetlands treating livestock wastewater. Therefore, in order to improve pollutant removal efficiency, many wastewater wetlands have been artificially aerated. A study on a similar surface flow treatment wetlands shows that artificial aeration can significantly increase mass reductions of total Kjeldahl-nitrogen (TKN = organic nitrogen + $NH_4$-N) and ammonium nitrogen ($NH_4$-N) (MacPhee 2009). The study of Jamieson et al. (2003) indicates that the continuous aeration has great potential to improve nitrification in constructed wetlands receiving agricultural wastewater.

However, due to the various factors that can affect the amount of oxygen in wetlands and the variations of hydrologic and biochemical conditions from site to site, it is important to conduct a site specific study on the oxygen production and consumption in a single system. Moreover, detailed information about the oxygen balance in a stormwater wetland is limited at present (Dong et al. 2011). Therefore, in order to gain insight, the amount of oxygen supply and consumption in an intermittently aerated stormwater wetland were determined to (i) analyze the oxygen balance during day time and night time and (ii) determine the necessity of artificial aeration in this wetland.

## 2. MATERIALS AND METHODS

### 2.1 Study area and dry day sampling

Oxygen supply and consumption analysis was done in a stormwater wetland in Jeongeup City, Korea. This wetland covers an area of 3083 m$^2$ and treats runoff from agricultural livestock area specifically cow-feeding lots. As shown in Fig. 1, the wetland is composed of a forebay, aeration pond, deep marsh, shallow marsh, and polishing pond. Supplemental oxygen supply is operated intermittently in a 3-hour on 3-hour off cycle. The wetland also includes an internal recycle wherein the water from the shallow marsh is recycled to the aeration pond with a flow rate that is six times the average flow rate in the wetland. Macrophytes which partially cover the wetlands include Phragmites autralis (common reed) in the shallow marsh, *Typha latifolia* (cattail) in the deep marsh, and Nelumbo nucifera (lotus) in the polishing pond.

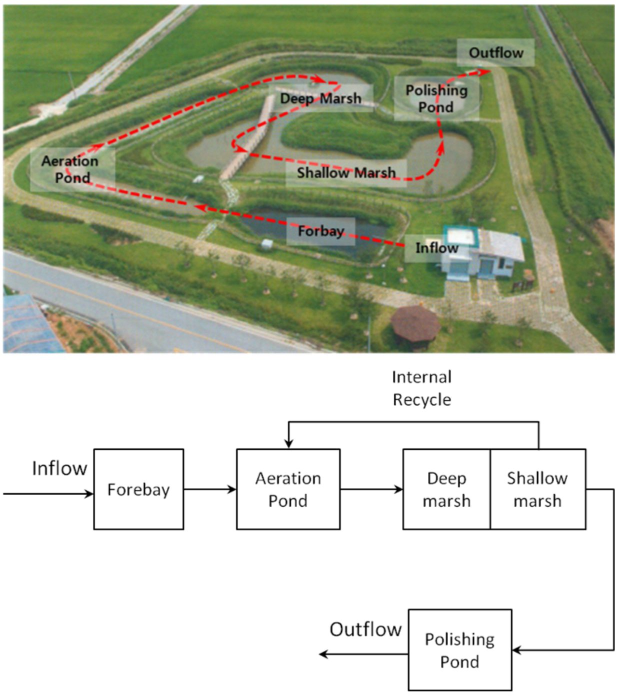


**Fig. 1.** Photo and schematic diagram of the stormwater wetland.

Table 1. Physical features of the stormwater wetland

| Section | Surface Area ($m^2$) | Volume ($m^3$) | Water Depth (m) |
|---|---|---|---|
| Forebay | 288 | 351 (8.7) | 1.10 ~ 1.30 |
| Aeration Pond | 660 | 708 (17.6) | 1.10 ~ 1.30 |
| Deep Marsh | 518 | 725(18.0) | 1.20 ~ 1.80 |
| Shallow Marsh | 1374 | 1867(46.4) | 0.45 ~ 1.50 |
| Polishing Pond | 243 | 373 (9.3) | 1.30 ~ 1.50 |
| Total | 3083 | 4024 | 1.32* |

*Mean; ( ) Percentage

The physical features of the wetland are provided in Table 1. The shallow marsh constitutes the largest surface area followed by the aeration pond and the deep marsh. The wetland has a total volume of 4024 $m^3$ and an average depth of 1.3 m.

The water quality of the inflow to the wetland was monitored monthly during dry days by random sampling from May to December of the year 2011. During the monitoring, temperature, pH and DO were measured in situ while using the YSI 556 MPS Multiparameter Instrument and YSI 5000 dissolved oxygen meter (YSI Inc., 2005). Plant density was measured by quadrat sampling (Fidelibus and Mac Aller, 1993). Chlorophyll a was determined by pigment extraction followed by spectrophotometric determination, and $NH_4$-N, TKN, $NO_3$-N, $COD_{Cr}$, and other essential parameters were also measured using the Standard Methods for the Examination of Water and Wastewater, 19th edition (APHA et al., 1995). Temperature ranged from 11.7℃ to 34.8℃ while pH and DO have values with ranges of 5.91 – 8.62 mg/L and 4.23 – 9.50 mg/L, respectively. In addition, the total amount of CODCr was mainly constituted by soluble CODCr while nitrogen was largely composed of organic nitrogen which most likely came from the livestock farms.

## 2.2 Dynamic Oxygen Transfer Test

To determine the oxygen transfer and oxygen uptake in the aeration pond, the well-known dynamic method (Tchobanoglous and Schroeder, 1985; López et al., 2006; Kadlec and Wallace, 2009) was used to simultaneously determine the oxygen transfer coefficient, $K_{La}$, and oxygen uptake rate (OUR). The dynamic model is given by the following equation:

$$\frac{dC_L}{dt} = k_L a(C_S - C_L) - OUR \qquad \text{Eq. 1}$$

where $dC_L/d_t$ is the oxygen accumulation, $K_La(C_S-C_L)$ is the oxygen transfer rate, $C_S$ is the saturation dissolved oxygen (DO) concentration and $C_L$ is the DO concentration in the water. During the desorption period where there is no aeration, the oxygen transfer rate is considered as zero or $K_La(C_S-C_L)=0$. Therefore, Eq. 1 can be integrated to Eq. 2 as shown. From this, $OUR$ can be determined as the slope of a plot of $C_L$ versus time.

$$C_L = -(OUR)t \qquad \text{Eq. 2}$$

During aeration, both oxygen transfer and consumption occur, and the $C_L$ versus time plot can now be described by the rearranged Eq. 1 given by the following:

$$C_L = \frac{1}{K_L a}\left\{\left(\frac{dC_L}{dt}\right) + OUR\right\} + C \qquad \text{Eq. 3}$$

To achieve the oxygen transfer and uptake in the aeration pond using the equations presented above, a continuous dissolved oxygen monitoring was done in the aeration pond on July 2011. Based on the dynamic equation, the measured oxygen concentrations during desorption were plotted in terms of time and the slope was determined as $OUR$. Then, the rearranged dynamic equation given in Eq. 3 was used to determine $K_La$.

To account for temperature difference during the monitoring period, $K_La$ was normalized to 20℃ using the following equation:

$$K_L a = K_{La20}\theta^{T-20} \qquad \text{Eq. 4}$$

where $K_La$,20 is the oxygen transfer coefficient at 20℃ ($h^{-1}$), $\theta$ is the temperature coefficient (typically 1.024), and T is the water temperature(℃).

## 2.3 Light and dark bottle test

To be able to measure the total oxygen supply and consumption in the shallow marsh, the light and dark bottle test by Gaarder and Gran (1927) was conducted. This technique has also been used in several studies such as those done by Pratt and Berkson (1959) and has been reported in numerous references (Mara, 2003; Lung, 2001). In this test, wetland water samples from the shallow marsh were collected and kept in twelve 300mL Wheaton BOD bottles with glass robotic stoppers for a specified time. These bottles were submerged in the shallow marsh at about 10cm from the water surface to ensure an equilibrium temperature between the sample and the water in the wetland. Six of them were covered with aluminum foil to create a dark condition thus preventing oxygen production through photosynthesis while the remaining six were uncovered and kept under direct sunlight (Fig. 2). The initial temperature and DO were measured after which, one dark and one light bottle were recovered every hour and DO concentrations were immediately measured. This determines the internal oxygen production in the light bottle and consumption in the dark bottle.

For each month, a plot of DO concentration versus time was created from the light and dark bottles in this test. The slope of the plot from the light bottle represents net internal production rate ($NIP_{SM}$) while that in the dark bottle represents total loss rate ($TLR_{SM}$). Then, internal production ($IP_{SM}$) was computed as the sum of $NIP_{SM}$ and $TLR_{SM}$. To get internal production and total loss rate in the deep marsh ($IP_{DM}$ and $TLR_{DM}$), it was assumed that $IP_{SM}$ and TLRSM are proportional to the amount of algae represented by the *Chlorophyll* a concentration e.g. $(\mathrm{Chl-a})_{SM}:\mathrm{IP}_{SM}=(\mathrm{Chl-a})_{DM}:\mathrm{IP}_{DM}$.

Finally, to get the oxygen supply and consumption in kg/day, IP and TLR values were multiplied to the respective volumes of the shallow and deep marshes as presented in Table 1.

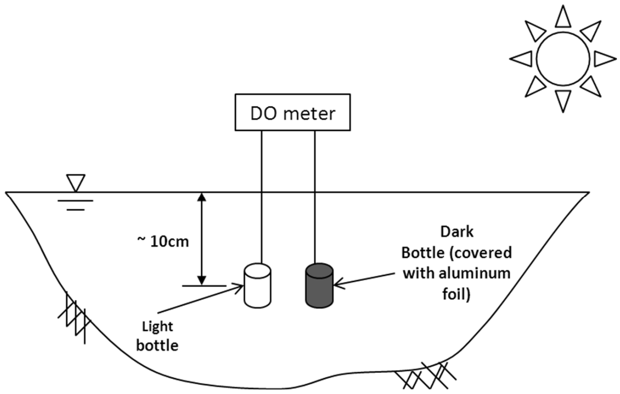


**Fig. 2.** Schematic diagram of the light and dark bottle test.

## 2.4 Estimation of oxygen consumption by nitrification and biodegradation

Oxygen requirement for nitrification and degradation of organic matter were estimated separately to better understand their contribution in the mass balance. Oxygen demand from nitrification is exerted primarily by ammonium but may be supplemented by the mineralization of dissolved organic nitrogen (Kadlec and Wallace 2009). Also, nitrification requires 4.57 g of oxygen per 1g of nitrogen. Thus, it was calculated as follows:

$$O_2 \text{ for nitrification } (kg-O_2/day) = \triangle TKN(g/m^3)\times Q(m^3/h)\times 4.57(g-O_2/g-N)\times(1kg/10^3g) \qquad \text{Eq. 5}$$

where △TKN is the change in TKN concentrations between the inlet and outlet of the wetland and Q is the average flow rate. On the other hand, oxygen demand for biodegradation was estimated using in Eq. 6, where △SCOD is the difference in concentration between the inlet and outlet of the wetland and Px is the daily cell production (kg/day). In this estimation, daily cell production was neglected based on the assumption that the wetland used in this study can be regarded as an extended aeration process (average hydraulic residence time was 14days), so that all the cells are eventually auto-oxidized in the wetland.

$$O_2 \text{ for biodegradation } (kg-O_2/day) = \triangle SCOD(g/m^3)\times Q(m^3/h)\times(1kg/10^3g)-1.42Px \qquad \text{Eq. 6}$$

## 2.4 Re-aeration, photosynthesis of macrophytes, and oxygen depletion by sediments

Oxygen released from plant roots were estimated based on available information from previous studies and were discussed in the following section. Macrophytes coverage was measured and from this, oxygen transfer rates per unit area of the same type of macrophytes in other studies were used to estimate the oxygen transfer from macrophytes in this study. Furthermore, assumptions on re-aeration and oxygen depletion were discussed.

# 3. Results and Discussion

## 3.1 Elements of oxygen supply and consumption in wetlands

Sources of oxygen production and demand in the wetland during the day time are schematically illustrated in Fig. 3 Oxygen supply elements include photosynthetic activity of algae and macrophytes, re-aeration through the interface between water and air and supplemental aeration. Oxygen consumption elements are algal respiration, microbial uptake, aerobic biodegradation, nitrogen transformation, and oxygen depletion in the interface between bulk water and sediments in the bottom of the wetland. Meanwhile, at night time, oxygen supply by algal activity would stop and consumption by algal respiration would dominate.

## 3.2 Analysis of dynamic oxygen transfer test data

As mentioned earlier in the previous section, oxygen transfer test was carried out in order to evaluate the supplemental oxygen supply and uptake rate and test results are provided in Fig. 4(a). Since aeration started, oxygen concentration gradually increased and reached a steady-state. When aeration was stopped, it started to decrease and reached about the same level as the test started.

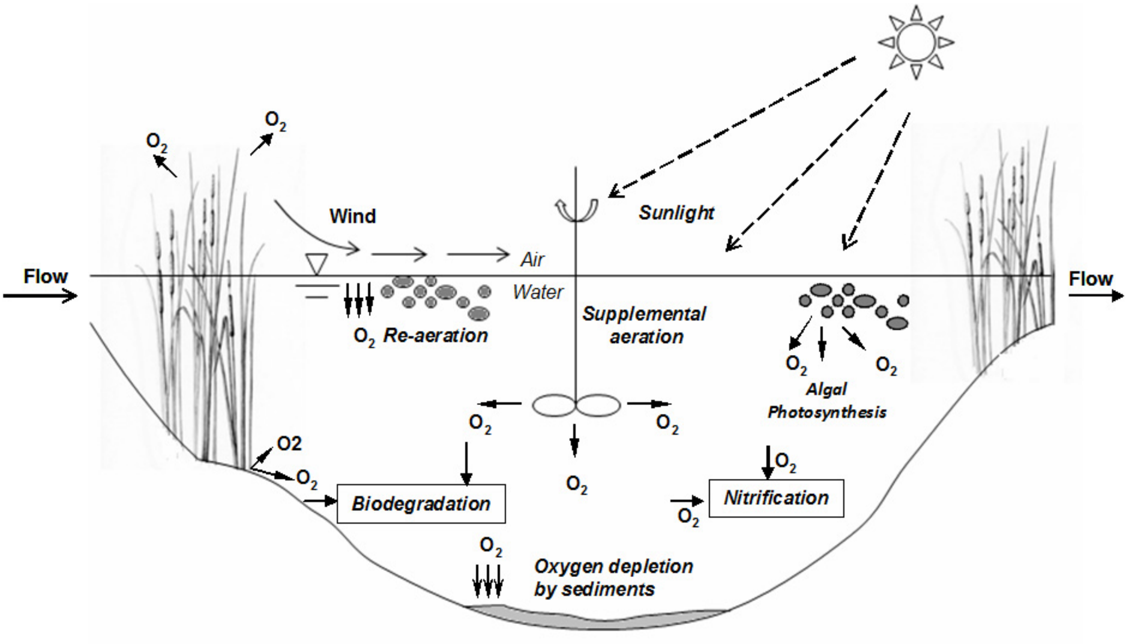
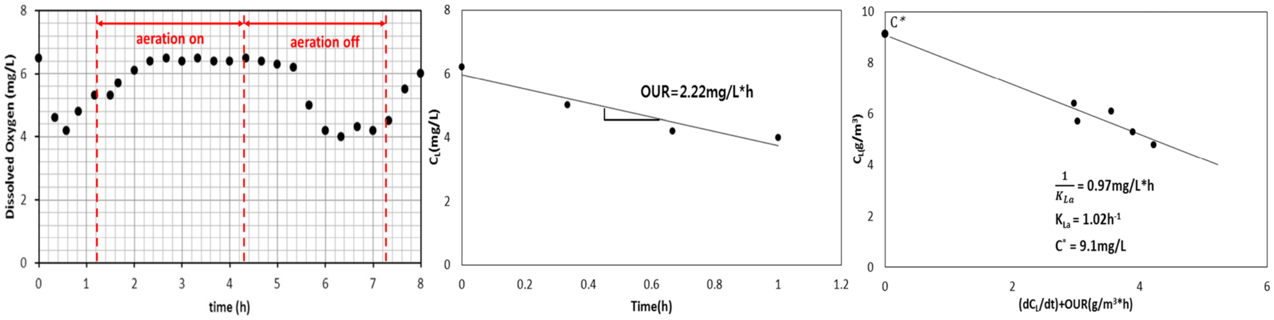


Fig. 3. Schematic diagram of oxygen supply and demand elements in wetlands.



(a) (b) (c)

Fig. 4. Field test results of dynamic oxygen transfer (July 2011).

Table 2. Oxygen transfer and uptake in the aeration pond

| Date | Temp (℃) | OUR (mg/(L*h)) | KLa ($h^{-1}$) | Total Supply (kg/day) | Total Consumption (kg/day) |
|---|---|---|---|---|---|
| Jun 2011 | 25.2 | 2.03 | 0.93 | 20.6 | 34.6 |
| Jul 2011 | 28.9 | 2.22 | 1.02 | 22.5 | 37.7 |
| Aug 2011 | 23.6 | 1.96 | 0.90 | 19.9 | 33.3 |
| Sep 2011 | 27.8 | 2.16 | 0.99 | 22.0 | 36.8 |
| Oct 2011 | 18.4 | 1.73 | 0.80 | 17.6 | 29.4 |

From this test results, overall $K_{La}$, $C_s$ and *OUR* value, saturation concentration and oxygen uptake rate were estimated and given in Fig. 4(b) and (c). Firstly, *OUR* was determined as 2.22 mg/(L*h), and then $K_{La}$ and $C_s$ were 1.02 $h^{-1}$and 9.10 mg/L, respectively, thus giving 2.70 mg/(L*h) of oxygen transfer rate.

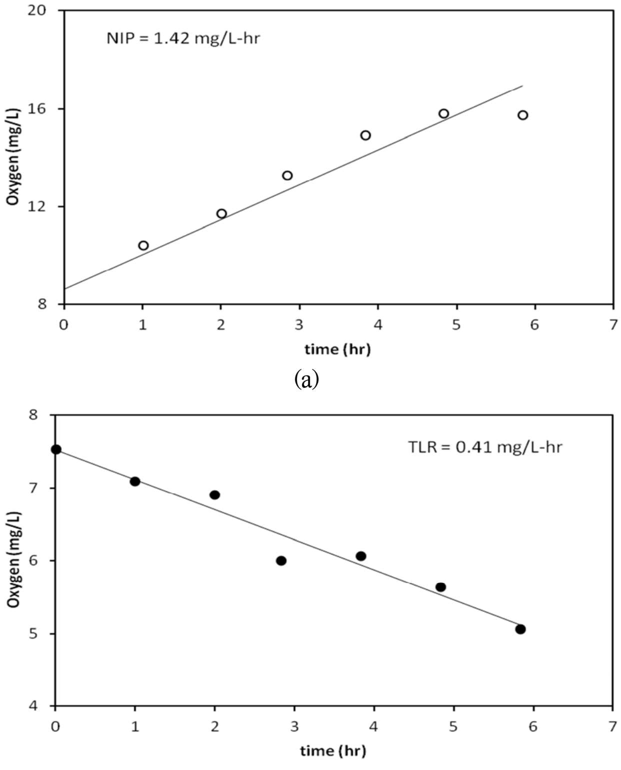
*OUR* in the aeration pond includes microbial uptake as well as depletion due to algal respiration because the water in the shallow marsh wherein algal growth is very active, is recycled to the pond being aerated. Saturation oxygen concentration $C_s$ was higher than the saturation value normally expected at 28.9℃ which is about 7.50 mg/L (Schwegler, 1978). This strongly indicates that the recycled water from shallow marsh is highly over-saturated due to algal activity. However, oxygen supply due to photosynthetic activity of algae was expected to be minimal as compared to supplemental aeration because of the large amounts of sediments that have been resuspended during aeration. These sediments tend to block the sunlight needed for photosynthesis and algal growth (Wang, 1974; Cloern, 1987). Therefore, in the aeration pond, the measured oxygen supply was mainly attributed to supplemental aeration while photosynthesis was considered negligible. OUR and KLa values required in oxygen mass balance for the other period were estimated using Eq. 4 and are given in Table 2.

### 3.3 Analysis of light and dark bottle test data

During the day, photosynthetic activity of algae in the light bottle will produce much DO while the consumption by algal respiration, nitrification, and biodegradation of organic matter is continuous throughout the day. Using the method discussed in the previous section, NIP and TLR values in the shallow marsh were determined as 1.42 mg/(L*h) and 0.41 mg/(L*h) respectively on July as shown in Fig. 5

From these results, NIP, TLR as well as IP values for each month were estimated and summarized in Table 3. The monthly IPDM and IPSM values ranged between 27.8-64.5 kg/day and 58.3-85.1 kg/day with average values of 42.9 kg/day and 73.5 kg/day respectively. It is apparent that production of oxygen in the shallow marsh is larger than that in the deep marsh. As shown in Table 4, Chlorophyll a concentrations were higher in the shallow marsh than in the deep marsh which can be attributed to the larger surface area in the shallow marsh. In addition, resuspension of sediment particles in the aeration pond caused larger concentration of suspended solids at its effluent. These particles entered the marsh wetland and also negatively affected the photosynthesis in the deep marsh. Once the water entered the shallow marsh, some particles have already settled so that inhibition in photosynthesis was lessened.

On the other hand, monthly TLRDM and TLRSM values ranged from 6 kg/day to 14.3 kg/day and 13.4 kg/day to 26.9 kg/day with average values of 10.2 kg/day to 7.90 kg/day respectively. Oxygen loss in the shallow marsh was higher than the deep marsh and this is also attributed to the larger algal biomass in this area.



(a)

(b)

**Fig. 5.** NIP and TLR due to algal photosynthetic activity in shallow marsh (July).

Kadlec and Wallace (2009) reported oxygen release rates of 0.15 - 5.2 g/m$^2$/day from submerged aquatic vegetations including algae. This is much lower than the equivalent production of 82.8 g/m$^2$/day and 53.5 g/m$^2$/day in the deep and shallow marshes, respectively. This is most probably due to the very large amount of algae and the ease of sunlight penetration in the water which induced an active algal photosynthesis in the wetland in this study. Nevertheless, additional data from a more frequent monitoring at different times of the year may help present more representative value. Moreover, an investigation of different variables or site conditions and their effect on oxygen transfer in wetlands may be necessary.

### 3.4 Re-aeration

According to Kadlec and Wallace (2009), the mass transfer

**Table 3.** Internal production and total loss of oxygen in the marsh wetland

| Date | Deep Marsh | | | Shallow Marsh | | |
|---|---|---|---|---|---|---|
| | Chl-a (μg/L) | IPSM (kg/day) | TLRSM (kg/day) | Chl-a (μg/L) | IPDM (kg/day) | TLRDM (kg/day) |
| Jun 2011 | 130.4 | 80.7 | 26.9 | 154.5 | 37.1 | 12.4 |
| Jul 2011 | 63.0 | 80.7 | 17.9 | 129.8 | 64.5 | 14.3 |
| Aug 2011 | 101.8 | 62.7 | 13.4 | 116.3 | 27.8 | 6.0 |
| Sept 2011 | 73.7 | 58.3 | 17.9 | 110.6 | 33.9 | 10.4 |
| Oct 2011 | 24.4 | 85.1 | 13.4 | 38.0 | 51.4 | 8.1 |

coefficient in wetlands is affected by four factors namely the flow velocity, water depth, rainfall intensity and wind speed. However, the first two factors are usually dominant only in turbulent water bodies such as streams and rivers. Typically, the observed flow velocity in wetlands is very low resulting to very weak turbulence. In the studied wetland, an average hydraulic residence time was about 14 days. Moreover, macrophytes in the vegetated section of wetlands cancel out the effect of wind mixing specially for low wind speeds. Thus, the effect of re-aeration in the oxygen mass balance was not considered as it was expected to be very low as compared to supplemental aeration and oxygen production by algal activity.

## 3.5 Oxygen transportation from plant to root zone

Oxygen production and uptake have been measured by different methods in various studies. Specifically for plant oxygen transfer, determination methods include measurements from individual plant roots as well as direct measurements of oxygen uptake which can be done both in the field and in the laboratory. In some studies, the decrease in CBOD and ammonia has also been used to infer oxygen transfer although this method has been labeled as a “crude calculation”. Due to the variability of methods, it was reported that although it is certain that oxygen transfer from roots occur at a moderate rate, the exact amount that is released in excess of those that are consumed for plant respiration is much less definite (Kadlec and Wallace, 2009).

In this study, oxygen flux from wetland macrophytes was not measured directly. Instead, oxygen flux as well as the root surface area that were presented from previously published studies was considered. These values were used together with the measured plant density and plant coverage in the wetland in this study to estimate the potential oxygen release from the macrophytes. As an example, Jespersen et al., (1998) reported oxygen release rates of 1.26 mmol $O_2$ $m^{-2}$ $hr^{-1}$ from the roots of *Typha latifolia*. This is equivalent to 0.97 g $O_2$ $m^{-2}$ $day^{-1}$. He also reported a root surface area of 223 $cm^2$ for each plant. In our wetland, the measured plant coverage was 189.2 $m^2$ which is about 10% of the marsh wetland area. In addition plant densities of 39 ~ 48 plants/$m^2$ were measured from June to October 2011. From these data, the oxygen release from *Typha latifolia* were estimated from 0.16 ~ 0.20 kg/day. Similarly, Lawson (1985), the roots of *Phragmites australis* has a maximum oxygen flux of 4.3 g/$m^2$-day and Gries et al. (1990) calculated values ranging from 1-12 g/$m^2$-day.

Based on the reported oxygen fluxes, it was roughly estimated that the oxygen release was negligible as compared to the oxygen supply from aeration and algal photosynthesis. Also, these amounts were not entirely released to the water and a part is utilized by the macrophytes themselves. In addition, current design guidelines recommended by the US EPA (2000) also assumes that oxygen delivered by the plant roots to the water is negligible. Therefore, this aspect is not considered in this oxygen balance study.

## 3.6 Oxygen depletion by sediments

Organic materials that have settled on the sediment bed of lakes, reservoirs and wetlands provide an area for microbial activity and processes that require DO consumption. This oxygen demand caused by the sediment layer in wetlands has also been studied by other authors. According to Kadlec and Wallace (2009), the amount of sediment oxygen demand (SOD) can be related to the thickness of the sediment layer, the behavior of the surrounding water and the characteristics of the sediment-water interface. More importantly, it is reported that SOD is greatly affected by the composition of the sediment itself and higher SOD can be found in sediments that are rich in organics (Higashino and Stefan 2005). This is probable in wetlands which have been used for treatment for a long time. However, the wetland in this study has been operated for only about 2 years and significant oxygen demand is not to be expected. In addition, it constitutes a forebay which provides pretreatment thus, reducing the suspended solids before entering the wetland. Therefore, the oxygen requirement from this mechanism was not considered in this study.

## 3.7 Aerobic nitrogen transformation and organic matter biodegradation

Based on the calculation discussed in the previous section, monthly oxygen demand from nitrification was summarized in Table 5. The rate of oxygen consumption through nitrification was from 0.72 kg/day to 5.13 kg/day. It was expected that removal efficiency of TKN is proportional to the oxygen consumption. However, this phenomenon was not observed in our study. On the month of August, a high removal efficiency of 61.7 % was observed with the lowest consumption rate of 0.72 kg/day. Oppositely, on the month of June, although the removal efficiency was comparatively lower, an oxygen demand of 4.84 kg/day was observed. On the other hand, the oxygen demand from the biodegradation of organic matter ranged from 3.13 - 5.08 kg/day as shown in Table 6. With removal efficiencies

**Table 4.** Oxygen consumption through nitrification

| Date | TKN (mg/L) | | Removal Efficiency, % | Q ($m^3/h$) | Consumption Rate (kg/day) |
|---|---|---|---|---|---|
| | In | Out | | | |
| Jun 2011 | 7.2 | 4.5 | 37.3 | 13.7 | 4.84 |
| Jul 2011 | 1.3 | 0.6 | 55.9 | 27.4 | 5.13 |
| Aug 2011 | 0.5 | 0.2 | 61.7 | 19.7 | 0.72 |
| Sept 2011 | 1.6 | 0.9 | 42.2 | 30.9 | 1.93 |
| Oct 2011 | 3.3 | 0.7 | 78.7 | 14.4 | 4.09 |

**Table 5.** Oxygen consumption through aerobic biodegradation of organic matter

| Date | SCOD (mg/L) | | Removal Efficiency, % | Q ($m^3/h$) | Consumption Rate (kg/day) |
|---|---|---|---|---|---|
| | In | Out | | | |
| Jun 2011 | 36.1 | 20.8 | 42.4 | 13.7 | 3.42 |
| Jul 2011 | 19.7 | 21.1 | 27.4 | 27.4 | 5.08 |
| Aug 2011 | 19.7 | 13.2 | 33.1 | 19.7 | 3.13 |
| Sept 2011 | 21.6 | 13.1 | 39.7 | 30.9 | 4.52 |
| Oct 2011 | 31.0 | 19.5 | 37.1 | 14.4 | 3.97 |

ranging from 27.4 – 42.4%, the consumption rates did not vary significantly.

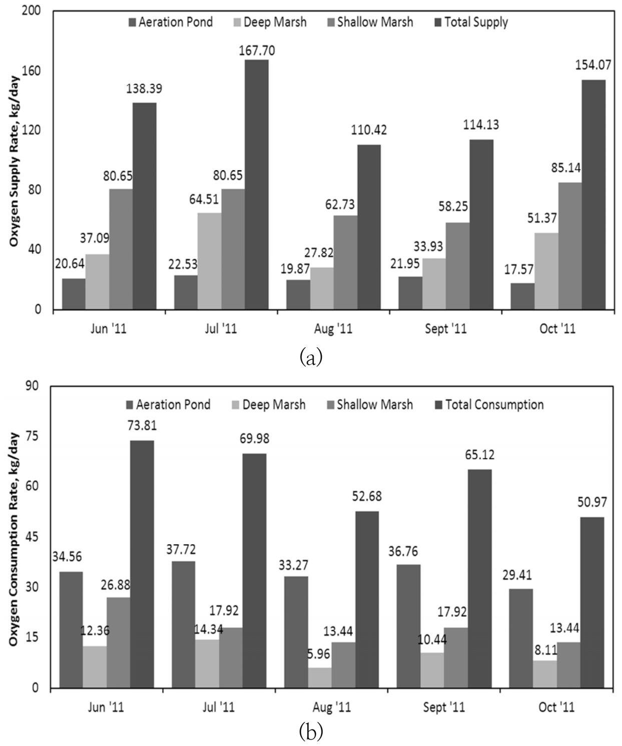
The estimated consumption rates imply that oxygen demand from nitrification and biodegradation accounted for only 5.35% and 6.43% of the total consumption in the wetland.

## 3.8 Oxygen Balance in the Wetland

The summary of the oxygen supply and consumption estimated in the different components of the wetland at daytime is given in Figure 6. The supply rates (Fig. 6(a)) and consumption rates (Fig. 6(b)) are varying in the different components of the wetland due to the different mechanisms involved. As mentioned previously, in the aeration pond, the main supply of oxygen came from the artificial aeration while consumption was mainly due to the algae and microorganisms carried by the recycled water from the shallow marsh. The consumption in this component was higher as compared to the two marshes probably because the recycle flow rate is about six times the average flow rate thereby carrying great amount of algae. In the marsh wetland, supply rates as well as consumption rates of the shallow marsh was higher than that of the deep marsh due to the active algal growth in this area. Furthermore, as compared to the deep marsh, it is easily penetrated by sunlight which promotes greater algal activity. The daily supply of oxygen is higher than the demand in all the components except for the aeration pond where algal photosynthesis is prevented by the suspended solids and supplemental oxygen is supplied intermittently.

During the day, there was an excessive production of oxygen in the wetland. However, at night, oxygen production through photosynthesis of algae stopped and caused an oxygen deficit as shown in Fig. 7 This deficit created an oxygen imbalance in the wetland which poses the need to increase oxygen supply at night. On another point of view, further decreasing the DO concentration can also enhance the denitrification capacity of the wetland. According to a previous study on the treatment performance of the same wetland in this study, it is very efficient for nitrification but denitrification is relatively low (Yu et al., 2012). Fig. 8 shows the distribution of nitrogen species in the inflow and outflow of the wetland based on 16 sets of grab samples done on the year 2011. The significant decrease in TKN concentration signifies the existence of nitrification. Nitrate removal was low and the effluent stormwater contained nitrate that can still be removed but TN removal signifies that denitrification also exists in the wetland. Thus, it was thought that nitrification happens during the day when there is abundant oxygen while denitrification becomes dominant at night when oxygen concentration is decreased to a low level.

Only a small percentage of the total oxygen consumption was contributed by nitrification and degradation of organic matter which accounted for 12% and 5% of the total oxygen consumption, respectively. It is evident that the main cause of oxygen depletion in the wetland was algal consumption. Apparently, the oxygen supply in the wetland is more than sufficient to provide the oxygen requirement for nitrification and degradation of organic matter. From the oxygen supply



(a)

(b)

**Fig. 6.** Oxygen supply and consumption in the stormwater wetland at daytime.

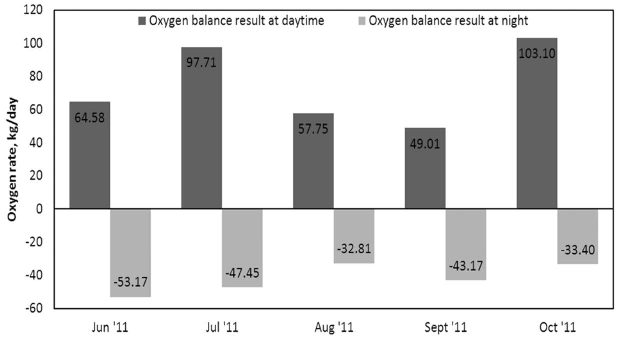


**Fig. 7.** Oxygen balance in the wetland during the day and at night.

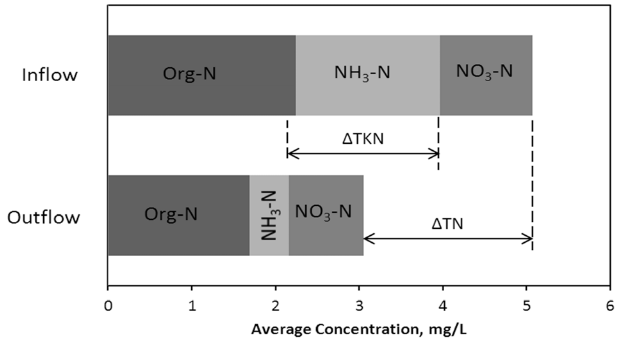


**Fig. 8.** Distribution of nitrogen species at the inlet and outlet of the wetland.

and consumption analysis determined above, the oxygen balance is expressed in Eq. 7. Net oxygen production (NOP) was calculated as the sum of supplemental oxygen supply (SOS) and internal production in the deep marsh (IPDM) and shallow marsh (IPSM), subtracted by the algal respiration in all the components (OCAP, OCDM, and OCSM).

$$NOP = SOS + IP_{DM} + IP_{SM} - OC_{AP} - OC_{DM} - OC_{SM} \quad \text{Eq. 7}$$

From this mass balance equation, overall net oxygen productions were estimated for each month. During the day, average daily NOP values were 49.0 – 103 kg-$O_2$ with a mean value of 74.4kg-$O_2$. The highest net oxygen production was observed on October while low productions were observed during August and September. These low oxygen productions can be attributed to the frequent rainfall wherein algae was often washed out resulting to lower oxygen supply from algal activity especially after a rainfall event. However, there is no concrete evidence of the effect of rainfall in the oxygen consumption and production in the wetland and the authors think that it should be given more attention for future studies.

In addition, the largest net production was in the shallow marsh. From these results, it is evident that the major supply of oxygen during the day came from algal photosynthesis. Hence, supplemental aeration may not be necessary at daytime because the amount of oxygen produced by algal activity is sufficient for the aerobic biological processes in the wetland.

However, at night, algal photosynthesis ceased and oxygen is largely depleted by algal respiration. Estimated net oxygen loss ranged from 32.8 kg/day to 53.17 kg/day with an average value of 42.0 kg/day. From this point, two options for operational measures can be made in terms of aeration. First, in order to prevent oxygen deficit, the current intermittent aeration can be changed to continuous supplemental aeration which would relieve the immense deficiency of oxygen at night. Second, since the oxygen is reduced greatly, an anoxic condition is created which induced denitrification that is not promoted during daytime. Therefore, supplemental aeration can be completely stopped to further lower oxygen concentration thereby enhancing denitrification potential of the wetland.

## 4. Conclusions

From the oxygen balance analysis, the supply of oxygen in the wetland largely came from the photosynthesis of algae. This is attributed to the active algal activity especially in the shallow marsh due to the large surface area available for algal growth and also because most of its parts are easily penetrated by sunlight. The major oxygen consumption element was found to be algal respiration and microbial uptake with oxygen required for nitrification and biodegradation contributing only 5.35% and 6.43% of the total consumption respectively. Algal respiration became dominant especially in the aeration pond because of the highly turbid water caused by the resuspension of sediment particles which partially inhibited algal photosynthesis. Consequently, this turbid water was transported to the subsequent parts of the wetland including the deep and shallow marshes.

During the day, an abundance of oxygen was observed in the wetland signifying that oxygen produced through algal photosynthesis is sufficient to meet the oxygen requirement of the wetland. Therefore, supplemental aeration at daytime may not be necessary

On the other hand, at night, significant net oxygen loss was estimated in the wetland and denitrification was promoted. Two operational options were concluded on this matter. First, continuous supplemental aeration may be implemented at night instead of the intermittent operation to prevent oxygen deficit in the wetland. Second, supplemental aeration may be stopped entirely to further enhance the denitrification capacity of the wetland.

The results of this study can greatly help in the operation and management of treatment wetlands specially those that are requiring additional costs and maintenance for supplemental aeration. Also, the estimation of the oxygen supply and consumption in a specific system can improve the understanding on the effect of oxygen transfer in the removal of pollutants such as ammonia.

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