Variation in Water Quality of a Stormwater Pond from Diurnal Thermal Stratification

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***Abstract*-The city of Calgary, Canada, has considered reusing stormwater from detention ponds for the irrigation of public lands. The diurnal variability in the water quality of these ponds was studied to ensure public safety. Field observations of diurnal thermal stratification and diurnal variation in water quality were conducted in a stormwater pond during the 2007 irrigation season normally from late June to September. Diurnal thermal stratification occurred in the upper water column, from the surface to approximately 1.2 m in depth. Diurnal variations in microorganisms involved high concentrations during the day and low concentrations at night. Increases in physicochemical water quality parameters at night were observed at the bottom of the water column, at a depth of 1.0 m. Observations suggest that the effects of diurnal thermal stratification alter pond hydrodynamics, and thus, alter the diurnal variation of water quality in turn.**

Keywords*- *Diurnal Stratification; Microorganisms; Stormwater Pond; Water Quality

I. INTRODUCTION

Physicochemical quality parameters such as water temperature, dissolved oxygen (DO) and pH display diurnal variations in aquatic environments in response to the diel weather cycle. Diurnal variations in pH, DO, and temperature are exhibited in freshwater ponds [1], wastewater ponds [2, 3], and lakes [4]. Kayombo *et al*. [2] developed exponential regression equations of DO and pH for waste stabilization ponds, and suggested that pH might be estimated by DO concentration.

Understanding the daily variation in microbiological quality is essential when water is used for drinking [5], recreation [6], and other microbiological sensitive uses (i.e. irrigation). Inflow pollutant load, physicochemical quality parameters, and other factors may cause variations in the microbiological quality of water bodies. Bordalo [6] ascribed the daily fecal coliform variation to the periodicity of raw sewage discharge and the tide status in urban beaches. Physicochemical parameters such as water temperature, pH and DO, are believed to influence the abundance and activity of microorganisms. Previous studies have investigated the variations of microorganisms and their relationships to certain physicochemical parameters in rivers [7], beaches [8], and bays [9]. However, these investigations were made over time scales longer than the diurnal time scale, using weekly or monthly sampling.

Diurnal thermal stratification, the daily alternation of stratification and destratification, often occurs in shallow water bodies [10]. Solar radiation heats the top water layer, causing thermal stratification during the day. At night, the drop in air temperature combined with wind action causes destratification. When a water body is thermally stratified, a density gradient is created and internal vertical mixing is compromised [11]. The internal hydrodynamic behavior of stratified water bodies significantly influences the movement of suspended particles and organisms in the water column [12]. In contrast, the breakdown of stratification enhances water mixing. Time-dependent distribution of phytoplankton in diurnally stratified shallow lakes has been observed by Ganf and Horne [13]. Diurnal thermal stratification was also shown to have impacts on microorganism densities in the vertical water column of a stabilization pond [14].

In Calgary, Canada, reusing stormwater for the irrigation of public parks has prompted water quality monitoring to ensure public safety. As part of the overall efforts to ensure public safety, this study developed two objectives: (i) to characterize the diurnal variations of hydrodynamics (thermal stratification) and physicochemical and microbiological quality; (ii) to assess the influence of the pond's fluid hydrodynamic regime on the water quality on a diurnal time scale.

II. MATERIALS AND METHODS

A. Study Area

The Inverness Stormwater Pond is located in southeast Calgary, adjacent to a public park, which is surrounding the pond. The total drainage area of the pond is approximately 150 ha. The majority of the drainage area is a developed residential (single-family housing) area. The pond consists of a permanent water pool with a capacity of 170,000 m^3 and approximately 95,000 m^3 of active storage. The design water depth is 3.8 m (without outflow). There are six stormwater outfalls surrounding the pond. The pond water drains through an outlet built in the northwest corner when the water level exceeds the designed permanent water level (PWL 1028.8m). Fig. 1 shows the location of the pump wet well which withdraws stormwater for irrigation. The intake pipe is located approximately 1.0 m below the PWL. The city of Calgary generally starts preparing for

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irrigation at the beginning of May. June is the wettest month, so actual watering often takes place from late June until the end of September.

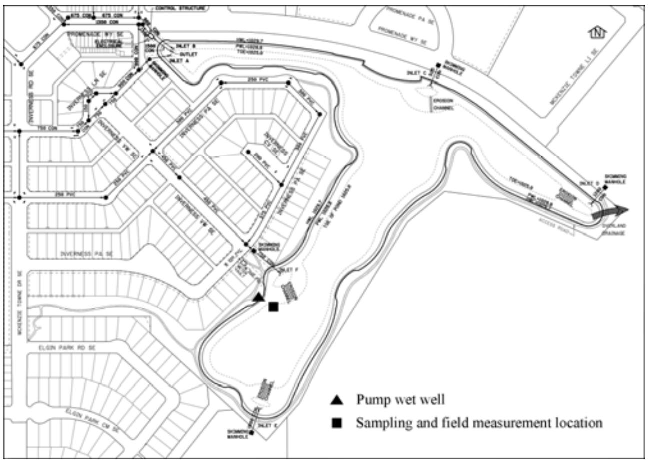

Fig. 1 Study area

B. Water Sampling and Field Measurements

Water samples and field measurements were taken at a location close to the wet well pump intake (Fig. 1). During the 2007 irrigation season, 24-hour water sampling and field measurements were conducted once per month from July through September. Water sampling and field measurements were taken at the water surface (0.3 m depth) during dry periods, when irrigation was needed, on July 15-16 (Event 1). Measurements were taken 1.0 m below the surface on August 06-07 (Event 2) and September 16-17 (Event 3). The events were planned to capture both temporal and spatial (in the vertical direction) variations in water quality. Although the events were initiated during dry conditions, a thunderstorm occurred from 19:30 hours to 21:35 hours on July 15 (rainfall = 8.4mm) during Event 1 and a low intensity storm occurred from 02:25 hours to 08:05 hours on September 17 (rainfall = 5.7mm) during Event 3. During the three events, a YSI 6600 multi-parameter water quality Sonde was placed in the pond to continuously record quality parameters including water temperature, DO, pH, conductivity and turbidity at 5 minute intervals. Prior to each event, the YSI 6600 was calibrated according to its calibration procedures, and the calibration was always performed in similar conditions (controlled room temperature at the Civil Engineering Wastewater Laboratory of the University of Calgary). In the meantime, hourly pond water samples were collected using a Sigma automatic sampler from the same depth in each event. Ice was continually placed into the sampler to keep the water samples cool. Recovered water samples were delivered to the Provincial Laboratory for Public Health in Calgary within one hour for assay of microorganisms, fecal coliform and *Escherichia Coli* (*E. coli*) using the membrane filter method. Pond temperatures were taken by four temperature sensors placed at four water depths (0.2 m, 0.7 m, 1.2 m, and 1.7 m) at 5 minute intervals in each event. Air temperature and wind speed data were obtained from the weather station at Calgary International Airport, which is approximately 30 km from the study site.

III. RESULTS AND DISCUSSION

A. Characterization of the Diurnal Variations in Physicochemical Quality

The fluctuation ranges (minimum and maximum) and average physicochemical parameters from each 24-hour event are presented in Table 1. Significant differences ($p< 0.05$) were detected in water temperature, pH, DO and turbidity using analysis of variance and a multiple comparison test. Results indicate the temporal and spatial variations in these parameters. Diurnal rhythm was observed in water temperature, DO and pH, but not observed in turbidity and conductivity. Normalized time series of water temperatures, DO, pH, and hourly air temperature for each event are illustrated in Figs. 2-4. Water temperature in the top water layer was influenced more by ambient temperature than in deeper water layers. Thus, for Event 1, fluctuations in water temperatures were similar to fluctuations in air temperatures but with a time lag of approximately 1.5 hours. In Events 2 and 3, water temperature time series at 1.0 m depth differed from air temperature fluctuations. Increases in water temperature during these two events were observed at night after the air temperature dropped. In particular, the highest water temperature was recorded in the middle of the night at 00:45 hours during Event 2. The variations in pH and DO generally followed water temperature fluctuation, although time lags between water temperature and DO and pH fluctuations were detected in Event 2. Clear peaks in water temperature, DO and pH were observed at approximately 17:30 hours at the surface during Event 1. The variability patterns in the parameters appear to be more complicated at 1.0 m depth than at the surface. In Events 2 and 3, temperature, DO and pH increased from early morning to a peak in late afternoon. Second major peaks in fluctuation were also found during Events 2 and 3 during the night.

Photosynthesis and respiration majorly influence diurnal variations in DO and pH in water bodies [3]. The fluctuation in water temperature was related to the variation in air temperature at the surface. Photosynthesis/respiration appeared to be the

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major determinant in daily periodic cycles in DO and pH at the surface. In contrast, the diurnal cycles of water temperature, pH and DO were not solely dependent on the daily climatic cycle at 1.0 m depth; at this water depth, increases in water temperature, DO and pH occurred at night time as well, despite a drop in air temperature after sunset. These indicated that increases were largely driven by a factor other than photosynthesis/respiration.

B. Modelling Pysicochemical Quality Using Regression Analysis

Close associations between water temperature, DO and pH were observed in each event, as shown in Figs. 2-4. Calculated Pearson's correlation coefficients ($p< 0.05$) between these parameters are shown in Table 2 for the three events. Strong positive correlations between water temperature, DO and pH were calculated for Events 1 and 3, while the positive correlations for Event 2 were not as strong due to their time lag after sunset (Fig. 3). High linear correlations between DO and pH were calculated for all three events and are demonstrated in Fig. 5. The three regression lines derived individually for each event, however, demonstrate significantly different slopes (tested with Analysis of Covariance at $p< 0.05$); this was somewhat expected because of the existence of spatial and temporal differences of pH and DO in all three events. Note that vertical variations in DO and pH have been observed in waste water ponds [3] and in marine water [15]. When all three events are combined, the coefficient of determination R^2 of the regression for DO vs. pH is 0.24; however, by incorporating temperature into the regression, the R^2 improves significantly to 0.67, as shown in Fig. 6. This suggests that a more generalized regression model for DO and/or pH can be produced by including water temperature. The most important mechanisms behind the relationships among water temperature, pH and DO are the biological processes of algae and macrophytes (photosynthesis and respiration), which vary diurnally. Photosynthesis, which is dominant during the day time, consumes CO_2 and produces oxygen, consequently increasing DO and pH simultaneously; during the night, respiration of algae and macrophytes consumes oxygen and increases CO_2 concentrations, in turn reducing both DO and pH. However, as shown and discussed later in this paper, diurnal thermal stratification and destratification would also affect DO, pH and water temperature.

TABLE 1 FLUCTUATION RANGES (MINIMUM - MAXIMUM) AND AVERAGES (IN PARENTHESES) OF PHYSICOCHEMICAL PARAMETERS FOR THREE 24-HOUR EVENTS IN 2007

Event	Air temp*(^{o}C)	Water temp*(^{o}C)	pH
Event 1 July 15-16	15.3-28.7 (20.87)	24.47-27.49 (25.69)	9.18-9.41 (9.31)
Event 2 Aug. 06-07	11.1-25.8 (18.71)	20.86-22.40 (21.60)	8.51-903 (8.79)
Event 3 Sept. 16-17	6.6-24.4 (14.91)	14.31-16.29 (15.19)	7.68-8.71 (7.68)

*Temp: temperature.

TABLE 2 CORRELATION COEFFICIENTS ($P< 0.05$) BETWEEN PHYSICOCHEMICAL PARAMETERS

Event	Correlation coefficient		
	Temperature & DO	Temperature & pH	DO & pH
Event 1	0.735	0.849	0.962
Event 2	0.279	0.323	0.923
Event 3	0.741	0.788	0.972

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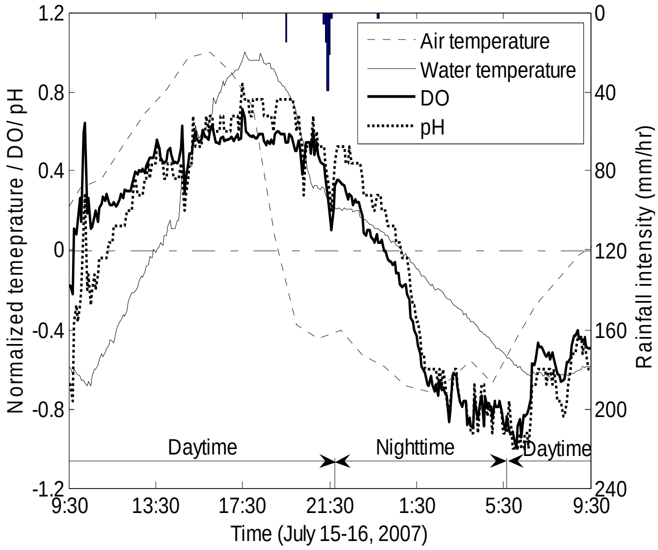

Fig. 2 Diurnal variations of physicochemical quality parameters in Event 1

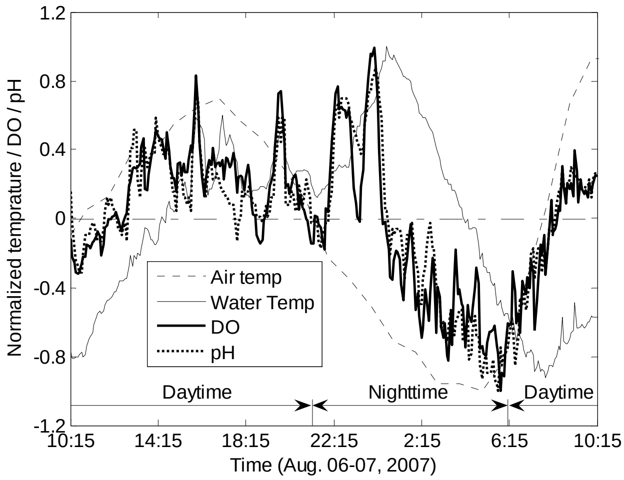

Fig. 3 Diurnal variations of physicochemical quality parameters in Event 2

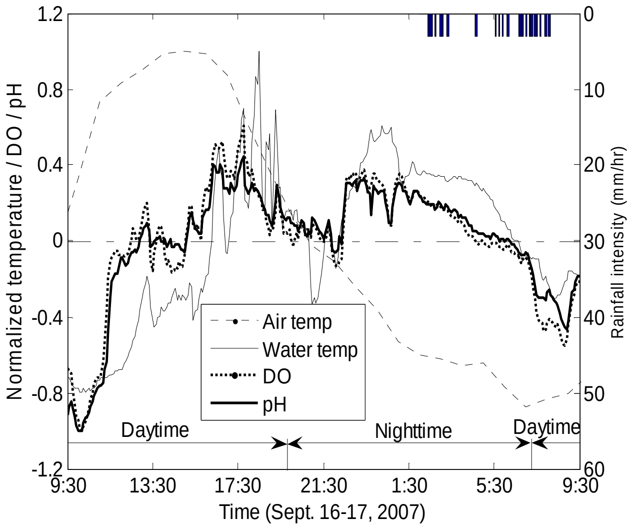

Fig. 4 Diurnal variations of physicochemical quality parameters in Event 3

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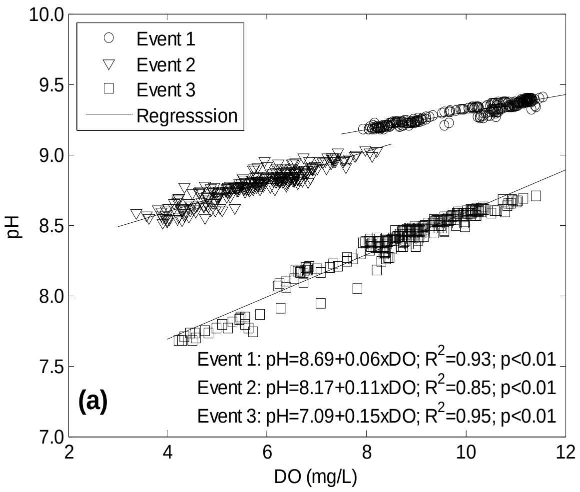

Fig. 5 Linear relationship between DO and pH

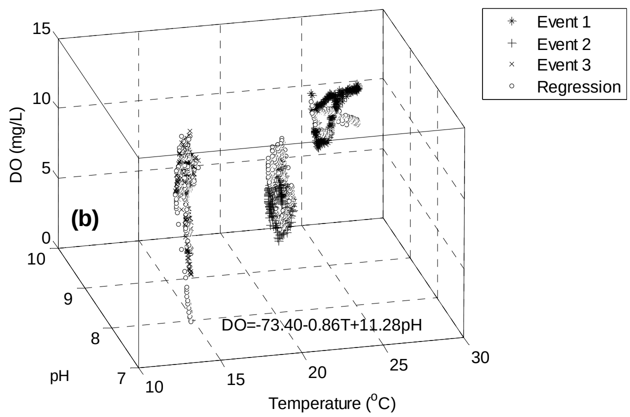

Fig. 6 DO predicted by both water temperature and pH

C. Characterization of the Diurnal Variations in Microbiological Quality

Water samples collected at the surface during Event 1 had concentrations of ≤20 cfu/100mL for both fecal coliform and *E. coli*. Fig. 7 presents hourly concentrations of fecal coliform and *E. coli* during the two 24-hour periods of Events 2 and 3; definite diurnal fluctuations in fecal coliform and *E. coli* were demonstrated in both Events. The correlation coefficients between fecal coliform and *E. coli* are 0.58 and 0.98 ($p < 0.05$) in Events 2 and 3, respectively. High microorganism concentrations were generally found during the day while concentrations were lower at night until early the next morning; maximum microorganism concentrations were found in the afternoon in both events. In these two events, the concentrations of fecal coliform and *E. coli* exceeded 200 cfu/100mL. The elevated concentrations suggest a high probability of the presence of pathogens, such as *Salmonellae* [16] and the consequent possibility of public exposure to waterborne illness if stormwater is reused for irrigation at the time when elevated concentrations of fecal coliform and *E. coli* were observed. Comparatively large fluctuations in microorganism concentrations were observed at night in Event 3. A stormwater outfall near the sampling location was placed roughly at the depth of the water sampling. During the night of Event 3, high concentrations of approximately 130 cfu/100mL were observed at 1:30 hours, but they did not seem to be associated with the rain event which occurred from 02:25 hours - 08:05 hours. The effect of rain on pH, DO and turbidity was not clear. Thus, the external pollutant loading in the rain event appeared to be negligible.

Sediment resuspension induced by external factors, e.g. storm events and other activities involved with water bodies, might cause variations in microbiological quality of the overlying water. Storm runoff and recreational activities that resuspend viable sediment-bound bacteria contribute to the deterioration of the microbiological quality of the water column [17]. Wind-induced hydrodynamic disturbance can induce sediment resuspension in shallow water bodies [18]. In the two 24-hour events at the Inverness Stormwater Pond, no rain fell in Event 2, but low intensity rain with strong winds occurred during the night of Event 3. However, the effects of rain and wind were not evident in turbidity measurements collected during the two events. The results suggest that both rain and wind are not necessarily strong enough to resuspend bottom sediment back to the overlying water layer at a depth of 1.0 m. Consequently, observed daily fluctuations in microorganisms in the pond at 1.0 m depth were not a consequence of bottom sediment resuspension induced by external factors.

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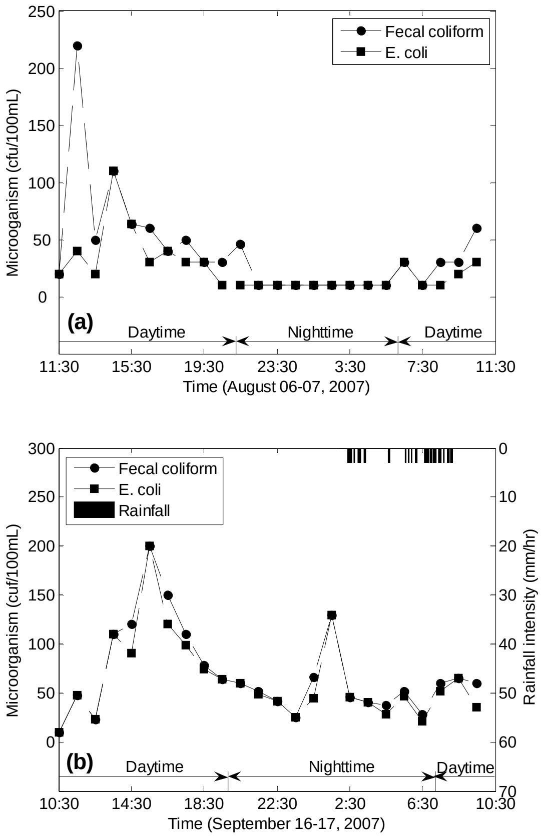

Fig. 7 Diurnal variations in microorganisms for (a) Event 2; and (b) Event 3

The growth and decay of microorganisms in the aquatic environment may be an additional factor to be considered, contributing to the microorganism variations. Davis *et al.* (2005) observed the growth of fecal coliform from lake water samples in dark in laboratory experiments; however the growth was not identified in illuminated water samples. The same study by Davis *et al.* [19] did not observe the growth of *E. coli*. The aquatic environment of low water temperature combined with low irradiance from night until early morning is beneficial for the repair of injured cells and the growth of microorganisms. At this study site, constantly low microorganism concentrations in Event 2 and fluctuations at night during Event 3 imply that the growth of microorganisms does not appear to occur during these time periods. Therefore, it is speculated that the growth and decay of microorganisms is not a governing factor contributing to the observed diurnal variations of fecal coliform and *E. coli*.

D. Assessment of the Pond's Fluid Hydrodynamic Regime and its Influence on Water Quality on a Diurnal Time Scale

Fig. 8 illustrates the temperature profiles during the three events; a definite diurnal stratification was observed. Diurnal cycles of water temperature were found in the upper water column from the water surface down to between 1.2 m and 1.7 m in depth. The water temperature below 1.7 m demonstrated no apparent diurnal cycle. In general, the stratification began after 10:00 hours and peaked in the late afternoon. Stratification gradually broke down and vanished several hours after sunset. Stratification breakdown occurred due to air cooling combined with wind action. The average wind speeds of Events 1, 2, and 3 at night were 3.44 m/s, 2.50 m/s, and 6.67 m/s, respectively; daytime average wind speeds were 3.34 m/s, 3.16 m/s, and 3.39 m/s, respectively. The destratification remained until the next early morning; diurnal thermal stratification was observed to disappear around end of September in 2007 season.

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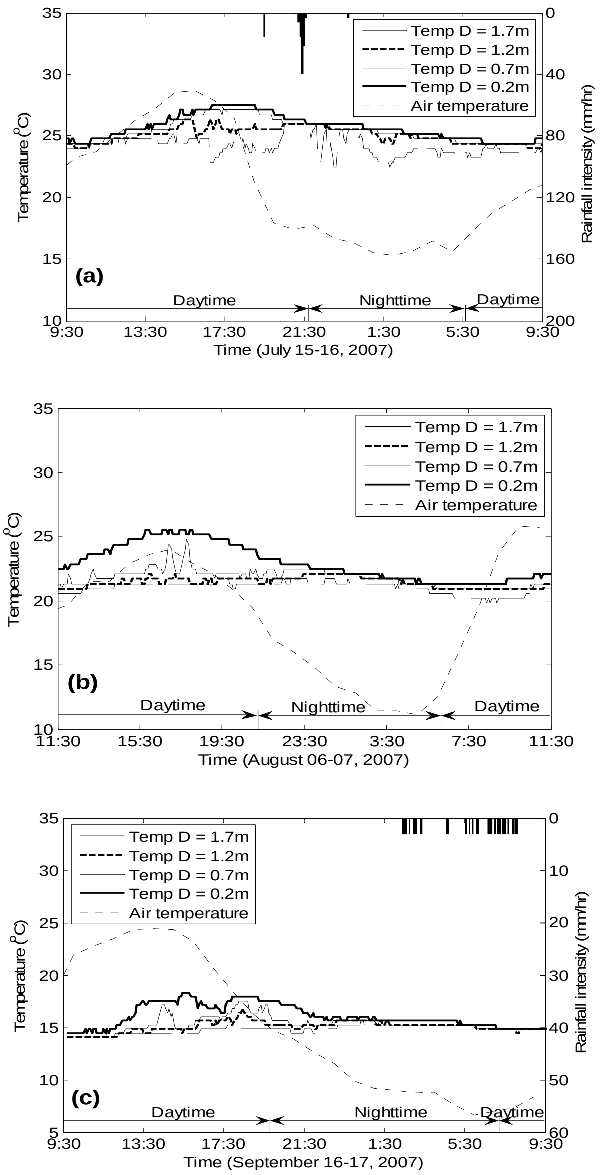

Fig. 8 Temperature profiles of (a) July 15-16, 2007 (Event 1); (b) August 06-07, 2007 (Event 2); and (c) September 16-17, 2007 (Event 3). Bar graphs in subplots (a) and (c) present hyetographs

E. Influence on Physicochemical Quality

Diurnal thermal stratification largely relies on the daily meteorological cycle, which determines the dynamic balance between stratifying energy and turbulent kinetic energy. The daily alternating stratification and destratification results in daily periodic change in the hydrodynamic regime. During stratification, a density gradient is created and internal vertical mixing is compromised [11]. The breakdown of stratification drastically modifies the internal water circulation and enhances internal water vertical mixing in water column. This diurnally varying hydrodynamic regime is associated with redistributions in the physicochemical quality parameters of a water column. Tanaka and Tsuda [20] proposed that a DO decrease in the epilimnion was caused by mixing with the low-DO water in the thermocline immediately after cool and windy weather in a large freshwater lake. Ganf and Horne [13] also observed an unexpected burst of oxygen production during the late afternoon in the diurnal changes of oxygen concentration as thermal stratification began to break down in Lake George.

In the Inverness pond, thermal stratification formed in the upper water column due to solar heating in the day, resulting in less dense water lying over a colder denser layer. The drop in air temperature along with wind action contributed to destratification. As shown in Figs. 3 and 4, variations in water temperature, DO and pH appear to follow the meteorological cycle during the day at the depth of 1.0 m in Events 2 and 3, but this was not true at night when the pond was destratified. Increases in water quality parameters were recorded as destratification began, after sunset. The observed phenomenon could be explained by vertical water mixing induced by stratification breakdown. The destratification caused the surface water with higher temperature, pH and DO concentration to mix with deep water; the mixing resulted in a temporary increase in those values at 1.0 m in depth.

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F. Influence on Microbiological Quality

The movement of suspended particles and organisms in the water column depends on fluid hydrodynamics. Condie and Bormans [12] theoretically demonstrated that stratification can significantly enhance the settling rates of particle populations. The effect of water mixing on plankton distribution was shown by Ganf [21] who observed the even and vertical distribution of plankton under isothermal conditions with higher concentration in deeper waters during thermal stratification in a shallow equatorial lake. Tracer tests conducted in a stabilization pond by Brissaud *et al*. [14] indicated that diurnal stratification influenced microorganism content within the pond and at its outlet; they also detected fecal coliform gradients under stratified conditions, and similar fecal coliform concentrations from the surface to mid-depth before stratification formed.

As discussed previously, external pollutant loading, sediment resuspension, and microorganism growth and death were not believed to contribute to the diurnal variations in the microorganisms at this study site. By examining water temperature profiles (Fig. 8) and diurnal variations of the microorganisms at a depth of 1.0 m (Fig. 7), it was observed that high concentrations occurred when the water layer was stratified during the day; the microorganism levels were low after stratification broke down at night. The diurnal fluctuation patterns of the microorganisms therefore might be associated with the diel cycle of stratification and destratification. The thermal gradients inhibit water vertical mixing and reduce turbulence in the water column so as to enhance the settlement of organisms. A study by Auer and Niehaus [22] quantified fecal coliform settling velocities 1.17 and 2.40 m/d for the small (0.45~10 μm) and large particle (>10 μm) classes, respectively, from samples collected following a storm event. Thus, a larger settling velocity is expected in a stratified water column. The settling velocity would tend to increase with an increase in the degree of the thermal stratification. Microorganisms in surface water layers could settle to deeper depths in a water column subjected to diurnal stratification.

Microorganism concentrations indicated an increasing trend with the increasing degree of thermal stratification after thermal stratification began. Microorganism concentrations peaked at approximately the same time as the peak in water temperature and then started to decline until stratification disappeared; the microorganisms at this depth were gradually diluted along with the breakdown of stratification. Microorganism densities remained consistently lower in the time period when the water column was well-mixed. At the same sampling location, water samples at different water depths were collected in the morning between 10:00 and 12:00 on several sampling days (without rain) in the irrigation seasons of 2006 and 2007. The sampling results (not shown) showed that both fecal coliform and *E. coli* were generally homogeneously distributed from the water surface down to approximately 1.2-1.5 m in depth, with an increase in concentration below that depth. Similar magnitudes of microorganism concentrations in the surface grab samples and irrigation water samples collected at 1.0 m depth in the early morning were found during the 2005 and 2006 irrigation seasons based on samples collected during a weekly water quality sampling program at the same pond [23]. The water depth with a homogeneous distribution of microorganisms coincided with the depth subjected to diurnal thermal stratification. The findings support the notion that vertical water mixing redistributes microorganisms evenly in the water layer. Thus, diurnal variations of the microorganisms could be interpreted as a function of diurnal thermal stratification. The movement of microorganisms might thus be predicted using the degree of the thermal stratification. In the prediction of microorganism diurnal variation, a model should be capable of presenting the microorganism variation in three regimes: stratification formation, stratification breakdown and destratification.

G. Implications of the Findings: Why is Understanding the Influence of Diurnal Hydrodynamics Important?

Public health is a key issue in stormwater reuse for recreation and irrigation. Microbial indicators such as fecal coliform and *E. coli* are commonly utilized to assess the microbiological quality of water. The diurnal variations in microorganisms suggest that test results from a sample collected randomly during the day are not sufficient for decision-making if water quality is subjected to diurnal hydrodynamics. Thus, a more illuminating water quality sampling scheme should be implemented to avoid potential risks. Moreover, the sampling and assessment of microbiological quality should target a specific time frame during the day when the water is actually collected for reuse. The pump wet well intake of the irrigation system was placed at a water depth subject to diurnal thermal stratification. The observed diel pattern in microbiological quality demonstrated high microorganism levels during the day, but improved microbiological quality at night at the same depth. This implies a lower public health risk if water is collected at night instead of during the day. This results support the irrigation scheme currently used by the city of Calgary, which waters public lands at night.

Stormwater is one of the more significant causes of water quality impairment in receiving waters; an ultimate purpose of a stormwater treatment facility is to reduce the negative influence of stormwater on receiving waters. In the engineering design of such facilities, it is generally assumed that the water bodies are completely mixed reactors. As the observations in this study demonstrate, the assumption of a completely mixed reactor is not appropriate for shallow ponds in which diurnal thermal stratification influences water quality. In the Province of Alberta, the minimum daily requirement for DO concentration is 5.0 mg/L and the range of pH is in 6.5 - 9.0 for protecting freshwater aquatic life. The allowable maximum concentration of fecal coliform for agricultural use is 100/100mL [24]. The observed diurnal pH, DO and microorganism levels in the pond violated certain requirements for receiving waters. The diurnal variations in water quality do suggest, however, that the negative impact of effluents from stormwater treatment ponds is likely reduced if the diurnal characteristics of water quality are considered in the design of outlet structures. For example, the pond water can be discharged at selected depths and at a specific time during the day, instead of only being released from the water surface when the water level exceeds a designed level. According to the

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observations in this study, it appears that the discharge from subsurface water layers at night was preferable in the quality requirements of pH and microorganism content, although DO concentrations were slightly below the allowable level.

IV. CONCLUSIONS

This study characterized the diurnal variation of physicochemical quality in a shallow stormwater pond. Definite diurnal variations in water temperature, DO, and pH were observed, and strongly coincided with the daily meteorological cycle at the water surface. At 1.0 m in depth, the pond hydrodynamic regime along with the daily meteorological cycle contributed to daily variations in the physicochemical water quality. Destratification at night was also an influence. A good linear model of DO as a function of water temperature and pH was determined. No discernible diel fluctuations in turbidity and conductivity were observed.

Fecal coliform and *E. coli* also demonstrated a diurnal rhythm at a 1.0 m depth. However, their diurnal fluctuations were not considered to be governed by the diurnal meteorological cycle, external factors, nor the growth and decay of microorganisms. Storm events and wind action, which may induce sediment resuspension, were not believed to be a cause of observed daily fluctuations in microbiological quality at this depth. The microorganism variations were likely a consequence of the diurnal thermal stratification, which leads to a deterioration in microbiological quality at lower depths. The diurnal variability in microorganisms can aid in the establishment of appropriate stormwater reuse schemes which reduce public health risk, and which should also be considered in the design of stormwater treatment ponds.

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REFERENCES

[1] Bhattacharya, T., Saha, R.K. & Chakrabarti, J., ‘‘Diel variations in the water quality, plankton population and primary production in a freshwater pond in Tripura,’’ Environment and Ecology 6(4): 928-932, 1988.

[2] Kayombo, S., Mbwette, T.S.A., Mayo, A.W., Katima, J.H.Y. & Jorgensen, S.E., ‘‘Diurnal cycles of variation of physical-chemical parameters in waste stabilization ponds,’’ Ecological Engineering 18(3): 287-291, 2002.

[3] Tadesse, I., Green, F.B. & Puhakka, J.A., ‘‘Seasonal and diurnal variations of temperature, pH and dissolved oxygen in advanced integrated wastewater pond system treating tannery effluent,’’ Water Research 38(3): 645-654, 2004.

[4] Robarts, R.D., Waiser, M.J., Arts, M.T. & Evans, M.S., ‘‘Seasonal and diel changes of dissolved oxygen in a hypertrophic prairie lake,’’ Lakes and Reservoirs: Research and Management 10(3): 167-177, 2005.

[5] Meays, C.L., Broersma, K., Nordin, R., Mazumder, A. & Samadpour, M., ‘‘Diurnal variability in concentrations and sources of Escherichia coli in three streams,’’ Canadian Journal of Microbiology 52(3): 1130-1135, 2006.

[6] Bordalo, A.A., ‘‘Microbiological water quality in urban coastal beaches: the influence of water dynamics and optimization of the sampling strategy,’’ Water Research 37(13): 3233-3241, 2003.

[7] Clark, M.L., & Norris, J.R., ‘‘Occurrence of fecal coliform bacteria in selected streams in Wyoming, 1990-99,” USGS Water Resources Investigation Report 00-4198. http://pubs.usgs.gov/wri/wri004198/ (accessed in April 2008), 2000.

[8] Shibata, T., Solo-Gabriele, H.M., Fleming, L.E. & Elmir, S., “Monitoring marine recreational water quality using multiple microbial indicators in an urban tropical environment,’’ Water Research 38(13): 3119-3131, 2004.

[9] Ortiz-Hernandez, M.C., & Saenz-Morales, R., ‘‘Effects of organic material and distribution of fecal coliforms in Chetumal Bay, Quintana Roo, Mexico,’’ Environmental Monitoring and Assessment 55(3): 423-434, 1999.

[10] Condie, S.A. & Bormans, M., “The influence of density stratification on particle settling, dispersion and population growth,’’ Journal of Theoretical Biology 187(1): 65-75, 1997.

[11] Chu, C.R. & Soong, C.K., ‘‘Numerical simulation of wind-induced entrainment in a stably stratified water basin,’’ Journal of Hydraulic Research 35(1): 21-41, 1997.

[12] Condie, S.A. & Webster, I.T., “Estimating stratification in shallow water bodies from mean meteorological conditions,’’ Journal Hydraulic Engineering 127(4): 286-292, 2001.

[13] Ganf, G.G. & Horne, A. J., ‘‘Diurnal stratification, photosynthesis and nitrogen-fixation in a shallow, equatorial lake (Lake George, Uganda),’’ Freshwater Biology 5(1): 13-39, 1975.

[14] Brissaud, F., Tournoud, M.G., Drakides, C. & Lazarova, V., ‘‘Mixing and its impact on faecal coliform removal in a stabilization pond,’’ Water Science and Technology 48(2): 75-80, 2003.

[15] Manasrah, R., Raheed, M. & Badran, M.I., ‘‘Relationships between water temperature, nutrients and dissolved oxygen in the northern Gulf of Aqaba, Red Sea,’’ Oceanologia 48(2): 237-253, 2006.

[16] National Research Council of the National Academies. Indicators for waterborne pathogens. The National Academies Press, Washington D.C. 2004.

[17] Crabill, C., Donald, R., Snelling, J., Foust, R. & Southam, G., “The impact of sediment fecal coliform reservoirs on seasonal water quality in Oak Creek, Arizona,’’ Water Research 33(9): 2163-2171, 1999.

[18] Kristensen, P., Sondergaard, M. & Jeppesen, E., ‘‘Resuspension in a shallow eutrophic lake,’’ Hydrobiologia 228(1): 101-109, 1991.

DOI: 10.5963/JWRHE0402008

[19] Davis, K., Anderson, M.A. & Yates, M.V., ‘‘Distribution of indicator bacteria in Canyon Lake, California,’’ Water Research 39(7): 1277-1288, 2005.

[20] Tanaka, Y. & Tsuda, R., ‘‘Daily fluctuations in thermal stratification, chlorophyll a, turbidity and dissolved oxygen concentration in Lake Biwa,’’ Japanese Journal of Limnology 57(4): 377-393, 1996.

[21] Ganf, G.G., “Diurnal mixing and the vertical distribution of phytoplankton in a shallow equatorial lake (Lake George, Uganda),” Journal of Ecology 62(2): 611-629, 1974.

[22] Auer, M.T. & Niehaus, S.L., ‘‘Modeling fecal coliform bacteria – I. field and laboratory determination of loss kinetics,” Water Research 27(4): 693-701, 1993.

[23] He, J., Valeo, C., Chu, A. & Neumann, N.F., ‘‘Water quality assessment of stormwater to be used for irrigating public lands,” Water Quality Research Journal of Canada 43(2/3): 93-107, 2008.

[24] Alberta Environment, Surface water quality guidelines for use in Alberta. Alberta: Science and Standards Branch, Alberta Environment, 1999.

DOI: 10.5963/JWRHE0402008