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Investigation into Heterotrophic Activities and Algal Biomass in Surface Flow Stormwater Wetlands

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***Abstract*—**Stormwater wetlands have been mainly designed in an empirical approach for water quality improvement, with little quantitative understanding of the internal microbial processes. This study investigated into heterotrophic bacterial production rate, heterotrophic bacterial mineralization percentage, and algal biomass in hypertrophic and eutrophic surface flow stormwater wetlands. Compared to a nearby wood leachate treatment wetland, the stormwater wetlands had much higher chlorophyll-*a* concentrations. The eutrophic stormwater wetland had improved water quality, whereas the hypertrophic stormwater wetland had degraded water quality. Heterotrophic bacterial activities in water were limited in the stormwater wetlands due to competition of algal growth for nutrients. The relative contribution of biofilms to the overall heterotrophic activities was higher in the stormwater wetlands than that in the wood leachate treatment wetland.

***Keywords*—**chlorophyll-a, constructed wetland, heterotrophic production, mineralization, stormwater

I. Introduction

STORMWATER contains a variety of contaminants that are mobilized during runoff events. Management of stormwater runoff, especially in urban areas, is becoming a new challenge to improvement of water quality. The US federal and state regulations require permits for stormwater discharges from municipal separate storm sewer systems and construction sites disturbing more than 0.41 ha, and stormwater discharges associated with industrial activities. Some Canadian provinces (e.g., Alberta, Ontario and Quebec) also issue permits for stormwater discharge from industrial activities.

Constructed wetlands have been one of the best management practices for non-point pollution control [1]. Surface flow constructed wetlands are the predominant type of stormwater wetlands in operation [2], [3]. Water quality improvement in a surface flow stormwater wetland may involve a variety of processes such as flocculation, sedimentation, gas transfer, adsorption, biological degradation, photosynthesis, and plant uptake. However, the internal treatment mechanisms of stormwater wetlands have rarely been quantified. As Kadlec and Wallace [3] have reviewed, there are only a few design guidelines for stormwater wetlands, which mainly take an empirical approach to modeling water quality improvement.

Microorganisms play the most important role in the ultimate removal of organic matter in constructed wetlands. The majority of the microorganisms in surface flow constructed wetlands are often assumed to be attached to submerged plant surfaces (biofilms) and sediment [3], [4], including denitrifying bacteria in stormwater wetlands [5]. However, suspended bacteria in freshwater wetlands [6], wood leachate treatment wetlands [7], [8], and macrophyte beds treating piggery effluent [9] contributed significantly to the overall heterotrophic bacterial activities. The kinetics-based design models for constructed wetlands [3] usually lump all of the removal processes in water, sediment and biofilms together with one overall reaction rate constant. The current kinetic models provide little design guidance on water depth and vegetation in surface flow wetlands. Polprasert *et al.* [10] proposed a model to separate suspended and attached growth for biological removal of organic carbon in surface flow wetlands. However, application of such modified models has been rare due to lack of simultaneous investigation into microbial activities in the different wetland components. The main objective of this study was to investigate heterotrophic production rate and mineralization percentage in water, biofilms, and sediment of two stormwater wetlands at different trophic levels. Simultaneous investigation of microbial activities in the three wetland components provides supporting data for mechanistic modeling of surface flow stormwater wetlands.

To enhance sedimentation and retention of sediment-associated contaminants, fringe wetlands are typically constructed around a deep pond. In shallow lakes, which have environments similar to fringe wetlands, algae, bacteria and protozoa form a microbial loop [11], [12]. Algae fix inorganic carbon, assimilate inorganic nutrients, and produce oxygen through photosynthesis. Heterotrophic bacteria mineralize organic matter and transform nutrients. Protozoa feed on bacteria and algae. This study simultaneously examined algal biomass along with heterotrophic bacterial activities in two fringe stormwater wetlands. Revealing the interaction of heterotrophic bacteria and algae in stormwater wetlands will improve the design considerations.

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II. Materials and Methods

This study investigated two surface flow stormwater wetlands near the west coast of Canada, Jericho stormwater retention wetland and Fishtrap Creek stormwater detention wetland. This area has mild, wet winters and warm, drier summers. According to Canadian Climate Normals 1971–2000 [13], the daily average temperature was lowest in January, 2.6–3.6°C, and highest in August, 17.1–17.7°C. Annual precipitation was 1278–1573 mm, with 70–72% during the period from October to March.

Jericho wetland (Fig. 1) is in the center of Jericho Beach, a municipal park of the City of Vancouver, British Columbia, Canada. It is located at 49°16' N and 123°12' W. The wetland has no surface discharge and retains runoff from 0.25 km^2 of forests and play fields. The bulk open water and vegetated fringe has a total area of 0.03 km^2. The vegetated fringe has a width of over 2 m, dominated by broad-leaved cattails (*Typha latifolia*). Water depth along the inner boundary of the vegetated fringe is up to 10 cm in summer. The rooting substrate of the vegetated fringe is mainly composed of fine and medium gravel (0.2–2.0 cm).

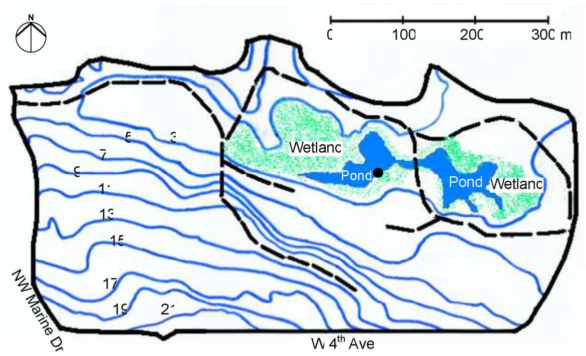

Fig. 1 Catchment of Jericho stormwater wetland. ● = sampling point; dash lines = walkways; numbers = elevation of contours.

Fishtrap Creek stormwater wetland (Fig. 2) is in the City of Abbotsford, British Columbia, Canada. It is located at 49°03' N and 122°21' W, 67 km southeast from Jericho wetland. Fishtrap Creek wetland was built before 1994 to control flood while enhancing wildlife habitat. The wetland catchment drains 9.5 km^2 of urban and forest lands. The bulk open water and vegetated fringe has a total area of 0.97 km^2. The vegetated fringe is dominated by broad-leaved cattails and surrounded by trees. Wetland water is discharged to Fishtrap Creek via a diversion structure. Water depth in the vegetated fringe varies substantially with weather conditions, usually in the range of 5–20 cm along its inner boundary. There is a 1.5-m thick layer of soft detritus on the bottom.

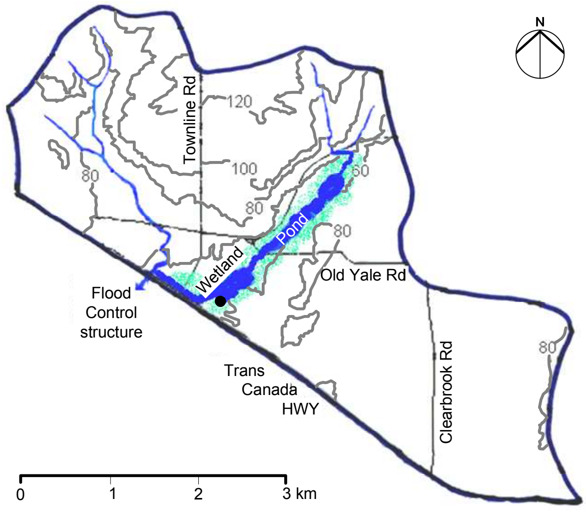

Fig. 2 Catchment of Fishtrap Creek stormwater wetland. ● = sampling point; numbers = elevation of contours.

To identify the factors that affect heterotrophic production and mineralization, the stormwater wetlands were compared with a nearby surface flow wetland treating wood leachate [8]. The wood leachate treatment wetland was constructed in 1998. It was located at 49°08' N and 122°22' W, about 18 km north of Fishtrap Creek stormwater wetland. It was a rectangular basin, having a full-berm width of 5 m and length of 17 m. It was covered uniformly by broad-leaved cattails with a water depth varying between 13 cm and 26 cm.

Water temperature, pH, and dissolved oxygen concentration were measured in-situ (Fig. 1 and Fig. 2) at the depth of 7 cm with a portable meter. Water samples were collected for chemical analysis in a lab. Chemical oxygen demand as well as tannins and lignins were analyzed by the colorimetric methods [14]. Volatile fatty acids were determined by gas chromatography (HPGC 5880A, Supelco Inc., Bellefonte, PA, USA). Ammonia, nitrate and orthophosphates were determined by a Lachat QuickChem 8000 automatic flow-injection ion analyzer, following standard methods [14].

Water, biofilm and sediment samples were collected for microbiological examination. Algal biomass was determined as chlorophyll-*a*, which was extracted with aqueous acetone at 4°C in the dark and measured by the fluorometric method [14]. Mineralization percentage of heterotrophic bacteria was determined as the percentage of an organic substrate that was respired to CO_2 over the total uptake by heterotrophic bacteria during 1–2 h of incubation of samples with ^{14}C-labeled D-glucose and acetate, following the methods used by Tao *et al.* [8] and Tao and Hall [7]. Heterotrophic bacterial production rate was determined by measuring the rate of ^{3}H-leucine incorporation into bacterial proteins after incubation of samples with ^{3}H-labeled leucine [8]. In-situ measurements and sample collection were made weekly with the wood leachate wetland and 4-5 times with Jericho wetland and Fishtrap Creek wetland between July 25 and October 5. Each field sample was examined with 2-3 replicates.

III. Results and Discussion

Water quality monitoring results are presented in Table I. Jericho stormwater wetland had chlorophyll-*a* concentrations (Table II) at the hypertrophic level in the trophic classification system for inland waters [15]. Consequently, dissolved oxygen in the surface water was substantially oversaturated and pH was raised to alkaline by daytime algal photosynthesis. Despite the eutrophic level of chlorophyll-*a* concentrations in water (Table II), Fishtrap Creek stormwater wetland also had dissolved oxygen oversaturated to 108–201%. Compared to the stormwater wetlands, the nearby constructed wetland receiving wood leachate had lower water temperatures and much lower concentrations of dissolved oxygen and chlorophyll-*a*. The dark color of wood leachate might have curtailed light penetration and hindered algal growth in the wood leachate wetland. Unlike stormwater runoff, the wood leachate was acidic and had very high chemical oxygen demand.

TABLE I
WATER QUALITY OF STORMWATER WETLANDS AND A NEARBY WOOD LEACHATE TREATMENT WETLAND

	Jericho stormwater wetland	Fishtrap Creek stormwater wetland	Wood leachate wetland
Water temperature (^oC)	26.8 ± 5.2	22.6 ± 5.8	13.8 ± 3.4
Dissolved oxygen (mg/L)	>20	11.9 ± 2.4	0.4 ± 0.1
pH	8.2 ± 1.1	7.6 ± 0.5	5.1 ± 0.4
Tannins and lignins (mg/L)	1.8 ± 0.2	0.7 ± 1.0	583 ± 242
Volatile fatty acids (mg/L)	5.9 ± 6.6	5.6 ± 6.7	340 ± 219
Ammonia-N (mg/L)	0.21 ± 0.30	0.04 ± 0.01	0.16 ± 0.10
Nitrate-N (mg/L)	0.29 ± 0.27	0.04 ± 0.01	0.07 ± 0.05
Orthophosphate-P (mg/L)	0.06 ± 0.01	0.01 ± 0.01	0.66 ± 0.32
Chemical oxygen demand (mg/L)	71 ± 52	43 ± 12	2265 ± 1129

Note: Mean ± Standard deviation. *n* = 4 for stormwater wetlands and 10 for wood leachate wetland.

Fishtrap Creek stormwater wetland had concentrations of chemical oxygen demand, nitrate, and orthophosphate lower than the event mean pollutant concentrations of the stormwater from typical US mixed urban land use areas [1], indicating contaminant removal in the stormwater wetland. Jericho stormwater wetland had concentrations of chemical oxygen demand and orthophosphate higher than the typical event mean values of stormwater from urban open areas [1], suggesting degraded water quality. The hypertrophic status of Jericho wetland was attributed to fertilizer application to the playing fields and its long retention time during the warm, drier summer.

The environments of low organic substrates and inorganic nutrients favor attached bacterial growth than suspended growth [8], [16], [17]. Unlike the nearby wood leachate treatment wetland that had high concentrations of volatile fatty acids and chemical oxygen demand (Table I), Jericho and Fishtrap Creek stormwater wetlands had limited availability of organic substrates and orthophosphates. Consequently, the stormwater wetlands had lower heterotrophic production rates by bacteria suspended in water than the nearby wood leachate treatment wetland (Table III). Contrarily, bacteria in biofilms and sediment had much higher production rates in the stormwater wetlands than the wood leachate wetland. The stormwater wetlands had obviously higher biofilm:water ratio for heterotrophic bacterial production, suggesting an important role of emergent plants in stormwater wetlands despite a minor role of plants in wood leachate treatment wetlands [8].

TABLE II
CHLOROPHYLL-*a* CONCENTRATION IN STORMWATER WETLANDS AND A NEARBY WOOD LEACHATE TREATMENT WETLAND

	Jericho stormwater wetland	Fishtrap Creek stormwater wetland	Wood leachate treatment wetland
Water (µg/L)	519 ± 159	5.4 ± 2.8	0.9 ± 1.0
Biofilms on plants (mg/m^2)	3.9 ± 0.6	2.6 ± 0.9	0.5 ± 0.9

Note: Mean ± Standard error. *n* = 5 for stormwater wetlands and 9 for wood leachate wetland.

TABLE III
HETEROTROPHIC BACTERIAL PRODUCTION RATE IN STORMWATER WETLANDS AND A NEARBY WOOD LEACHATE TREATMENT WETLAND

	Jericho stormwater wetland	Fishtrap Creek stormwater wetland	Wood leachate treatment wetland
Water (µg C/L·d)	4.7 ± 3.0	5.8 ± 4.4	10 ± 6
Biofilm (µg C/m^2·d)	53 ± 15	184 ± 149	18 ± 15
Sediment (µg C/g·d)	No data	7.2 ± 2.4	0.8 ± 0.7

Note: Mean ± Standard error. *n* = 4 for stormwater wetlands and 8 for wood leachate wetland.

Relative to other freshwater wetlands [6], [18], the two stormwater wetlands had moderate levels of heterotrophic production by bacteria suspended in water and attached on sediment. Bacterial production rates in marsh water determined by Moran and Hodson [6] with ^{3}H-leucine incorporation varied greatly (25- to 55-fold) over long periods. Bacterial production in stormwater wetlands could be stimulated by the substrates released soon after senescence of emergent plants. Like freshwater wetlands, stormwater treatment wetlands may be subject to temporal variations in heterotrophic production due to the seasonal change in plant growth and diurnal fluctuation in algal growth. This needs to be investigated in the future.

The two model substrates, glucose and acetate, produced similar results in heterotrophic mineralization percentage (Table IV). Compared to the eutrophic Fishtrap Creek wetland, the hypertrophic Jericho stormwater wetland had lower heterotrophic production rate and mineralization percentage in water, possibly due to increased competition between algae and heterotrophic bacteria for the limited nitrogen and phosphorus. The higher mineralization percentage of sediment in Jericho stormwater wetland was likely due to release of organic substrates and inorganic nutrients from the decaying algae accumulated on the sediment surface. Similarly, the lower mineralization percentages in the stormwater wetlands relative to those in the wood leachate treatment wetland could be attributed to the limited availability of organic substrates.

TABLE IV
MINERALIZATION PERCENTAGE OF GLUCOSE AND ACETATE BY BACTERIA IN STORMWATER WETLANDS AND A NEARBY WOOD LEACHATE TREATMENT WETLAND

	Jericho stormwater wetland	Fishtrap Creek stormwater wetland	Wood leachate treatment wetland
Glucose			
Water	19.3 ± 6.8	37.7 ± 8.5	53.7 ± 11.9
Biofilm	36.8 ± 19.4	31.6 ± 9.7	67.0 ± 18.5
Sediment	36.5 ± 42.6	5.5 ± 2.2	63.8 ± 27.5
Acetate			
Water	17.4 ± 5.4	33.9 ± 17.0	70.7 ± 15.2
Biofilm	30.1 ± 37.6	40.0 ± 14.1	70.2 ± 21.9
Sediment	40.5 ± 4.8	13.1 ± 5.5	94.8 ± 4.5

Note: Mean ± Standard error. n = 4 for stormwater wetlands and 10 for wood leachate wetland.

IV. CONCLUSIONS

Stormwater wetlands may improve water quality at proper hydraulic retention as in the Fishtrap Creek stormwater detention wetland. The Jericho stormwater retention wetland that had no discharge suffered from water quality degradation.

There is a remarkable relation between primary production and heterotrophic activity in surface flow stormwater wetlands. Algal growth competed over heterotrophic bacteria in water for inorganic nutrients in the stormwater wetlands, while decaying algae enhanced heterotrophic mineralization in sediment.

Biofilms contributed more to heterotrophic bacterial activities in stormwater wetlands than the wood leachate treatment wetland. Therefore, emergent plants may play a more important role in stormwater wetlands than wastewater treatment wetlands.

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