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Event-based stormwater management pond runoff temperature model

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ABSTRACT

Stormwater management wet ponds are generally very shallow and hence can significantly increase (about 5.4 °C on average in this study) runoff temperatures in summer months, which adversely affects receiving urban stream ecosystems. This study uses gene expression programming (GEP) and artificial neural networks (ANN) modeling techniques to advance our knowledge of the key factors governing thermal enrichment effects of stormwater ponds. The models developed in this study build upon and compliment the ANN model developed by Sabouri et al. (2013) that predicts the catchment event mean runoff temperature entering the pond as a function of event climatic and catchment characteristic parameters. The key factors that control pond outlet runoff temperature, include: (1) Upland Catchment Parameters (catchment drainage area and event mean runoff temperature inflow to the pond); (2) Climatic Parameters (rainfall depth, event mean air temperature, and pond initial water temperature); and (3) Pond Design Parameters (pond length-to-width ratio, pond surface area, pond average depth, and pond outlet depth). We used monitoring data for three summers from 2009 to 2011 in four stormwater management ponds, located in the cities of Guelph and Kitchener, Ontario, Canada to develop the models. The prediction uncertainties of the developed ANN and GEP models for the case study sites are around 0.4% and 1.7% of the median value. Sensitivity analysis of the trained models indicates that the thermal enrichment of the pond outlet runoff is inversely proportional to pond length-to-width ratio, pond outlet depth, and directly proportional to event runoff volume, event mean pond inflow runoff temperature, and pond initial water temperature.

1. Introduction

Urbanization and climate change negatively affect stream hydrology and ecology due to increase in the frequency of floods, sediment loads, chloride loads, and increase in summer stream temperatures due to impervious surfaces and shallow stormwater ponds (Klemetson and Rogers, 1985; Xie and James, 1994; James and Verspagen, 1996; Anderson et al., 2002; Haq and James, 2002; Starzec et al., 2005; Thompson et al., 2008; Booth and Bledsoe, 2009; Betts et al., 2014, 2015; Asnaashari et al., 2015; Trenouth et al., 2015a,b,c). Stormwater management ponds have been widely applied across many developed nations to mitigate flooding in urban watersheds; however, they may also cause negative thermal effects on aquatic habitats (Hester and Bauman, 2013; McEnroe et al., 2013; Song et al., 2013). Herb et al. (2009) observed that the average pond outflow water temperature was 1.2 °C higher than inflow temperature, indicating that heat energy was added to water within the pond. They also reported that the rate of heat outflow from the pond decreased as the ratio of volumetric outflow rate to inflow rate decreased; as a result, although the duration of impacts increased, temperature impacts to a receiving system decreased. Thermal pollution in stormwater ponds is clearly an important area of study, still requiring further attention.

There are several models reported in the literature capable of modeling thermal enrichment of stormwater runoff in urban watersheds that may include stormwater management wet ponds. The WEP model (Water and Energy transfer Processes model) developed by Jia et al. (2002) is one of the first physically-based spatially distributed models that is capable of predicting water and energy budgets in urbanized and partially-urbanized watersheds. The model requires the availability of large amounts of data: precipitation, wind velocity, air temperature, sunshine hours, humidity, water level, land use, topography, soil, river network characteristics, pipe network and flow diversions, and population.

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Nomenclature

ANNs	artificial neural networks (–)
AVGD	average pond depth (m)
BMPs	best management practices (–)
CDRA	catchment drainage area (m^2)
NSE	coefficient of efficiency (Nash–Sutcliffe) (–)
EMTA	event mean temperature of air (°C)
EMT	event mean temperature (°C)
EMTI	event mean temperature of inlet (°C)
EMTO	event mean temperature of outlet (°C)
EPR	evolutionary polynomial regression (–)
ET	expression tree (–)
GEP	gene expression programming (–)
GRCA	Grand River Conservation Authority (–)
GTI	Guelph Turfgrass Institute (–)
LWRO	pond length to width ratio (–)
MAD	mean absolute deviation (–)
MCS	Monte Carlo simulation (–)
MINUHET	Minnesota urban heat export tool (–)
MLP	multi-layer perceptron (–)
PCSWMM	personal computer storm water management model (–)
PDF	probability density function (–)
PINT	pond initial water temperature (°C)
PODT	pond outlet depth (m)
PSUA	pond surface area (m^2)
Q	runoff flow rate (m^3/s)
RDPT	rainfall depth (mm)
RMSE	root mean squared error (–)
S_n	normalized sensitivity coefficient (–)
SWMPs	stormwater management ponds (–)
Y	EMTO/EMTA (–)
TURM	thermal urban runoff model (–)
WEP	water and energy transfer processes (–)
X_1	PSUA/CDRA (–)
X_2	LWRO (–)
X_3	PODT/AVGD (–)
X_4	RDPT/AVGD (–)
X_5	EMTI/EMTA (–)
X_6	PINT/EMTA (–)
X_7	AVGD ∗ RDPT/PSUA (–)

The temperature urban runoff model (TURM) developed by Roa-Espinosa et al. (2003) and advanced by Thompson et al. (2008) is another example of a complex heat-balance model that requires extensive weather variables. The required input climatic data includes; maximum and minimum daily air temperature, maximum daily solar radiation, hourly air temperature, relative humidity prior to the storm, hourly wind speed, solar radiation during the storm, storm rainfall depth and duration, and rain temperature.

Lamoureux et al. (2006) introduced the Pond Heat and Temperature Regulation (PHATR) model. They included thermal radiation from pond surface and solar radiation absorbed by the pond to simulate the performance of heated and unheated ponds. And most recently, Herb et al. (2009) developed the Minnesota Urban Heat Export Tool (MINUHET), which is an analytical model capable of simulating stormwater runoff and its associated heat content for urban watersheds. The model produces a time series of flow rates and water temperatures at the outlet of a watershed for each rainfall event. The model requires extensive hydrologic, temperature and weather data for combining the heat flux components.

While existing models have their advantages, the following limit their application:

- Some provided very simple relations neglecting important contributing parameters.
- Some did not include heat flux from rainfall.
- More recent ones were too complex requiring extensive data over a long time span for calibration/validation and for running the model.

In view of these limitations, the present study aims to use a monitoring program and novel modeling techniques to advance our knowledge of the key factors governing thermal enrichment effects of stormwater ponds, including: (1) Upland Catchment Parameters (catchment drainage area and event mean runoff temperature inflow to the pond); (2) Climatic Parameters (rainfall depth, event mean air temperature, and pond initial water temperature); and (3) Pond Design Parameters (pond length-to-width ratio, pond surface area, pond average depth, and pond outlet depth).

2. Materials and methods

2.1. Site description

Four urban sub-watersheds with stormwater management ponds were selected for study based on accessibility and availability of design reports to collect a broad range of data for different design components. Two ponds were studied in each of the cities of Guelph and Kitchener, Ontario, Canada (Fig. 1) and monitored during three summers (2009–2011) to calculate event mean temperatures of the pond inlets (EMTI) and outlets (EMTO). Design parameters for the ponds are listed in Table 1. It is worth noting that Ponds 33 and Church were very shallow with average depths less than 0.5 m and very large relative surface areas (ratio of pond surface area to catchment area) of 4%; while the other two ponds 53 and 74 were much deeper ponds with much smaller relative surface areas of only 1% (Table 1).

2.1.1. Pond 33

Pond 33 (Fig. 2) has a contributing area of 19.4 ha and is located in the City of Guelph, on South Creek Trail, next to Preservation Park (latitude 43.50953, longitude −80.21835). A pond inlet forebay had been constructed to restrain larger sediment particles. The forebay was designed with 2:1 length-to-width ratio, 1.2 m maximum depth and 7:1 side slopes. The total forebay volume is 1500 m^3. All flows up to the five-year rainfall event discharge through the quality control outlet structure which is designed to detain the “first flush” 25 mm rainfall event for a minimum of 24 h. The flow rates from the quality outlet structure are controlled by a 200 mm diameter outlet pipe. Both the quality and quantity outlets from the pond drain discharge to riprap dispersion structures prior to discharging to a receiving system (City of Guelph Works Department, 1996).

2.1.2. Pond 53

Pond 53 (Fig. 2) is located in the City of Guelph at the intersection of York and Watson streets (latitude 43.56326, longitude −80.21019) with a contributing area of 79 ha draining to Clythe Creek. Clythe Creek is located south of the site and eventually