Science of the Total Environment 559 (2016) 141–150

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Temperature dynamics of stormwater runoff in Australia and the USA

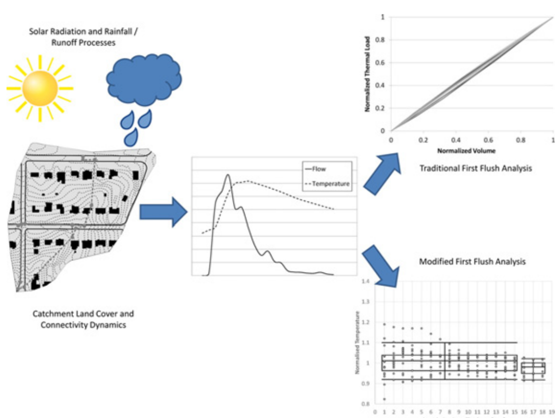
J.M. Hathaway [a,*], R.J. Winston [b], R.A. Brown [c], W.F. Hunt [b], D.T. McCarthy [d]

[a] University of Tennessee, Knoxville, TN, USA
[b] North Carolina State University, Raleigh, NC, USA
[c] United States Environmental Protection Agency, Edison, NJ, USA
[d] Environmental and Public Health Microbiology Laboratory, Civil Engineering Department, Monash University, Melbourne, VIC, Australia

HIGHLIGHTS

- The influence of scale was noted as temperature dynamics varied based on catchment size
- Traditional methods for first flush analysis were ill suited for evaluating temperature patterns
- Using a modified approach, a temperature first flush was observed for the first time in literature

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 21 March 2016
Accepted 21 March 2016
Available online 6 April 2016

Editor: D. Barcelo

Keywords:
First flush
Temperature
Urban runoff
Thermal pollution

ABSTRACT

Thermal pollution of surface waters by urban stormwater runoff is an often overlooked by-product of urbanization. Elevated stream temperatures due to an influx of stormwater runoff can be detrimental to stream biota, in particular for cold water systems. However, few studies have examined temperature trends throughout storm events to determine how these thermal inputs are temporally distributed. In this study, six diverse catchments in two continents are evaluated for thermal dynamics. Summary statistics from the data showed larger catchments have lower maximum runoff temperatures, minimum runoff temperatures, and temperature variability. This reinforces the understanding that subsurface drainage infrastructure in urban catchments acts to moderate runoff temperatures. The catchments were also evaluated for the presence of a thermal first flush using two methodologies. Results showed the lack of a first flush under traditional assessment methodologies across all six catchments, supporting the results from a limited number of studies in literature. However, the time to peak temperature was not always coincident with the time to peak flow, highlighting the variability of thermal load over time. When a new first flush methodology was applied, significant differences in temperature were noted with increasing runoff depth for five of the six sites. This study is the first to identify a runoff temperature first flush, and highlights the need to carefully consider the appropriate methodology for such analyses.

* Corresponding author.
E-mail address: hathaway@utk.edu (J.M. Hathaway).

http://dx.doi.org/10.1016/j.scitotenv.2016.03.155
0048-9697/

1. Introduction

Urban stormwater has been shown to transport numerous types of pollutants to surface waters, including metals, nutrients, sediment, and microbes. However, an often under-evaluated consequence of urbanization is an increase in stream temperature, known as thermal pollution (Leopold, 1968). This thermal pollution is detrimental to aquatic ecology, which is a concern since biological communities within streams and lakes are critical to integrated ecological systems and are economically important as food- and game-fishing resources (Bhat et al., 1998). Productivity of coldwater ecosystems is dependent upon the thermal regime of surface waters (Beschta et al., 1987). For instance, Wang and Kanehl (2003) correlated higher stream temperatures to low macroinvertebrate biodiversity, and stream temperature spikes can directly impact the development of coldwater fish at all life stages by influencing egg development, metabolism, resistance to disease and parasites, migration, spawning habits, and survival (Beschta et al., 1987; Hokanson et al., 1977; Armour, 1991; Caissie, 2006). However, these effects are not confined to cold water species. Although water temperatures in urban streams may not reach levels resulting in mortality for many species, reduced growth rate and higher stress are likely under the elevated temperatures in urban streams (Somers et al., 2013; Hester and Doyle, 2011; Beitinger et al., 2000). Such sub-lethal effects are capable of affecting stream ecology (Rose, 2000).

Although few studies have investigated spatial and temporal temperature variations in urban streams, research by Somers et al. (2013); Nelson and Palmer (2007), and Booth et al. (2014) has begun to examine these patterns. Impervious surfaces transfer heat to runoff during storm events, resulting in elevated runoff temperature as it enters receiving streams (Thompson et al., 2008; Jones et al., 2012; Van Buren et al., 2000; Kieser et al., 2004). Somers et al. (2013) and Nelson and Palmer (2007) discuss the influence of urban runoff on stream temperatures, quantifying the maximum temperature and change in temperature experienced during storm events for numerous catchments in North Carolina and Maryland, respectively. Across the ten most-developed streams evaluated by Somers et al. (2013), temperature fluctuations ranged from −2.5 to 4 °C during the 24 h period surrounding a storm, while Nelson and Palmer (2007) observed surges in temperatures averaging 3.5 °C during rain events and noted maximum temperature increases exceeding 7 °C.

Land use, in particular impervious area, has a major impact on thermal fluctuations (Walsh et al., 2005; Nelson and Palmer, 2007; Herb et al., 2008; Sabouri et al., 2013; Booth et al., 2014). Somers et al. (2013) correlated urban development in a given catchment to the maximum stream temperature surge during storm events. Detailed investigation into land use impacts were performed by Jones et al. (2012), who explored the influence of urban land surface attributes on runoff temperatures, investigating differences due to pavement materials, tree canopy presence, and conveyance pathways. Characteristics such as overhanging mature tree canopies and light colored pavements produced lower runoff temperatures relative to dark colored pavements exposed to full sun light. Such studies support additional site scale observations of variable urban surface effects on air temperature (Huang et al., 2008), inferring the differential influence of some surfaces on heat retention and subsequent release to runoff during storm events. Thus, catchment makeup has a substantial influence on thermal inputs from stormwater runoff, allowing the use of temperature to better understand catchment processes.

Although these studies have begun to classify the in-stream impacts of stormwater runoff, the intra-event thermal dynamics of stormwater runoff prior to discharge into surface waters are not well defined. Examining thermal dynamics in urban runoff will aid in understanding how these signals propagate through the urban system and within nearby waterways. Further, previous studies have not explored these dynamics at various scales, from parking lots to larger open channel systems. Exploring these scales will result in a more robust understanding of the influence of urban runoff on surface waters, and how thermal patterns change based on the point of reference. As drainage intensity typically increases with catchment size, and as subsurface drainage has been shown to cool stormwater in such studies as Jones et al. (2012), the influence of scale in urban systems is critical.

Pollutants in urban stormwater are commonly evaluated to determine their pattern of transport. One common characterization is the extent to which pollutants exhibit a first flush, that is, the extent to which a proportionally higher export of a pollutant occurs during the initial portion of the storm event. Numerous thresholds have been defined to signify a first flush (Sansalone and Cristina, 2004; Hathaway et al., 2012). Studies such as Bertrand-Krajewski et al. (1998); McCarthy (2009), and Hathaway and Hunt (2011) have defined the first flush as the percentage of pollutant load transported in the first 30% of storm volume. In one of the few previous studies of intra-event temperature trends in urban stormwater, the thermal first flush effect was analyzed by Deletic (1998) on two small asphalt catchments in Belgrade, Yugoslavia. Deletic (1998) showed a fairly consistent linear relationship between temperature loading and runoff volume, indicating no first flush effect. More recently, similar results were reported by Kertez and Sansalone (2014) for a parking lot in Florida, USA. However, studies such as McCarthy et al. (2012) and Sabouri et al. (2013) show catchment complexity influences pollutant relationships in urban runoff. Thus, the first flush effect may vary based on catchment size, land use, and percent imperviousness. Further, new methodologies proposed by Bach et al. (2010) to examine the presence of the first flush may be more applicable to examinations of temperature dynamics.

Research into abatement of thermal pollution by stormwater control measures (SCMs) has shown surface detention systems to be a thermal source, and filtration-based SCMs and underground storage/piping to be thermal sinks (Jones and Hunt, 2009, 2010; Natarajan and Davis, 2010; Winston et al., 2011; Wardynski et al., 2013). However, very few SCMs are currently designed for thermal mitigation. An understanding of how thermal flux varies in urban catchments during rainfall-runoff events is needed to improve SCM designs in temperature sensitive catchments, and understand what management and treatment mechanisms should be employed to address thermal pollution.

Although thermal pollution is a concern for surface waters worldwide, the intra-event dynamics of temperature in urban runoff are not well understood. Defining temperature variability during storm events across multiple scales will elucidate the timing and delivery of thermal pollution to surface waters, and allow more targeted design of SCMs. Thermal dynamics may also be used to better understand catchment processes such as the differential runoff production due to varied spatial patterns of land cover (as runoff temperature varies by land use). The purpose of this study is to explore thermal dynamics in six catchments in two continents representing a variety of spatial scales to better understand how temperature varies during storm events, and if these patterns differ at various scales.

2. Methods

2.1. Site description

Six catchments were monitored to quantify runoff hydrographs and temperature dynamics in Australia and the USA (Table 1). The catchments varied in size from 0.13 ha to >11,200 ha and had connected imperviousness varying from 15 to 100%. Between 15 and 93 event hydrographs and thermographs (temperature vs. time) were collected for each catchment over nine to twenty-one months. For Louisburg, data were only collected during the summer months. Land uses represented in the catchments were generally residential and/or commercial. These data allowed for a robust thermal first flush analysis across land use, imperviousness, catchment area, and catchment complexity. Catchment complexity refers to the extent to which the catchment is sewered with subsurface infrastructure, which typically happens to a higher