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Metrics for assessing thermal performance of stormwater control measures

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ABSTRACT

Urban runoff can impact the thermal regime of surface waters and degrade valuable aquatic ecosystems. Some stormwater control measures (SCMs) have been shown to mitigate the effects of thermally-enriched runoff, but previous studies lacked consistency when characterizing the thermal behavior of SCMs. Ecologically-relevant parameters such as maximum outflow temperature, duration of temperatures exceeding thresholds for coldwater species, and thermal load have all been considered in past research. Standard metrics that properly represent the downstream impacts of urban stormwater were needed. This paper evaluated thermal metrics to provide designers and regulators with catchment-scale methods for assessing thermal performance and compliance. It was concluded that multiple metrics must be employed to account for both thermal load and biologically-based reference temperature limits. Metrics for temperature evaluations were broken out by data requirements. When only SCM temperature data are available, event mean temperature estimation appears to be the most rigorous metric. Groundwater temperature may also be employed as a surrogate metric for SCM discharge temperatures if conservative protection of coldwater stream health is desired. When SCM temperature and flow data exist, thermal load reductions should be explored.

Efficacy of the low impact development (LID) strategy for temperature mitigation (retaining onsite greater than the 95th percentile storm event) was evaluated using field-collected permeable pavement data. Based on these data, retaining the 95th percentile storm event was determined to be an effective technique for thermal protection of surface waters.

However, the most rigorous metrics involve long-term temperature and flow data from local reference streams. The best metric currently available is the uniform continuous above threshold (UCAT) method, in which it is necessary to consider continuous exposure duration when comparing against biological thresholds. These analyses can be tailored to specific species of interest within a targeted ecoregion. Combined with thermal load and mixing analysis in-stream, the UCAT method can provide a real-world estimation of the impacts of development. Additionally, evaluation of mixing zones in-stream should also be employed to adequately assess thermal impacts. However, these methods are the most data intensive.

The metrics discussed in this paper can be used to inform new and existing design methodologies for regulating stormwater temperature, duration, and thermal load.

1. Introduction

Streams and lakes provide valuable ecosystem services to humans, and have been valued at US\$8500 $ha^{-1} yr^{-1}$ (Costanza et al., 1997). Biological communities supported by surface waters (particularly coldwater systems) are economically important as food- and game-fishing resources (Bhat et al., 1998). For instance, the direct economic output from coldwater angling in North Carolina and Minnesota have been respectively estimated at US\$146 million and US\$150 million per year (Responsive Management and

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Southwick Associates, 2009; Gartner et al., 2002). Productivity of these valuable coldwater ecosystems is dependent upon the thermal regime of surface waters (Beschta et al., 1987).

Stream temperature affects the metabolism, physiology, and lifecycle behaviors of aquatic organisms, as well as influencing biodiversity, productivity, and nutrient cycling (Ebersole et al., 2001; Allan, 1995). As stream temperatures increase, biological activities and feeding rates of invertebrates follow suit; increased microbial metabolism can deplete water of dissolved oxygen, which compounds the effect of decreased oxygen solubility at higher temperatures, and could lead to premature decomposition of the overall stocks of food sources available to organisms during summer months (United States Environmental Protection Agency (USEPA), 1986; Suberkropp et al., 1975; Cummins et al., 1973; Webster and Benfield, 1986). Minshall (1968) reported decreases in invertebrate diversity and abundance in reaches of a spring-fed stream where temperatures were elevated due to lack of riparian vegetation; more recently Wang and Kanehl (2003) correlated higher maximum weekly stream temperatures and percent imperviousness to lower macroinvertebrate biodiversity. Aquatic ecosystems with abundant and diverse biota support healthy fish populations, so it is therefore important to preserve a thermal regime that is appropriate for the biota that inhabit the stream (Beschta et al., 1987).

In addition to trophic effects, 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 mortality (Beschta et al., 1987; Hokanson et al., 1977; Armour, 1991; Caissie, 2006). The upper lethal limit at which salmon eggs become non-viable ranges from 13.5 to 16.5 °C (Seymour, 1959; Combs, 1965), and Rossi and Hari (2007) found that the lethal threshold for adult trout survival after 1 h of exposure was 25 °C. Trout and salmon species prefer maximum daily stream temperatures below 21 °C (upper avoidance temperature), and tend to be more abundant when mean weekly maximum temperatures are less than 22 °C (Coutant, 1977; Barton et al., 1985). Maximum daily and weekly mean temperature thresholds for brown and brook trout were field-measured in Wisconsin and Michigan at 25.3 °C and 23.3 °C, respectively (Wehrly et al., 2007). Warming of winter and spring water temperatures can also lead to early migration and decreased survival, even when upper avoidance and lethal temperatures are not exceeded (Holtby, 1988).

The thermal regime of streams is controlled by many interacting factors, and can be aggravated by human activities within a catchment. Degrading thermal effects due to logging and riparian buffer removal (Beschta and Taylor, 1988; Holtby, 1988; Rutherford et al., 1997), impoundments (Lessard and Hayes, 2003), industrial/power plant cooling applications (Walker, 1989; Meier et al., 2003), and wastewater discharge (Kinouchi et al., 2007; Kinouchi, 2007) on streams and water bodies have been studied. The United States Environmental Protection Agency (USEPA) (1986) established water quality standards for temperature in 1986. At present, temperature is the tenth most common cause of impairment to United States rivers and streams, accounting for the assignment of 2040 regulated total maximum daily loads (TMDLs; United States Environmental Protection Agency (USEPA), 2012). However, stormwater runoff had rarely been specifically addressed as a source of thermal impairment until recent years, with the development of thermally targeted SCM designs in Minnesota and thermal loading TMDLs, such as that in the Chagrin River Watershed, Ohio (Minnesota (MN) Pollution Control Agency (MPCA), 2014; Ohio Environmental Protection Agency (EPA), 2007).

Runoff from impervious surfaces can reach temperatures in excess of 39 °C (Jones and Hunt, 2009). Consequently, thermally-enriched runoff has been shown to increase stream temperatures in North Carolina by over 9 °C (Wardynski et al., 2013), and in Maryland by over 7 °C (Nelson and Palmer, 2007). These temperature surges can affect streams for up to 10% of summer days, with the highest runoff temperatures and thermal impacts occurring during late afternoon storms (Nelson and Palmer, 2007; Herb et al., 2009; Winston et al., 2011). It should be noted that these spikes in runoff temperature are dependent upon regional climate, pavement type and color, percent impervious cover, and shading of the impervious surfaces in the catchment (Jones et al., 2012; Sabouri et al., 2013). Consequently, temperature was specifically mentioned as a parameter of concern in the U.S. Energy Independence and Security Act (EISA) of 2007, which dictated all federal development or redevelopment projects shall "...maintain or restore, to the maximum extent technically feasible, the predevelopment hydrology of the property with regard to the temperature, rate, volume, and duration of flow" (U.S.C. (United States Code), 2007).

Existing water quality standards, largely based on maintaining target temperature ranges in receiving waterways, do not provide guidance for mitigating the temperature of water from an urban catchment. Unlike point-source discharges, urban catchments often drain to sewerage systems, which impact thermal regimes (Jones et al., 2012; Sabouri et al., 2013). These catchments discharge at a highly variable rate and frequency. Because of the spatial and temporal variability of runoff, runoff temperature, and thermal load (the combination of temperature and stormwater volume), it is difficult to evaluate the effects of runoff on receiving water temperature from an individual urban catchment without 2-dimensional modeling. Qual2K/Qual2E can provide diurnal heat budgets given hydrologic and temperature inputs (United States Environmental Protection Agency (USEPA), 1995). However, this is often not practical, given time and budgetary constraints as well as lack of data for most development projects.

The thermal behaviors of several stormwater control measures (SCMs) have been studied, but there is little consistency in reporting of results (Lieb and Carline, 2000; Jones and Hunt, 2009, 2010; Natarajan and Davis, 2010; UNH Stormwater Center, 2011; Winston et al., 2011; Wardynski et al., 2013). What metrics can researchers, designers, and regulators use to assess whether a site will have a thermal impact on downstream aquatic systems? How can one evaluate whether predevelopment hydrologic temperatures have been maintained after development of a site? How do stormwater thermal metrics apply to various climates, ecosystems, and locations within a watershed? This paper will assess temperature-based water quality standards and evaluate metrics for evaluating the thermal performance of SCMs.

2. Methodology

To demonstrate the strengths and limitations of stormwater thermal metrics presented hereafter, a permeable pavement parking lot (specifically permeable interlocking concrete pavers, or PICP) in Boone, North Carolina, was evaluated. In addition, Boone Creek, into which the PICP parking lot drained, was monitored for stormwater temperature during the seven-month study (Wardynski et al., 2013). These data were compared against a nearby thermally-non-impacted reference reach, since streams supporting trout in the region could likely serve as a target condition for urbanizing or urbanized streams. Ten metrics were demonstrated using these data; these are listed below in the order discussed.

1. Event mean temperature reduction within an SCM.