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REVIEW PAPER

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Swimming through the urban heat island: Can thermal mitigation practices reduce the stress?

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Abstract

Green infrastructure (GI) and other stormwater management practices are commonly designed to reduce stormflow volume and pollutant loads by using infiltration, retention, and evapotranspiration to capture stormwater. Although these methods are be designed to reduce impacts of stormwater volumes and pollutant loads, they may not be designed to mitigate thermal load from stormwater runoff in urban areas. This review of literature identifies key drivers of stream temperature in urban streams, including heat transference from stormflow and effects of pipe networks and evapotranspiration on baseflow. Recent simulation studies indicate the need for more than bioretention, increased infiltration, and tree canopy mitigation practices to reduce heat stress in urban streams. These studies show greatest reductions in thermal load by applying cool surfaces as a single thermal mitigation practice (TMP) and comprehensive applications of TMPs to all available areas at the watershed scale. This review of available literature suggests that incorporating TMPs into current and future GI designs will help maintain water resources, water quality, aquatic ecosystems, and coldwater stream species across the landscape. Further research is needed on the most effective ways to implement TMPs as part of our current and future GI designs for stormwater and how to best incorporate these measures into urban design concepts at larger spatial scales.

KEYWORDS

bioretention, coldwater fish, cool surfaces, effective impervious, forest canopy, thermal load, urban stormwater

1 | INTRODUCTION

Urbanization is known to impact stream fish communities, with previous research relating percent impervious surface in watersheds to changes in fish species diversity and tolerance to pollution (Roy et al., 2005). Specific stormwater hydrology processes related to impervious surfaces that drive temperature and thermal habitat characteristics for coldwater fish have not been explored extensively by the literature. Fish require specific ranges of temperatures to survive, successfully spawn, and recruit all life stages into the next generation, and thermal habitat connectivity throughout stream networks needs to be maintained (Al-Chokhachy, Wenger, Isaak, & Kershner, 2013). While stream water temperature increases have been documented throughout the United States, rates of increase are the greatest for urban streams (Kaushal et al., 2010). With urban land use in the United States projected to increase by 79% from 39.5 million hectares in 1997 to 70.5 million hectares by 2025, it is vital to understand the magnitude and mechanisms of thermal impacts to urban streams (Alig, Kline, & Lichtenstein, 2004) both from traditional and “green” urban infrastructure.

Green infrastructure (GI) to treat stormwater is commonly designed to reduce stormflow volume and pollutant loads by using infiltration, retention, and evapotranspiration to capture stormwater. Examples of stormwater, infiltration-based GI include bioretention cells, rain gardens, bioswales, permeable pavement, and green roofs. Other retention-based stormwater treatment practices, such as wet detention ponds and stormwater wetlands are also designed to flatten the peak flow curve (Burns, Fletcher, Walsh, Ladson, & Hatt, 2012; Lim & Welty, 2018). The effect of GI and other stormwater treatment practices on stormflow and baseflow dynamics is difficult to assess and model (Hamel, Daly, & Fletcher, 2013). Furthermore, stormwater control is not traditionally designed with thermal pollution reduction in mind or frequently assessed for performance in thermal pollution mitigation (Winston, Hunt, & Lord, 2011). This paper will state the case for the need to connect stormwater management with coldwater species management and synthesize the current literature that discusses the ability of stormwater treatment practices designed using hydrological criteria to also address thermal load to reduce urban impacts to aquatic habitats.

2 | URBAN HEAT PROCESSES

The warming effect of urban landscapes, or the urban heat island (UHI) effect, is known to dramatically increase air temperatures by 5 to 15°C (Mohajerani, Bakaric, & Jeffrey-Bailey, 2017; Santamouris, 2013). In urban areas, the thermal processes and exchanges are modified in such ways that they contribute temperature excess. Figure 1 illustrates the main heat process differences between urban and natural landscapes. For instance, paved surfaces, building walls, roofs and other impervious surfaces efficiently absorb solar radiation and have a greater heat capacity and thermal conductivity in comparison to natural surfaces (grass, trees, etc.) (Akbari & Kolokotsa, 2016; Luan et al., 2020). Urban surfaces re-emit this heat, acting as heat-sources, while forests and water act as heat-sinks (Yu et al., 2020). Therefore, structures in cities influence the urban energy balance, inducing urban excess heating (Arnfield, 2003). Urban area landscape properties influence albedo, emissivity, thermal capacity, thermal conductivity, thermal inertia, and humidity that can greatly increase the sensible heat flux. In addition, green vegetation (green roofs, trees, etc.) in urban areas can have a cooling effect by influencing shading and evapotranspiration processes (Akbari, Pomerantz, & Taha, 2001; Forman, 2014; Voogt & Oke, 2003). Moreover, the physical architecture of urban landscapes can have an effect on air movements by either reducing (buildings block wind) or increasing (building wind corridors) wind speed movements, as well as latent and sensible heat fluxes (Santamouris, 2014).

The net effect of these urban landscape influences significantly affects the surface energy balance and thus, urban thermal patterns and heterogeneity (Forman, 2014) producing the UHI effect (Gros, Bozonnet, & Inard, 2011; Voogt & Oke, 2003). Both UHI and the modified heat exchanges act in synergy to induce higher surface temperature, thereby warming water runoff temperature and even inducing urban stormwater thermal surges depending on the speed of the heat transfer between precipitation and the urban surfaces (Croghan, Van Loon, Sadler, Bradley, & Hannah, 2019; Ragab, Rosier, Dixon, Bromley, & Cooper, 2003).

Recent research has demonstrated that the UHI effect not only impacts surface air and water temperatures but also subsurface water and ground temperatures. Urban structures may be responsible for at least 50% of the additional energy stored in the subsurface, creating thermal anomalies known as subsurface heat islands (SUHIs) (Rivera, Blum, & Bayer, 2017). The main drivers of SUHIs are heat fluxes between urban structures (e.g., buildings, roads) and the ground

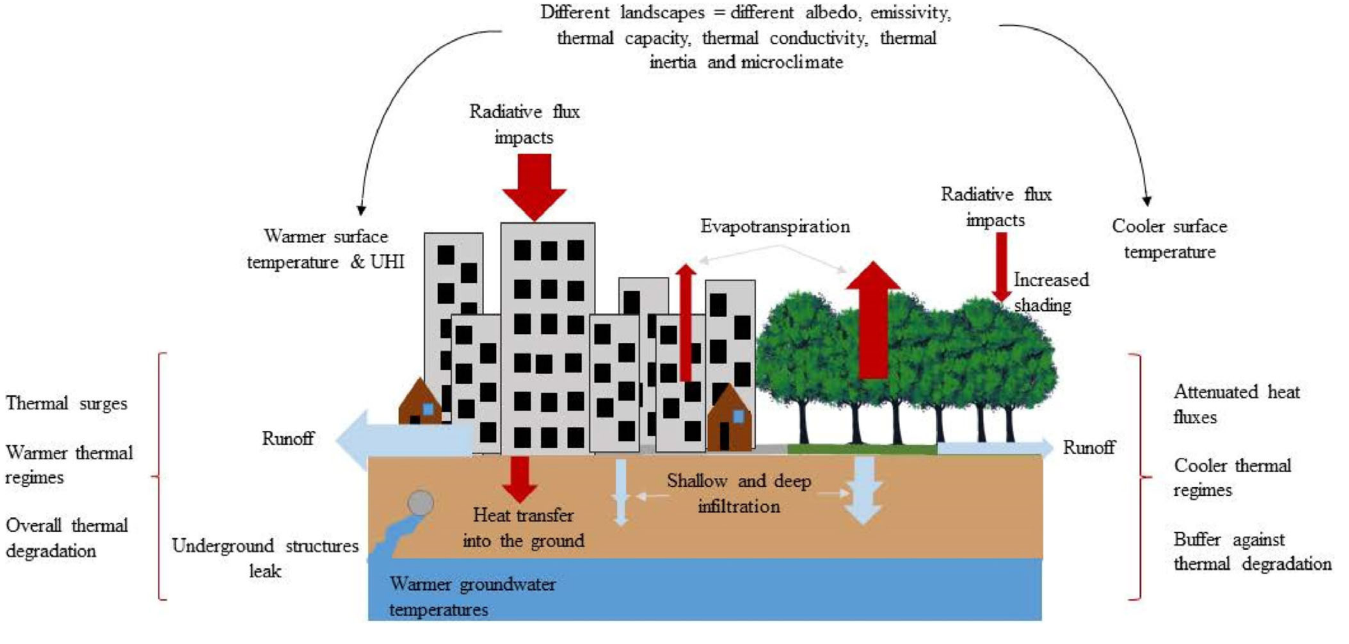

FIGURE 1 Heat and water process differences in urban and forested environments, with the size of the arrows indicating proportional differences between urban and forested heat flux (radiative flux, heat transfer, evapotranspiration) and water flow (runoff, infiltration). In this figure, UHI refers to urban heat island, red arrows represent heat flux, and blue arrows represent water flow [Colour figure can be viewed at wileyonlinelibrary.com]

(Benz, Bayer, Menberg, Jung, & Blum, 2015). The infiltration of warmed surface water may also influence groundwater temperature, as well as stream baseflow temperatures (Beltrami, Bourlon, Kellman, & González-Rouco, 2006). These modifications to heat fluxes and groundwater temperature, in addition to the fact that urban streams typically experience reduction in base flow, greatly increase their vulnerability to thermal degradation (Croghan, Van Loon, Sadler, Bradley, & Hannah,, 2019).

In spite of having an understanding of the different pathways ofheat in urban areas that can influence stream temperature, there is still a need to investigate the seasonal and diurnal patterns of the budget to fully understand heat fluxes in urban areas. Continuous improvements of thermal remote sensing technology, next-generation satellite-based sensors, and high resolution portable thermal scanners will provide further essential insights into sensible heat flux (SHF) in urban landscapes (Akbari & Kolokotsa, 2016; Yu et al., 2020) and SHF links to urban stream thermal dynamics (Baruch et al., 2018; Zeiger, Hubbart, Anderson, & Stambaugh, 2016). These research gaps need to be addressed to unravel the complexity of the mechanisms by which urban areas cause thermal degradation.

3 | IMPERVIOUS SURFACE AND AQUATIC SPECIES

Previous research has documented relationships between thresholds of percent effective impervious surface in watersheds and changes to stream fish species diversity and tolerance to pollution. Effective impervious (EI) surfaces are impervious surfaces that have a direct flow pathway to stream channels via stormwater infrastructure or pipe networks, and this direct connection is most likely to impact stream habitats and temperatures (Booth & Jackson, 1997; Walsh, 2004). Hydrologic alteration and changes to temperature in urban streams due to runoff from impervious surfaces may affect availability of preferred habitats at the right time for fish to establish populations via spawning and successful recruitment of early life stages (Freeman, Bowen, Bovee, & Irwin, 2001).

A number of studies have attempted to identify significant relationships between urban hydrology, landscape variables, and fish community variables despite the absence of long-term data sets of fish survey data specific to urban streams. Previous studies have conducted regression analyses using land cover data, habitat assessment scores, and index values such as fish IBI scores (index of biotic integrity) and tolerance to pollution values (Wenger, Peterson, Freeman, Freeman, & Homans, 2008). For example, Wang, Lyons, and Kanehl (2001) identified an 8–12% EI threshold at the watershed scale for impacts to fish diversity, tolerance, and density in Wisconsin based on regression analysis of 16 land use variables ($r^2 = 0.55$, $p < .01$). In the United States, the most recent, published research to investigate relationships between urban hydrology metrics and fish community variables has been done in the Etowah River watershed, near Atlanta, Georgia. This watershed has a high percentage of fish diversity, number of endemic fish species, and a range of catchments with low (<10%), medium (10–20%), and high (>20%) percent impervious cover (Roy et al., 2005). In this watershed, stormflow variability and peak flow magnitude were the most significant predictors of decreased richness for endemic ($p = .015$), widely ranging ($p = .037$), and sensitive fish species ($p = .007$) (Roy et al., 2005).

4 | THERMAL HABITAT AND TEMPERATURE STRESS

In the United States, stream fish thermal habitat types have traditionally been defined as coldwater, coolwater, and warmwater. Eaton and Scheller (1996) defined coldwater (≤24.3°C), coolwater (26.5–29.9°C), and warmwater (≥30°C) habitat based on 57 fish species, using fish presence records from throughout the United States and highest weekly mean temperature encountered, based on daily mean water temperature recorded values. In another study using data from 212 sites only from Connecticut, Beauchene, Becker, Bellucci, Hagstrom, and Kanno (2014) defined cold water, <18.29°C; cool water, 18.29–21.70°C; and warm water, >21.70°C based on fish presence data and June–August, daily mean water temperature values.

All aquatic organisms, at every life stage have specific temperature stress tolerances and behavioural responses, and impacts to growth and fecundity can vary depending on exposure times, the general stream water quality conditions, and the interactions with other stressors (Baxter & McPhail, 1999; Gaston, Butlin, & Snook, 2017; Turschwell, Balcombe, Steel, Sheldon, & Peterson, 2017). The critical thermal maxima (CTM) level temperature is a threshold temperature where an organism can no longer maintain equilibrium or perform normal functions to survive (Hutchinson, 1961; Lutterschmidt & Hutchison, 1997). Previous research to identify specific thermal stress and CTM threshold temperatures has primarily focused on coldwater species by exposing them to increasing water temperatures in tanks in the laboratory until indicators of temperature stress and loss of equilibrium are observed (see Table 1). Indicators of equilibrium loss include a fish's inability to swim (Becker & Genoway, 1979); or a freshwater mussel's foot becoming fully extended so that it can no longer secure itself into the stream bed (Galbraith et al., 2012). This loss of equilibrium occurs because thermal stress in fish induces physiological stress responses such as increased values of plasma glucose, cortisol, and heat shock protein concentrations (Breau, Cunjak, & Peake, 2011; Chadwick, Nislow, & McCormick, 2015; Ouellet, Pierron, Mingelbier, Fournier, & Marlène, 2013). Thermal stress can also lead to a loss of body mass if the extra energy costs are obtained from the body tissues (e.g., fat processing) or if temperatures rise above the values for optimal growth (metabolic decline) (Elliot, 1976; Elliott & Elliott, 2010).

5 | URBAN HYDROLOGY AND TEMPERATURE

5.1 | STORMFLOW

Urban stream aquatic communities experience thermal stress on a regular basis as a result of runoff events over low albedo, paved surfaces that have

TABLE 1 Thermal stress (abbreviated here as TS) and critical thermal maxima (CTM) threshold water temperatures for coldwater fish and freshwater mussel species

Scientific name	Common name	Threshold temperature	Reference
Onchorynchus mykiss	Rainbow trout	20 to 22°C (TS)	Hartman & Porto, 2014
		31°C (CTM)	Hartman & Porto, 2014
Onchorynchus clarkii utah	Bonneville cutthroat trout	22 to 24°C (TS)	De Staso & Rahel, 1994; Hillyard & Keeley, 2012
Salvelinus fontinalis	Brook trout	22 to 24°C (TS)	Wehrly, Wang, & Mitro, 2007
		29.8°C (CTM)	Lee & Rinne, 1980
Onchorynchus apache	Apache trout	29.4°C (CTM)	Lee & Rinne, 1980
Salmo trutta	Brown trout	30°C (CTM)	Lee & Rinne, 1980
Salmo salar	Atlantic salmon	33°C (CTM)	Elliot & Elliot, 1995
Alasmidonta varicosa	Brook floater	39.5 to41.1°C (CTM)	Galbraith, Blakeslee, & Lellis, 2012
Strophitus undulatus	Creeper	40.0 to42.3°C (CTM)	Galbraith et al., 2012
Eliptio complanata	Eastern elliptio	41.4 to42.7°C (CTM)	Galbraith et al., 2012

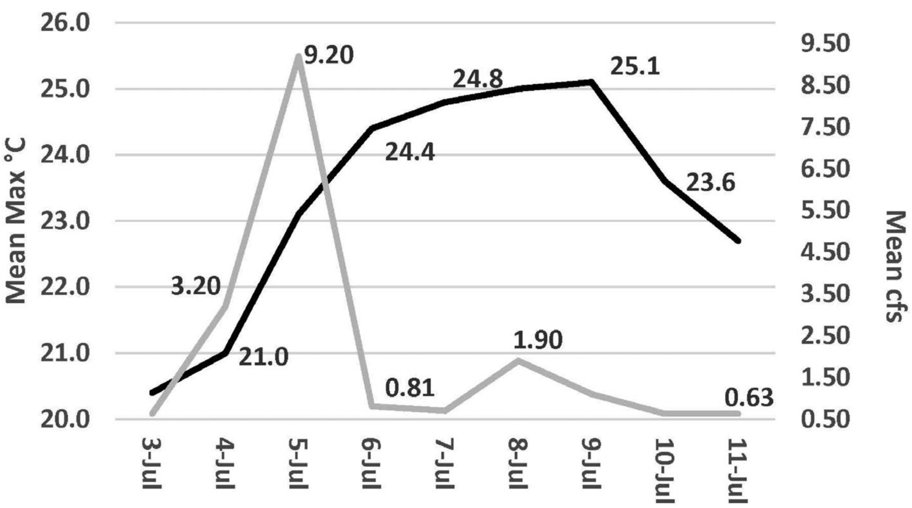

FIGURE 2 Scott's Level Branch, USGS gage (watershed area, 8.37 km^2) Rockdale, Maryland mean discharge (ft^3/second, cfs) and mean daily maximum temperature data, showing storm event and response of stream temperature, July 3 to July 11, 2016

absorbed solar radiation, with most heat transference occurring early in the runoff generation process (Hathaway, Winston, Brown, Hunt, & McCarthy, 2016; Van Buren, Watt, Marsalek, & Anderson, 2000) (Figure 1). Nelson and Palmer (2007) documented average temperature surges of 3.5°C in 30 minutes and 3-hour dissipation times during storm events in first to third order urban streams in Washington, D.C. This study also documented thermal surge events with >7°C maximum temperature increases and 7-hour dissipation times. In another study, Somers, Bernhardt, McGlynn, and Urban (2016) investigated heat-pulse event magnitude and dissipation distance in relation to spatial configuration of stormwater outfalls and forested riparian areas within a 1.5 km stream reach (11% impervious) in Durham, North Carolina. In 1 year, they detected >1°C heat pulses for 42 out of 54 storm events (78%) and 11 storm events with >1°C heat pulses that travelled 1 km downstream. In this case, 38.4 km of 40.4 km (95%) of the streams within the municipal boundary of Durham were within 1 km downstream of a stormwater outfall, and likely to experience urban stormwater heat pulses.

While the rising limb portion of the stormflow hydrograph, at the beginning of stormflow events, contribute the greatest thermal load, thermal loading continues through the stormflow portion of the hydrograph and into, and perhaps beyond, the hydrologic recession to pre-storm baseflow discharge (Nelson & Palmer, 2007). For example, Figure 2 shows a storm event on July 4, 2016 based on USGS gage stream flow and temperature data from Scotts Level Branch, Baltimore County, Maryland (watershed area, 8.37 km^2, 33% impervious cover for drainage area to gage location). This storm event resulted in an increase in discharge from <1 mean daily cfs to 9.2 mean daily cfs that receded to pre-storm flow by the following day for a total of 3 days. As a result of this storm event, the mean daily maximum stream temperature increased from <21°C (threshold for thermal stress for trout) to 24.4°C (known thermal stress for trout) during those 3 days and continued to increase to 25.1C and remain elevated for a total of 6 days before it receded to pre-storm temperatures (Figure 2).

5.2 | BASEFLOW

Baseflow in urban streams can vary widely as a result of changes in stormflow volume, decreased infiltration on impervious surfaces, influence of human drinking and wastewater infrastructure, and the process of evapotranspiration by trees (Bhaskar, Hopkins, Smith, Stephens, & Miller, 2020). As urban areas developed, extensive pipe networks were built to convey stormwater and wastewater to receiving streams, many of which were integrated into the subterranean urban pipe network via the process of stream burial (Elmore & Kaushal, 2008). These urban pipe networks can either be designed as separate systems for stormwater and sewer (see Figure 3) or as combined systems where stormwater and sewage flows through the same pipes with or without a barrier separating the sewer effluent from stormflow. The likelihood of sewer pipes leaking is often underestimated (Kaushal, Groffman, Band, Elliott, & Kendall, 2011). For example, the estimated average flow volume in the Gwynns Falls stream, Baltimore, Maryland was found to be 65% leakage from sewer pipes (Kaushal & Belt, 2012). In addition, there is a separate network of drinking water pipes that are pressurized and known to leak water at a 20–30% leakage rate to the groundwater table that becomes a source for baseflow (Garcia-Fresca, 2007). Leaks from pipe networks can significantly contribute to baseflow, and this network of integrated pipes in the subsurface of urban catchments has been termed "urban karst" (Kaushal & Belt, 2012). Baseflow derived from urban karst can result in a cooling effect because the pipes are cooled underground and may be connected to the groundwater. In addition, the urban karst network can result in a hydrograph-stabilizing effect due to continuous source flow (Garcia-Fresca, 2007; Sabouri, Gharabaghi, Mahboubi, & McBean, 2013), thereby influencing stream baseflow thermal dynamics. However, it is important to note that pipeflow thermal impacts resulting from urbanization likely varies considerably geographically due to regional variations in climate, standard urban stormwater and sewerage design, and regional groundwater elevations (Bhaskar, Hopkins, Smith, Stephens, & Miller, 2020).

Trees cool impervious surfaces via shade and influence water availability for baseflow via the process of evapotranspiration, (Armson, Stringer, & Ennos, 2012; Li, Sharkey, Hunt, & Davis, 2009; Livesley, McPherson, & Calfapietra, 2016). The evapotranspiration function of trees can influence infiltration volumes and baseflow depending on the water use efficiency (WUE) of tree species, local weather, site conditions, and amount of necessary irrigation (McCarthy, Pataki, & Jenerette, 2011; Wullschleger, Meinzer, & Vertessy, 1998). As highlighted in Figure 1, evapotranspiration

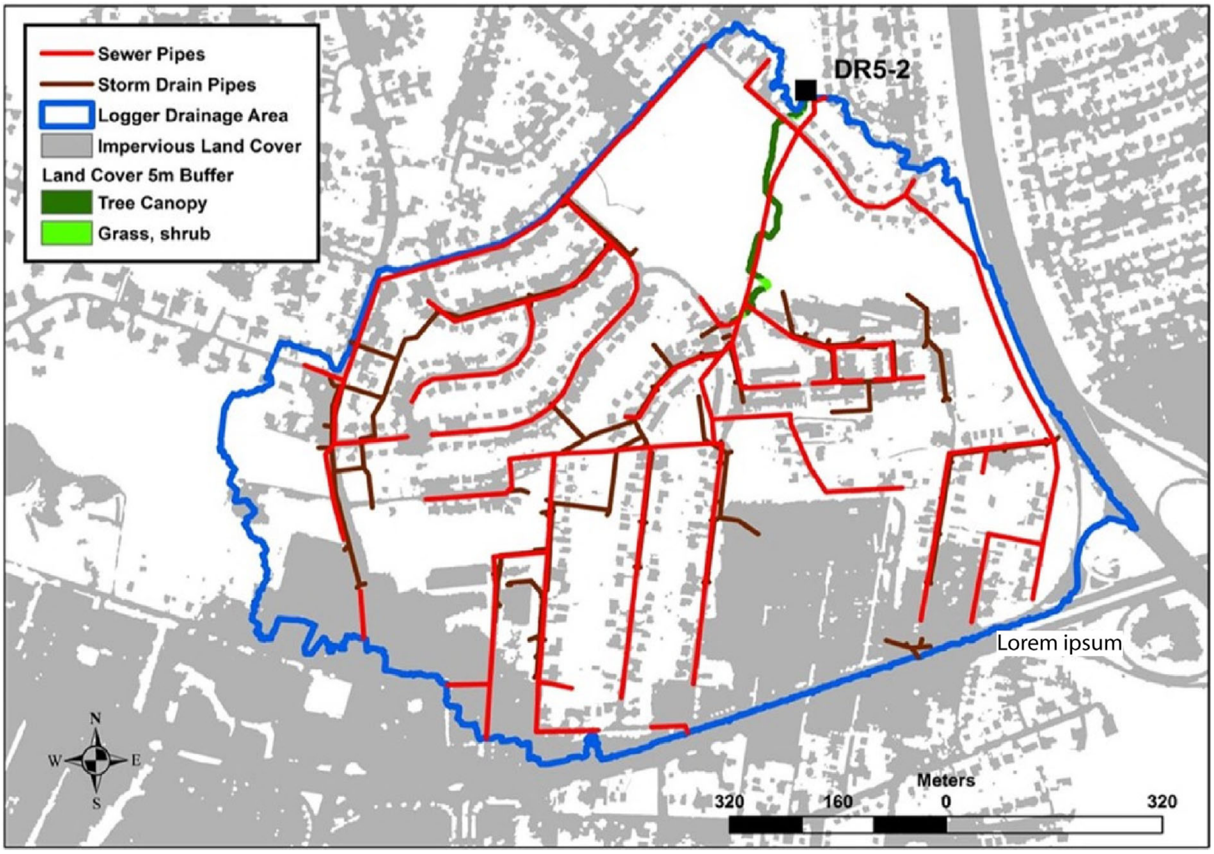

FIGURE 3 Example of sewer and storm drain separate pipe networks in the Dead Run stream near Baltimore, Maryland. This catchment has 5,269 m of storm drain pipe and 1,569 m of stream length or a 3.36 stormwater pipe to stream ratio. (Geospatial data sources: sewer and storm drain pipe data, Baltimore County; high-resolution land cover, Chesapeake Bay Conservancy) [Colour figure can be viewed at wileyonlinelibrary.com]

processes differ for natural forested, pervious areas compared to urban, impervious surfaces, as a result of differences in shallow and deep infiltration and extent of thermal stress. Current data that compares site level measurement of evapotranspiration functions and water use for trees in urban forests compared to natural forests is not available in published literature (Pataki, McCarthy, Litvak, & Pincetl, 2011).

Human choice of tree species for large-scale plantings can potentially have large impacts on stream water temperatures and local baseflow depending on structural characteristics, tree metabolism, and WUE of the selected trees (McCarthy, Pataki, & Jenerette, 2011). For example, tree structural characteristics such as crown area, surface area of leaves, and height of leaves off the ground can affect shade and evapotranspiration cooling functions (Armson, Stringer, & Ennos, 2012). In urban areas, studies have shown large differences in species ability to process water, with evapotranspiration estimates ranging from 3.2 ± 2.3 kg per tree per day for Canary Island Pine (*Pinus canariensis*) to 176.9 ± 75.2 kg per tree per day for London planetree (*Platanus hybrida*) (Pataki, McCarthy, Litvak, & Pincetl, 2011). Selecting non-native tree species that are not physiologically adapted to local climate or that require a lot of irrigation can impact local water availability for base flow or human water sources. For example, Pataki, McCarthy, Litvak, and Pincetl (2011) suggested that selecting a high-water use species for a "million new trees" planting in an irrigated, semi-arid area like the Los Angeles, California, United States area would result in a 30 million gallons per day (5% total daily municipal water use) loss in local water supply during the hottest part of the summer.

6 | GREEN INFRASTRUCTURE

GI has become an increasingly more common component of city designs to reduce the impacts of increased stormwater runoff from impervious area. GI can apply the process of infiltration for drainage efficiency of water into permeable surfaces, which is the case for bioretention cells, rain gardens, and permeable pavement. GI can also apply the processes of water retention or attenuation of runoff volume to help reduce effects of stormflow, slow drainage rates, and reduce pollutant loads where water is contained. The presence of trees and other plants that are part of the design can help to reduce volumes via evapotranspiration. Examples of this approach are wet detention ponds and stormwater wetlands (Jefferson et al., 2017; Lim & Welty, 2018).

The bioretention cell is the most commonly used infiltration-based GI approach for stormwater management in the United States. It can reduce peak flows 14–99% at the subcatchment scale and reduce pollutant loads via uptake of pollutants into plant roots and adsorption to soil media (Davis, Hunt, Traver, & Clar, 2009; Hatt, Fletcher, & Deletic, 2009; Hunt, Smith, Jadlocki, Hathaway, & Eubanks, 2008). Bioretention cells can reduce stormwater runoff temperature and may offer cooling treatment effects as a result of contact with soil media that have high hydraulic conductivity (Long & Dymond, 2014). In addition, Da Silva, Mohammad, Hammad, Haddad, and Vazquez (2020) offer a review of green roofs and summarize known water retention (13–100%) rates and runoff volumes (26 to 100%) treated according to green roof type and design.

Wet detention ponds are another stormwater management practice that may retain water for a longer time period and discharge water with elevated temperatures when exposed to solar radiation (Sabouri, Gharabaghi, Mahboubi, & McBean, 2013). For example, water temperatures at the outlet of wet detention ponds can be 1.2°C greater than water temperatures at the inlet (Herb, Mohseni, & Stefan, 2009; Jones & Hunt, 2010). Jones and Hunt (2010) measured temperatures at the outlet of two bioretention basins in North Carolina that consistently exceeded their threshold for maintaining trout (≤21°C), with maximum runoff temperatures of 30.4 and 32.7°C that are above 29.8°C; CTM temperatures for trout native to North Carolina (Lee & Rinne, 1980) (Table1).

7 | STORMWATER THERMAL MITIGATION PRACTICES

A recent study by Ketabchy, Sample, Wynn-Thompson, and Yazdi (2019) applied the US EPA Stormwater Management Model (SWMM) (Rossman, 2009); Minnesota Urban Heat Export Tool (MINUHET) (Janke, Herb, Mohseni, & Stefan, 2013); and a hybrid model (Ketabchy, Sample, Wynn-Thompson, & Yazdi, 2018) to investigate thermal mitigation practices (TMPs) and their potential for reducing total heat load (THL) to streams to maintain temperatures below the threshold for maintaining trout (<21°C). The models were applied to simulate effects of different spatial configurations of TMP within a headwater catchment (32% impervious) of Stroubles Creek Watershed Blacksburg, Virginia. Simulations applied different TMPs separately and in combination, including cool surfaces, bioretention systems, and increased forest canopy. The following sections (7.1–7.4)) will use the term "simulation study" to refer to Ketabchy, Sample, Wynn-Tompson, and Yazdi (2019).

7.1 | Cool surfaces

Traditional asphalt used for pavement is a low albedo, dark-coloured material that absorbs greater amounts of solar radiation. As a result, asphalt paved surfaces can be 20 to 60°C greater than other higher albedo, light-coloured surfaces (Santamouris, 2013; Stempihar, Pourshams-Manzouri, Kaloush, & Rodezno, 2012; Takebayashi & Moriyama, 2012). Cool surfaces used as TMPs for the simulation study included concrete pavement and acrylic coated galvalume (ACG) roofing that are higher albedo materials (Li, Harvey, Holland, & Kayhanian, 2013). Results of the simulation study indicated that replacing all conventional asphalt surfaces (roofs and pavements) with cool surfaces within the watershed reduced the THL the greatest when assuming application of only one TMP (42% reduction).

7.2 | Green infrastructure

Wet pond or stormwater basins that are exposed to solar radiation can introduce water with elevated temperatures at the outlet (Herb, Mohseni, & Stefan, 2009). Bioretention designs that use coarse sand and gravel and have deeper cells are more likely to result in effective infiltration and prevent elevated temperatures (Jones & Hunt, 2010; Long & Dymond, 2014). For the simulation study, bioretention was added to all parking lots that were ≥4,645 m^2 within the catchment, for a 11% reduction in THL.

7.3 | Increased forest canopy

Forest canopies can provide shade from solar radiation and create cool, humid microclimates over streams to help maintain cold water temperatures for trout (Dugdale, Malcolm, Kantola, & Hannah, 2018; Garner, Malcom, & Hannah, 2014). Past research suggests that when 80% or more of the stream bank is covered by forest ≥30 m wide, stream water temperature is maintained at or below lethal temperatures for cold-water fish populations (Barton, Taylor, & Biette, 1985; Sweeney & Newbold, 2014). For urban areas, previous research measured temperatures 5–7°C cooler under trees in urban parks (Armson Stringer, & Ennos, 2012). For the simulation study, forest canopy was increased on all available pervious surfaces in the catchment, resulting in a 24% reduction in THL.

7.4 | Combined TMPs

Comprehensive application of multiple types of infiltration and detention-based GI at the watershed scale is likely to have the greatest impact on stormwater management (Miles & Band, 2015). For the simulation study, applying all three TMPs (cool surfaces, increased forest canopy, and bioretention) to the maximum area possible at the watershed scale resulted in the greatest overall reduction in THL (62%).

8 | DISCUSSION

Stormwater-based thermal pollution from runoff in urban areas is a clear risk to coldwater species. This review of the literature suggests that current GI designed to reduce urban stormflows, runoff volumes, and pollutant loads do not necessarily reduce thermal loads to maintain coldwater stream habitat and research on TMP design criteria effectiveness is needed. This review indicates that bioretention cells and tree canopy may be inadequate to reduce heat stress in urban streams, as cool surfaces reduced thermal loads to the greatest extent of all individual TMPs applied in the simulation study . This paper also reminds us that reduction of EI and comprehensive applications of GI and TMPs at the watershed scale are likely to have the greatest impact on stormwater thermal pollution, with consideration that only a 62% reduction in thermal load may be possible, according to this one simulation study.

This synthesis of literature identifies key drivers of stream temperature in urban streams, including stormflows that result in thermal surges, which are known to travel and affect stream habitats as far as 1 km downstream (Somers, Bernhardt, Mcglynn, & Urban, 2016). Impacts of these thermal surges include elevated temperatures above known CTMs for trout that remain elevated longer than the hydrologic recession to pre-storm baseflow discharge (Nelson & Palmer, 2007). In addition, the effect of creating extensive pipe networks in cities can have impacts on urban stream temperatures as a result of interactions with groundwater and leaks that result in cooling effects (Kaushal & Belt, 2012).

This paper reviews and synthesizes the primary scientific literature related to aquatic species thermal habitat types, urban stormwater hydrologic drivers of stream temperature, and effectiveness for both GI and TMPs to reduce thermal loads to streams in urban areas. This literature review identified clear lines of research that need more effort, with a surprising lack of literature connecting the impacts of urban stormwater to urban stream temperatures and potential effects on coldwater species. Quantifying effects of specific GI and stormwater management practices on stream temperature is difficult because effects are highly site specific and vary according to stormwater runoff volume and receiving stream watershed size. Further review of grey literature is also an important source for information on these topics and synthesis for these resources is warranted, especially related to design effectiveness of GI to treat stormwater runoff for reducing thermal loads to streams.

8.1 | Green infrastructure and thermal load

This study focused on the most common types of GI for stormwater control and their potential to have an impact on stream temperature. Further research is needed to investigate effectiveness of wet detention basins and infiltration-based GI (bioretention cells, rain gardens, green roofs, permeable cool surfaces) for preventing increased thermal loads to stream channels. Based on current available research, bioretention cells can reduce stormwater runoff temperatures, and have the greatest potential for offering cooling effects if designed with high hydraulic conductivity soil media (Long & Dymond, 2014). Cool surfaces on roofs and parking lots reduced thermal loads the most (42%) compared to other TMPs in the simulation study and have great potential for reducing thermal pollution to streams. Further work is needed to quantify current spatial extents and potential areas for cool surface application at the watershed and landscape scale relevant to thermal load reduction for coldwater species temperature stress. The Jones and Hunt (2010), Winston, Hunt, & Lord (2011), Long and Dymond (2014), and Ketabchy et al. (2019) papers represent the very few studies that target direct effectiveness of GI for also reducing thermal load to streams, and all three papers acknowledge the need for further research on TMP design effectiveness to reduce thermal loads to trout streams.

8.2 | Quantifying groundwater interaction

Research related to pipe network interaction with groundwater in the shallow surface layers of urban pervious surface requires further attention (Jefferson et al., 2017; Kaushal & Belt, 2012; McGrane, 2016). Applications of three-dimensional groundwater models could be used to identify hydraulic subsurface characteristics for the best spatial configurations of pipe networks and GI within watersheds for effective stormwater management (Lim & Welty, 2017). Steffy and Kilham (2006) documented occurrence of coldwater patches (≥3°C colder) associated with groundwater flow in an urban watershed (17% impervious) of Philadelphia, Pennsylvania, and further mapping of groundwater in cities may identify other urban thermal refugia (McGinty, 2003; Steffy & Kilham, 2006; Steffy, McGinty, Welty, & Kilham, 2004).

8.3 | Quantifying and applying evapotranspiration

The majority of work on the relationship between evapotranspiration and stormwater management has been quantified using large spatial scale models designed for climate and air quality applications. However very few empirical studies have been done to quantify on-site removal of urban stormwater by trees (Fletcher, Andrieu, & Hamel, 2013; Jefferson et al., 2017; McGrane, 2016). One study of bioretention-based GI (4.5% of catchment area) documented a 19% loss of inflow volume due to evapotranspiration (Li, Harvey, Holland, & Kayhanian, 2009). Better understanding of the evapotranspiration function and water processing efficiency rates would help improve the effectiveness of GI retention-based designs that use trees and plants to harvest retained water volumes. Tree species selection at the local GI site scale needs to be considered to a greater degree, and further research is needed on which tree species offer the greatest water harvest efficiency and shade potential for specific site conditions and local climates. In addition, understanding the evapotranspiration function and its relationship to microclimate and groundwater table connection would help us to better understand its potential water harvest efficiency as part of TMP designs in urban watersheds (Jefferson et al., 2017; McGrane, 2016). Study designs to quantify evapotranspiration at the site scale are complex; and sapflow rates for multiple species of trees, site weather conditions (temperature, rainfall, solar radiation, relative humidity, vapour pressure), soil moisture, and groundwater elevation data would all be required (McCarthy & Pataki, 2010; Wullschleger, Hanson, & Todd, 2001).

8.4 | Effectiveness monitoring and prioritization

This review of available literature suggests that incorporating TMPs into current and future GI designs for stormwater treatment will help maintain water resources, water quality, aquatic ecosystems, and coldwater stream species across the landscape. Urban areas are especially important to consider. Further development of design criteria and research to assess on the ground effectiveness of TMPs for thermal load reduction to stream networks at local, subwatershed, and watershed scales is needed. Subwatershed and watershed scale data may help identify effects of thermal load on availability of preferred thermal habitat for coldwater species. Available literature suggests that data sets for effectiveness monitoring and design considerations listed in Table 2 may provide insight into GI design effectiveness to help reduce thermal loads from urban stormwater.

A landscape scale watershed prioritization strategy can help inform the retrofitting or implementation of new stormwater TMPs. Communities of practice and integrated communication strategies can share lessons learned on stormwater TMP retrofits and implementation for TMPs. Active communities of practice may also help establish integrated teams of people that can work on hydrology, aquatic species management, and stormwater TMP implementation together. Information on known physical drivers of urban stream temperature can help inform prioritization (see Table 3). Detailed methods and references to use to measure each of the suggested data sets are not included here. This review of literature suggests that watershed or

TABLE 2 Data to collect to quantify thermal mitigation practice (TMP) effectiveness

TMP	Data sets to collect	Design considerations	References
GI (wet detention and bioretention)	Inflow, outflow rate and temperature	Deeper cells	Jones & Hunt, 2010
	Stormwater runoff and groundwater temperature	Add tree canopy	Long & Dymond, 2014
	Evapotranspiration rate, water use efficiency	Cool surfaces at site	Mohajeranet al., 2017
			Pataki, et al., 2011
Increase canopy	Solar radiation	Shade, evapotransporation	McCarthy, et al., 2011
	Temperature under canopy	Thermal connectivity	Pataki, et al., 2011
	Soil moisture, temperature		
	Sapflow per tree		Dugdale, Malcolm, Kantola, & Hannah, 2018
	Stream water temperature		

Note: These TMPs are potential design elements that could be added to future installations of GI to treat stormwater for thermal load reduction.

TABLE 3 Data sets that can help inform prioritization of watersheds or comprehensive thermal mitigation practice retrofits

Data sets	References
Temperature-	
Annual variability, summer maximums	Steel, Beechie, Torgersen, & Fullerton, 2017
Upstream, downstream of stormwater inputs	Somers et al., 2016
Hydrology	
Stormflow magnitude, frequency	Nelson & Palmer, 2007
	Hathaway et al., 2016
Groundwater flow	Miles & Band, 2015
	Lim & Welty, 2017
Infrastructure	
Effective impervious (EI)	Walsh, 2004
Stream burial percentage	Elmore & Kaushal, 2008
Pipe network density (PND)	Sabouri et al., 2013
	Kaushal & Belt, 2012
Biological	
Species presence, thermal tolerance	Wehrly et al., 2007
	Steffy & Kilham, 2006
Spatial	
Current, potential GI, tree canopy	Ketabchy et al., 2019
Cool surfaces, roofs	Mohajerani et al., 2017

subwatershed scale data sets are likely to be most useful, but spatial scale of the data may depend on availability or priorities for stormwater and aquatic species management at the local scale.

9 | CONCLUSIONS

The urban heat island effect results in greater air and ground surface temperatures in cities, but it can also result in greater water temperatures from stormwater runoff over low albedo EI surfaces. These increased water temperatures can result in aquatic species thermal stress and significant impacts to aquatic habitats as a result of changes to chemical processes, water quality, and ecosystem health. GI that is typically installed for flood control and water quality improvement also offers opportunities to reduce thermal loads to urban streams to maintain necessary water temperatures for coldwater species. This research synthesis supports the need for new approaches to watershed prioritization for aquatic habitat according to thermal pollution risk to coldwater stream species at the landscape scale, with high EI watersheds especially important to consider. Further research is needed on the most effective ways to implement TMPs as part of our current and future GI designs for stormwater and how to best incorporate these measures into urban design concepts at larger spatial scales.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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