Urban stormwater runoff thermal characteristics and mitigation effect of low impact development measures
Junqi Li, Yongwei Gong, Xiaojing Li, Dingkun Yin and Honghong Shi

ABSTRACT

Thermal pollution has become a severe environmental problem in China, but studies on thermal characteristics of urban stormwater runoff are scarce. The thermal enrichment of runoff from typical land surfaces was assessed during 2012–2014 in Beijing and Shenzhen, China. The temperature of stormwater runoff from rooftops, grass surfaces and different types of road surfaces was investigated under different rainfall conditions. The mitigation effects of low impact development (LID) measures were also evaluated. Impervious asphalt or concrete surfaces store and transfer heat, and were found to cause thermal enrichment of runoff from the start of a rainfall event. In addition to surface types, pre-event weather conditions and rainfall intensity influenced runoff temperature. The pervious surface of open graded friction course (OGFC) pavement postponed the time of peak runoff temperature. The retention volume of bioretention cells resulted in thermal energy mitigation by directing runoff into the soil and vegetative cover. The grass swales showed effective reduction of runoff temperature by approximately 1–2°C compared to asphalt, concrete and marble pavements. Therefore, LID measures, such as OGFC porous pavements, bioretention cells and grass swales, can mitigate the thermal impacts of urban stormwater runoff and alleviate resulting ecological problems.

Key words | bioretention cell, grass swales, low impact development (LID), open graded friction course (OGFC), porous pavements, stormwater runoff thermal effect

INTRODUCTION

Water temperature is one of the key parameters affecting flora and fauna in aquatic environments. Increases in water temperature impact metabolism, behavior, enzyme function and reproduction of numbers of aquatic organisms (Caisse 2006; Jones & Hunt 2010; Bobat 2015). Water thermal pollution may also accelerate chemical reaction rates, promote bacterial reproduction rates, reduce oxygen solubility, increase solubility of toxic hydrocarbons and metals and promote eutrophication (Buren et al. 2000; Benedini & Tsakiris 2013; Huang et al. 2014).

Both natural and anthropogenic factors may impact the temperature of receiving waters. Natural factors include climate, the presence or absence of near-stream shading, the morphological conditions of the receiving waters, and the discharge of groundwater into the aquatic system. Anthropogenic factors include discharge from hydroelectric power stations with storage lakes, discharge of industrial cooling water and discharge of urban stormwater during rain events (Rossi & Hari 2007). The thermal impact of industrial discharges has been reduced through the application of heat exchange processes using cooling tower technology. However, thermal enrichment of receiving waters by urban stormwater runoff tends to be overlooked.

Watershed urbanization can change the surface cover dramatically, and profoundly impact the local climate, hydrology, water quality and habitat of the water system.
(Yang et al. 2014; Chen et al. 2016). Conventional urban conveyance systems deliver runoff rapidly to receiving waters. Rapid urbanization may result in water pollution, including thermal pollution, through stormwater runoff (Nelson & Palmer 2007; Thompson et al. 2008; Zeiger & Hubbart 2013). Urban site developments, such as increased impermeable area, vegetation loss, soil compaction and loss of natural drainage patterns may cause changes of urban temperature. Typically, urbanization leads to extensive increases in impervious surfaces such as roads, roofs, parking lots and pavements. These impervious surfaces absorb and retain more heat from solar radiation during summer months than during the rest of the year. These aspects can directly or indirectly lead to the thermal pollution of stormwater runoff. Sabouri et al. (2013) modeled a 3°C increase in stormwater temperature after impervious coverage of the study catchment area increased from 20% to 50%.

Thermal energy is also transferred from impervious surfaces to receiving waters. Altered volume and duration of delivery of stormwater runoff contribute to acute thermal loading of receiving waters. James & Xie (1999) observed that urban runoff from warm asphalt pavements increased stream temperatures by 5°C and 10°C–12°C in normal and extreme conditions, respectively.

In general, thermal impacts are often neglected in stormwater best management practices (Jia et al. 2015). Previous research has shown that conventional large-surface systems such as stormwater wetlands and wet ponds are ineffective at controlling thermal pollution, suggesting that these best management practices may be sources of increased temperature to receiving waters (Jones & Hunt 2010; Roseen et al. 2010). However, low impact development (LID) stormwater management measures, such as bioretention (Jones & Hunt 2009), level spreader-vegetative filter strips (Winston et al. 2011) and porous pavements (Wardynski et al. 2013) can reduce thermal pollution loads to waterways by transferring water through cooler subsurface media or by reducing discharge volume (Kamali et al. 2017). Conventional approaches to control runoff are not fully adequate to protect the water resources. Comprehensive protection of the aquatic environment should include thermal pollution management of urban stormwater runoff. Management solutions should replicate natural hydrologic conditions of watersheds through reasonable site planning and development. Effective stormwater management is of great importance in controlling urban runoff thermal pollution and reducing its negative impacts.

The impact of urban stormwater runoff on chemical contaminants in aquatic ecosystems has been extensively studied (Djukić et al. 2015; Jia et al. 2015). However, little work has focused on the issue of thermal pollution of urban stormwater runoff from paved surfaces. Moreover, traditional stormwater drainage designs have not considered temperature mitigation as a critical design criterion. Open graded friction course (OGFC) has been used in urban roads. As an open grade asphalt mixture design, OGFC pavement has higher porosity and better drainage than conventional asphalt pavement. Combined effects (OGFC and bioretention cell, asphalt concrete pavement and bioretention cell) on runoff temperature have not been examined. Besides, China is currently vigorously developing sponge city construction, which aims to relieve the heat island effect in urban areas (Jia et al. 2017; Ren et al. 2017). While many studies are available on water quality and quality of LID facilities, fewer studies on alleviating the thermal pollution of runoff have been undertaken. This research examined the thermal characteristics of stormwater runoff from typical underlying surfaces and evaluated the mitigating effects of LID measures in Beijing and Shenzhen, China. The effects of impervious surfaces (e.g. roads and rooftops) on runoff temperature were evaluated and compared with those of LID facilities built with porous pavements, bioretention cells, and grass swales. This study can help to predict the resilience of the sponge city to the heat island effect.

MATERIALS AND METHODS

Study area

Beijing is located in northern China (Figure 1) within the Haihe River Watershed. With an annual mean air temperature of about 17.8°C, the climate falls into the category of temperate monsoon climate. Average annual precipitation is 626 mm, and the majority of this precipitation occurs in the summer.
Shenzhen is a coastal city in southern China and located in the east coast of the Pearl River estuary. The annual average temperature of Shenzhen is 24.4°C. Shenzhen has a subtropical monsoon climate with a rainy season lasting from April to October and an average annual precipitation of 1680 mm. Guangming New District (triangles on Figure 1 show the study sites) of Shenzhen was one of the first districts to implement LID stormwater management in China.

Monitoring plans

Data collection in Beijing

The temperature of stormwater runoff from typical urban surfaces (asphalt roads, concrete rooftops and grass) on the campus of Beijing University of Civil Engineering and Architecture (BUCEA) in Xicheng District was recorded during four rainfall events in June and July 2013. The runoff temperature during the rainfall events was monitored at 5-min intervals with a needle thermometer. The temperature of runoff from asphalt road surfaces was measured on the road surface prior to entering the storm drain inlet. The same temperature monitoring method was used on the grass surface. The distance between the measuring point on a grass surface and the downspout from the rooftop was 1.5–2.0 m. The temperature of the concrete rooftop runoff was measured at the downspout. We read the data of runoff temperature when the probe of the needle thermometer touched the surface of the road and the probe was completely immersed in rainfall runoff. Air
temperature, precipitation and solar radiation were logged by HOBO Automatic Weather Stations (ONSET HOBO U30) installed on the roof of the experimental building at BUCEA. The experimental building is about 25 m high and the height of the temperature sensor was 1.7 m above the roof surface.

**Data collection in Shenzhen**

The temperature of runoff from conventional and LID roads, concrete rooftop, porous concrete and bioretention cells was monitored in Guangming New District, Shenzhen from 2012 to 2014. The LID roads were constructed with OGFC porous asphalt and had sand settling tanks and bioretention cells on both sides of the road (Figure 2). The section of road is a six-lane dual carriageway, 40 m wide and 600 m long. The green belt consists of bioretention cells, with the storm sewer pipes laid underneath. The thickness of the OGFC layer is 0.05 m. The bioretention cells are located 0.4 m lower than the OGFC surface and have a width of 2.75 m. Sand settling tanks designed to pretreat sediment during the initial period of runoff are situated at the entrance of the bioretention cells. The runoff overflows to the bioretention cell when the sand settling tank is full. The runoff temperature was monitored at the entrance and exit of each LID management feature. Monitoring of the marble surface was conducted at the west side of the Guangming Park, at a site with an average slope of about 3.9%. The porous concrete pavement was monitored at the west side of Guangming Park, at a site with an average slope of about 1.7%. For porous concrete pavement, the monitoring site was on the surface of the porous concrete pavement rather than in the underground drain. The grass swales are also located on the west side of Guangming Park. The total length of road and grass swales is about 90 m, the road width is 7 m and the vertical slope is about 3.0%. The runoff first flows over the traditional asphalt pavement, and then into the grass swales. During the rainfall events in 2013, the temperature of the surface runoff at LID roads was measured at 5-min intervals using a needle thermometer. In 2014, runoff temperatures were measured at 2-min intervals on the asphalt road, marble surface, porous concrete and grass swales. A Davis Model 7852 Rain Collector with a resolution of 0.2 mm was used to record rainfall in 2013 while a HOBO Rain Gauge was used to record rainfall data in 2014. The air temperature in Shenzhen was measured using a microlite hygrothermograph of ±0.3°C accuracy placed on a 1 m-high shelf in the open area of the study area.

**RESULTS AND DISCUSSION**

**Runoff temperature of different surface covers**

In Beijing, the temperature of asphalt road runoff during the four observed rainfall events reached a maxima of 22.8–26.6°C, which was higher than the air temperature of 20.9–28.1°C (Figure 3(a)). The average temperatures of air, grass runoff, rooftop runoff, and road runoff from all recorded data for the four rainfall events were 22.2°C, 22.8°C, 23.6°C and 24.5°C (open squares in Figure 3(a)), respectively. The average temperature of road runoff was 2.3°C higher than the average air temperature.
In Shenzhen, the temperature of runoff from the asphalt road for the six-observed rainfall events in 2013 reached a maxima of 30.2–34.1°C, whereas the highest corresponding air temperature ranged from 22.7–29.4°C (Figure 3(b)). The average temperature of runoff was 5.8°C higher than the average air temperature.

The data from these two cities show that both asphalt and concrete pavements stored large amounts of heat which was then transferred to the stormwater runoff during hot weather. Kieser (2004) also presented evidence that runoff is thermally enriched when it absorbs heat stored in impervious surfaces. The differences between stormwater runoff temperature and air temperature were always positive for asphalt road, concrete road and concrete roof.

Based on the data of rainfall runoff monitoring conducted from June to July 2013 (Figure 3), the rainfall runoff temperature analysis of asphalt roads in Beijing and Shenzhen showed that all the surface runoff temperatures were higher than the corresponding air temperature. The road mean temperature was 2.2°C higher than the air temperature in Beijing, and 6.5°C higher than the air temperature in Shenzhen. The average runoff temperature of the asphalt road in Shenzhen was about 4.5°C higher than that in Beijing, and the difference of mean rooftop runoff temperature between these two cities was about 3.5°C. In higher air temperature conditions, the difference between the road runoff temperature and the air temperature was greater. However, the effect of runoff temperature increases on local aquatic ecology is also not the same in different climate conditions, so the influence of the increase of runoff temperature on the local aquatic ecology needs to be analyzed according to the characteristics of the urban aquatic ecology system.

**Factors impacting stormwater runoff thermal pollution**

**Characteristics of surface cover**

Rainfall and weather conditions for the Beijing rainfall events are summarized in Table 1. Runoff temperature varied depending on heat storage and exchange characteristics of the surface cover. During all events, the runoff temperature from impervious surfaces decreased at the beginning of the rainstorm and then remained stable, and the runoff temperature was always higher than the air temperature at the stable stage (Figure 4).

The notable difference in runoff temperature of asphalt roads, concrete rooftops and grass indicates that
the heat storage and exchange characteristics of these impervious surfaces can affect runoff temperature. The lowest runoff temperature was measured for rooftop runoff which flowed through a grass surface and the runoff temperature of the grass surface was very close to the air temperature with minimal fluctuation range.

Pre-event weather conditions

Weather conditions prior to precipitation events influenced the heat storage of surfaces. During the June 24 and 28 events (Figure 4(b) and 4(c)), the asphalt road runoff had a higher temperature (1.5–2.7°C) than the concrete rooftop during storms that occurred most often in the evening and

Table 1 | Summary of four observed rainfall events in Beijing, in June and July 2013

<table>
<thead>
<tr>
<th>Date</th>
<th>Start time</th>
<th>Duration (min)</th>
<th>Total precipitation (mm)</th>
<th>Average air temp. during the event (°C)</th>
<th>Storm types</th>
<th>Pre-event weather condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/16/2013</td>
<td>13:00</td>
<td>70</td>
<td>1.2</td>
<td>21.8</td>
<td>Light rain</td>
<td>Cloudy</td>
</tr>
<tr>
<td>6/24/2013</td>
<td>19:15</td>
<td>90</td>
<td>6.4</td>
<td>23.4</td>
<td>Moderate rain and thunder shower</td>
<td>Sunny to overcast</td>
</tr>
<tr>
<td>6/28/2013</td>
<td>21:25</td>
<td>70</td>
<td>3.8</td>
<td>22.3</td>
<td>Moderate rain and thunder shower</td>
<td>Sunny to overcast</td>
</tr>
<tr>
<td>7/1/2013</td>
<td>20:45</td>
<td>140</td>
<td>51.4</td>
<td>23.2</td>
<td>Heavy rain</td>
<td>Cloudy</td>
</tr>
</tbody>
</table>

Figure 4 | Observed air temperatures, measured runoff temperatures of road, rooftop and grass, and precipitation versus time in BUCEA, Beijing, during rainfall events on June 16 (a), June 24 (b), June 28 (c) and July 1 (d), 2013.
night, indicating that the asphalt stored more heat than the concrete. Meanwhile, rooftop runoff temperature was slightly increased during the June 28 rainfall event. The data show that asphalt paved surfaces have higher capacity for heat storage than other surfaces (e.g. concrete and sod). In addition, the amount of stored heat is also affected by the thickness of the concrete rooftop, asphalt and underlying materials.

The two rainfall events of June 24 and 28 were thunder showers and the pre-event weather conditions were sunny to overcast during the daytime. The ensuing rainfall caused a rapid drop in air temperature. However, the runoff temperature remained relatively stable, indicating that stormwater runoff was gaining thermal energy from surface produced runoff. Thunder showers often immediately follow a hot daytime period followed by a cloudy intermediate period of short duration. Paved surfaces store more heat on hot days than rainy days, and then release the heat to runoff during thunder storms. Janke et al. (2014) came to similar conclusions that antecedent weather conditions are more important for driveway surfaces with large heat storage capacity than for rooftops with smaller storage capacity.

Rainfall intensity and duration

Rainfall intensity and duration also affected the runoff temperature. Runoff temperature measurements for all surfaces during the night of July 1, 2013 are shown in Figure 4(d). This was the largest rainfall event of the four events in this study, with 51.4 mm of rain measured over a period of roughly 2.5 h beginning at 20:45. Runoff temperatures from all surfaces were closer to air temperature during this event than during the three other less intense events. The road runoff had only a slightly higher temperature than the air temperature at the beginning of this storm. When the rainfall intensity increased at 21:05, runoff temperatures of both the rooftop and road were close to air temperature, until after the peak rainfall, then the temperature tended to stabilize. These patterns show that intense, longer rainfall events have a smaller thermal effect than shorter, less intense rainfall events. Thermal enrichment is the process by which the heat of the surface is transferred to runoff, but when rainfall intensity increased and the duration became longer, the runoff volume also increased. With the increase in runoff, the thermal enrichment would also be reduced if the catchment area is constant. However, the study cannot show these two processes systematically due to lack of runoff volume data. This will be further studied in future work. Modeling efforts by Janke et al. (2009) also found that runoff heat export is more sensitive to rainfall intensity, rainfall duration and antecedent pavement temperature than to the physical properties (slope, roughness and length) of the paved surface. Roa-Espinosa et al. (2003) reported higher runoff temperature in association with shorter or less-intense rainfall events in Thermal Urban Runoff Model simulations, consistent with our field monitoring results.

Influences of LID measures on runoff temperature

Some LID measures are effective in mitigating high temperature runoff because they can mimic natural hydrology processes. This study monitored runoff temperature in the following LID measures: bioretention, grass swales and porous pavements. One monitoring road in Guangming New District, Shenzhen, had a combined OGFC and bioretention system. Air temperature and runoff temperatures from the porous asphalt, settling tank and bioretention cell were recorded during six storm periods. Figure 5 shows box plots of measured temperatures during each storm event. Average temperatures of runoff from OGFC porous pavements and the concrete settling tank were higher than

![Figure 5](image-url)
air temperature and similar to conventional impervious pavements (Figure 5(b)). This is due to the large amount of heat stored inside these surfaces before the rainfall started. The average and maximum temperatures of the bioretention cell effluent were much lower than the corresponding temperatures of influent runoff from the concrete settling tank. This indicates that the bioretention cell was able to reduce the thermal impact associated with the stormwater runoff, as observed by Jones and Hunt (Jones & Hunt 2009). The bioretention cell had a positive cooling effect on runoff. The bioretention system generated less outflow, which can in turn effectively reduce the thermal load into the receiving water body.

The combination of two LID facilities, OGFC and bioretention cells, was effective at mitigating runoff temperature, as shown during one representative rainfall event on September 13, 2012 (Figure 6). Although the runoff temperature of OGFC pavements and concrete settling basins exceeded 30°C, the porous asphalt structure postponed the time of peak temperature. OGFC runoff temperature increased more slowly during the rainfall process than that of runoff from conventional impermeable surfaces. There was a roughly 30-min delay after which the effluent runoff temperature of the system dropped to 26.4°C. Bioretention can mitigate thermal energy load into receiving water bodies mainly through directing runoff into the soil. The performance of OGFC and bioretention systems may vary with the construction, location, and watershed area. Further research is needed on the thermal exchange mechanisms associated with LID.

Runoff temperature of grass swales, conventional asphalt pavement, marble pavement and porous concrete pavement on July 7, 2014 are shown in Figure 7(a). Runoff temperature of the grass swales and conventional asphalt road on May 8, 2014 are shown in Figure 7(b). The runoff temperatures of four kinds of pavement were higher than the air temperature, but the runoff temperature of grass swales did not show much fluctuation and did not exceed 30°C from the beginning of the rainfall event to the end. The runoff temperature of grass swales was approximately 1–2°C lower than that of the other three pavements (Figure 7). The grass swales showed a positive effect on alleviating runoff thermal pollution. The runoff temperature

![Figure 6](https://iwaponline.com/jwcc/article-pdf/10/1/53/533145/jwc0100053.pdf)

**Figure 6** | Observed runoff temperatures from a LID facility and precipitation during a rainfall event on September 13, 2012.

![Figure 7](https://iwaponline.com/jwcc/article-pdf/10/1/53/533145/jwc0100053.pdf)

**Figure 7** | (a) Observed runoff temperatures from four kinds of road and precipitation during a rainfall event on July 7, 2014. (b) Observed runoff temperatures from conventional road runoff, combination of road and grass swales, and precipitation during a rainfall event on May 8, 2014.
data of the porous concrete pavement were few because the porous concrete greatly reduced the runoff volume. In addition, due to the fact that our monitoring site was on the surface of the porous concrete pavement and the material of porous concrete was still concrete, the thermal enrichment phenomenon was still present. Therefore, the runoff of the porous concrete pavement is close to that of the marble pavement and the asphalt concrete pavement, but the runoff temperature of porous concrete is reduced when runoff infiltrates to the underground drain.

To sum up, LID facilities have the ability to mitigate thermal pollution from urban runoff and the potential to reduce the heat island effect in cities by reducing surface runoff temperatures. More experiments are needed to explain the relationship between thermal enrichment and runoff volume.

CONCLUSIONS

The results of this study on urban stormwater runoff temperature in Beijing and Shenzhen revealed the following:

1. Characteristics of surface cover, pre-event weather conditions, rainfall intensity and duration can affect stormwater runoff temperature.

2. Impervious surfaces such as asphalt or concrete material can store and transfer heat, resulting in thermal enrichment of runoff. This stored heat decreased after the onset of rainstorms and remained stable afterwards. Runoff temperature was higher than air temperature at the stable stage.

3. LID measures such as OGFC porous pavements, bioretention cells and grass swales were effective in mitigating high temperature runoff. The main role of an OGFC pervious surface is infiltrating runoff into the road subsurface to postpone peak temperature. The bioretention cells and grass swales played an important role in volume retention and thermal energy mitigation through infiltrating heated runoff into the soil and vegetative shade cover.

4. Our study shows that LID measures have the ability to alleviate urban runoff thermal pollution and ease the urban heat island effect. Therefore, LID facilities, suited to local conditions and actual demand would be useful to alleviate thermal enrichment of impervious pavements in cities.

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