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Assessing the impacts of the urban heat island effect on streamflow patterns in Ottawa, Canada

Jan Adamowski [a,*], Andreas Prokoph [b]

[a] Department of Bioresource Engineering, McGill University, 21 111 Lakeshore Road, Ste. Anne de Bellevue, QC, H9X 3V9 Canada
[b] SPEEDSTAT, 19 Langstrom Crescent, Ottawa, ON, K1G 5J5 Canada

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SUMMARY

Due to a variety of commercial and residential activities, large metropolitan areas in mid-to-high latitudinal ranges are experiencing rising air temperatures compared to their surrounding rural areas. This study investigated how this urban heat island effect (UHIE) may influence the streamflow of rivers crossing large urban areas on annual and multi-decadal time-scales. In order to detect, link, and quantify differences in meteorological and streamflow patterns between rural and large urban areas, this study developed a methodology based on the continuous wavelet transform (CWT), cross-wavelet transform (XWT), linear regression, as well as the Mann–Kendall (MK) test. A case study was carried out for the city of Ottawa, Canada as the metropolitan centre, along with three surrounding rural locations (Angers, Arnprior, Russell), with pristine rivers crossing these locations. From roughly 1970 to 2000, air temperature in Ottawa increased at a rate exceeding 0.035 °C/year, while parallel changes in rural areas were relatively stable, and varied by less than 0.025 °C/year. The urban warming that occurred during these decades was accompanied by a significant drop in the amplitude of annual temperatures (i.e. warmer winters). Precipitation in both urban and rural areas showed no significant trends, although the variability in the precipitation amount decreased in both settings. Concurrently, streamflow showed decreasing trends in both urban and rural areas. Annual amplitudes in urban streamflow (Rideau River through Ottawa, ON) correlated positively with annual air temperature amplitudes (i.e., less severe annual flooding with a decreasing winter/summer temperature contrast), whereas such a relationship was not apparent for the rural stations. Moreover, the timing of the annual daily minimum temperature cycle correlated significantly with the streamflow pattern in the urban area, i.e., early annual warming corresponded to earlier annual streamflow maxima. The precipitation pattern (i.e. distribution of rain and snowfall over time) significantly influenced the annual and long term streamflow pattern, but this influence differed little between urban and rural areas. It was also determined that the warming from the urban heat island effect, especially during winter months, was found to perhaps reduce the severity of the annual spring flood event in mid-to-high latitudinal continental settings.

1. Introduction

The expansion of urban centers has created, over the years, a pronounced warming in urban areas relative to their rural surroundings (Oke, 1973; Karaca et al., 1995; Arnfield, 2003). There are several mechanisms caused by urbanization that can influence streamflow. This includes human induced changes such as changes through construction, river flow regulation to water outfall and heated water disposal, as well as natural factors that are influenced by urbanization. These mechanisms include altered natural causes such ambient air temperature increases and altered precipitation patterns in urban centers. These altered natural mechanisms can lead to earlier snowmelt in the year, as well as changes in precipitation related runoff resulting in changes in temporal streamflow patterns compared to the rural surroundings. These differences in air temperatures in city centers, first observed by Howard (1833) as early as the 19th century, were eventually coined under the term "Urban Heat Island" (UHI) by Manley (1958), when he was investigating changes in snowfall patterns between rural and urban areas. Over the years, research has shown that as population increased and cities grew, so did the intensity of their UHIE (Oke, 1973; Li et al., 2004). It has also been observed that the UHIE provides additional warming to both an urban center and its immediate surrounding areas, and that this warming is more pronounced during the winter months when commercial and residential heating are at their highest (Karl et al., 1988).

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* Corresponding author. Tel.: +1 5143987786.
E-mail addresses: jan.adamowski@mcgill.ca (J. Adamowski), aprokocon@aol.com (A. Prokoph).

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UHIs have been studied in various parts of the world (Arnfield, 2003), with locations ranging as far as Alaska in northern latitudes (Hinkel et al., 2003) and in warmer and drier regions such as Spain and Turkey (e.g., Yague and Zurita, 1991; Karaca et al., 1995; Montávez et al., 2000; Yalcin and Yetemen, 2009). With regards to Canada, Oke has investigated temperature trends in urban centers in the St-Lawrence Lowlands as well as in the Pacific Northwest (Oke, 1973; Oke and Maxwell, 1975), with current research now focused in detecting correlations between meteorological conditions and the intensity of the UHI phenomenon in central Canadian cities such as Toronto and Regina (Stewart, 2000; Moshin and Gough, 2012).

While research on the UHIE has been previously geared towards identifying the effect of urban warming on ambient air temperatures, there has been in recent years some research that investigates the possible effect of urban heating on water resources. For example, Shepherd and Burian (2003) and Lin et al. (2011) have examined the impact of UHIs on rainfall anomalies in coastal areas. Their research showed that urban centers located near water masses are becoming warmer and drier because higher rates of evaporation in urbanized areas are blocking precipitation formation by inhibiting water vapor from being transported from the coast. Kinouchi et al. (2007) also investigated the effect of UHIs on water sources by looking at increases in stream temperatures related to heat inputs from urban wastewater. Their study revealed that there was a correlation between increases in urban stream temperatures and increases in urban wastewater temperatures, which they expect to increase even more in the future due to higher urbanization rates and a rise in energy demand and water consumption. More recently, Yalcin and Yetemen (2009) have brought forward the idea that UHIs can also have an impact on groundwater resources. From their analysis of temperature data in underground layers of streams and wells near Istanbul, they observed that the water temperatures in urban groundwater sources were on average 3.5 °C higher than the rural groundwater sources.

Whereas it can be seen from the above examples that research involving the UHIE on water resources is slowly gaining momentum, there is still a lack of studies that directly examine the effect of UHIs on urban streamflow patterns and variability, with past research having been predominately focused on rural streamflows (Lettenmaier et al., 1994; Krakauer and Fung, 2008). Zhang et al. (2001) determined that, in general, streamflow in Canadian rivers had decreased over the last 30–50 years, except for the months of March–April when spring streamflow had increased. Projected global climate warming over the coming century will clearly influence streamflow patterns in snowmelt-induced annual discharge cycles typical of mid-to-high-latitude continental climate settings, especially with regards to the patterns' magnitude and onset (Douglas et al., 2000). Many large, heavily populated urban centers such as Ottawa, Minneapolis, Chicago, Berlin, Kiev and Moscow are located in mid to high latitude continental settings. It thus becomes very important to characterize the effect of UHIE on the streams that are found within these particular urban centers.

Both wavelet analysis and the Mann–Kendall test have been used (although not together) to determine streamflow trends and other patterns, as well as to analyze climate records in Canada. The Mann–Kendall test (Yulianti and Burn, 1998) and wavelet analysis (e.g., Anctil and Coulibaly, 2004; Abdul Aziz and Burn, 2006; Burn et al., 2008; Adamowski et al., 2009) have been predominately used in determining long-term (multiannual) trends and relationships. These studies found a positive correlation between streamflows and patterns of both the El-Nino/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). They also revealed a shift in these streamflow patterns between 1950 and 1970. Nakken (1999) also used wavelet analysis to investigate the potential anthropogenic influences on streamflow, focusing specifically on the rainfall-streamflow pattern, and finding a strong relationship between them.

The purpose of this study is twofold: (i) Develop a criterion to determine and quantify the influence of overlying long-term regional and global climate trends on river flow patterns. Waveband-specific trends and climate-streamflow relationships which have been found to occur can be best addressed by using wavelet and cross-wavelet transform-based amplitude and phase-lag extraction techniques and significance of trend evaluations using Mann–Kendall tests and assessments of the significance of linear correlations. The aim is to determine if streamflow is significantly influenced by UHIE and, if so, at which wavelengths (time-scale). (ii) Complete a case study for Ottawa, Canada focusing on multidecadal *vs.* annual timescale impacts of meteorological variations on river flow patterns, based on continuous daily records from 1972 to 1998. Drawing on several rural and urban monthly climate records, Prokoph and Patterson (2004) used wavelet and trend analysis to determine the impact of the UHIE in the Ottawa area. Over the last fifty years, UHIE warming in Ottawa has occurred at a mean rate of 0.009 °C/yr, and has, in turn, strongly raised regional background warming to a rate of roughly 0.006 °C/yr. Particularly large increases in urban–rural temperature differences occurred during periods of accelerated population growth in Ottawa. Their results provide the basis for the climate record analysis undertaken in this study.

2. Methodological approach

The ability to access extensive streamflow and climate records (e.g. temperature, total precipitation) for Ottawa and its surrounding areas was an important aspect of this study. The records provided information on daily streamflow changes for rivers flowing from a rural area into a high heat-island-affected city centre. For this study, one pair of daily and monthly records from urban streamflow/meteorological stations, and, as a control set, a rural streamflow/meteorological pair of station records, were chosen for detailed comparison. Data from Environment Canada (weather.ec.gc.ca, and ec.gc.ca/rhc-wsc) was used as the primary source of data for these observations. In this case study, the streamflow discharge (F), both at daily- and monthly-averaged sampling rates were used as hydrological dependent records, while different types of precipitation (P) and air temperature records served as independent records. Other climate-related records such as evapotranspiration, snow-on ground/day, snowmelt/day or daily and monthly extreme values were not available at sufficient continuity to be used for this study. Monthly mean temperature ($\bar{T}$), daily maximium temperature ($T_{\max}$) and daily minimum temperature ($T_{\min}$) were used in this study. Monthly records are sufficient to analyse the general annual pattern, but important information is lost concerning diurnal fluctuations, represented by $T_{\min}$ and $T_{\max}$, that are important in characterizing UHIE (e.g., Karl et al., 1988). Ten methodological steps were carried out in this study to determine the potential influence of the UHIE on long-term and annual streamflow patterns (Fig. 1):

(i) Gathering pairs of nearby (<5 km apart) streamflow and climate records over the same time-interval, at the same sampling rate, and preferably with perfect completeness. These records were then grouped into potential UHIE influenced (urban) and non-influenced (rural) records.
(ii) Calculating descriptive statistics for each record to provide an overview of distribution and extreme values. This process was aided by visual observation of the plotted records.
(iii) Calculating and evaluating each record's sample distribution with regard to Gaussianity, a prerequisite for optimal signal detection and extraction using Fourier analysis and the