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The interaction of rivers and urban form in mitigating the Urban Heat Island effect: A UK case study

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ABSTRACT

The Urban Heat Island (UHI) effect already produces elevated temperatures in city centres therefore urban design has a key role to pay in reducing the UHI to create safe and pleasant places in which to live and work. Increased surface porosity and bodies of surface water have a role to play in increasing potential cooling through evaporation. Urban rivers may, therefore, have a place in reducing the UHI. This paper investigates the effectiveness that small urban rivers may have in reducing the UHI effect and also examines the role that the urban form on the banks of a river can play in propagating or reducing this potential cooling. The results from a field survey during spring and summer are presented for a river in Sheffield, UK. The level of cooling is related to the ambient air temperature, increasing at higher temperatures. However, there are also seasonal dependencies and relationships linked to the river water temperature, incident solar radiation, wind speed and relative humidity. A mean level of daytime cooling of over 1.5 °C was found above the river in spring, but this was reduced in summer when the river water temperature was warmer. The urban form on the river bank influenced the levels of cooling felt away from the river bank.

1. Introduction

It is becoming increasingly important to provide resilience to the urban infrastructure in order to withstand extreme events brought about by a changing climate. Flooding, high wind speeds and increased air temperatures all present different risks to cities. Increases in mean air temperatures and more frequent heat waves means the Urban Heat Island (UHI) is becoming an increasingly significant problem in the UK. An overview of the impacts of the UHI in the UK and methods for mitigation and climate change resilience has been reviewed by Smith and Levermore [1]. Globally, there is a significant body of research attempting to understand and quantify local microclimates, often with the aim of providing design guidance to generate better quality urban spaces. Of particular interest is the provision of vegetation and green spaces; both large and small parks have been found to provide cooling, with the effects propagating to a distance approximately half the park width away, dependent upon the local street layout [2–5]. The provision of large canopy street trees can offset the heat input from vehicles [6] and the choice of built environment surfaces with high solar reflectances (albedo) can result in lower levels of solar absorption and so cooler surfaces and adjacent air temperatures [7].

Alongside the provision of shading and cooling via evapotranspiration from vegetation, green spaces will also usually improve the surface porosity, thereby increasing the available capacity for water storage and so water availability for evaporative cooling. The reintroduction of water through the deliberate incorporation of porous surfaces, e.g. porous paving, or the presence of water bodies, such as ponds or rivers, has the potential to reduce the UHI by returning the surface moisture availability to values similar to rural areas. The process of evaporation has been studied, and resulting cooling for various cities demonstrated with models validated for a range of locations [8]. However, there is limited published research on the microclimate effects in the immediate locality of river corridors, with current published data limited to tropical climates. The process of daylighting a large stretch of watercourse in Seoul, Korea, provided the opportunity of a before and after study demonstrating cooling of the urban microclimate [9]. Another study in Nanjing, China [10] of the urban climate highlighted the cooling effects in the locality of a lake, river and sea. The cooling effect of the Ota River, Hiroshima, Japan was found to reach up to 5 °C directly above the river and propagated nearly 100 m from the river banks [11]. These studies demonstrate the potential cooling from rivers in hot climates. Further analysis of the

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influence of local urban form on the propagation of this cooling would be beneficial for providing guidance on river corridor regeneration for an improved microclimate.

Although there are limited published studies on the cooling effects rivers provide in Europe, the heat flux between the atmosphere and rivers has been studied extensively in relation to the thermal properties of the river water. This is mainly due to the resulting ecological implications such as fish spawning [12,13]. The heat budget of a river is related to the sensible, radiative and evaporative heat fluxes between it and the surroundings. The process resulting in the greatest effect is dependent upon the local environment. The direction of heat flux varies during the diurnal cycle, for instance absorbing solar radiation during the day, and radiating long wave radiation at night. However, it seems the radiative heat attenuated and absorbed by the river during the day is greater than that released to the environment during the evening and night, at least for rural areas [12]. In comparison to static absorption and release of radiation for most urban materials, the heat absorbed by the water and suspended particles will be carried downstream at a rate dependent on the river dynamics; heat absorbed will then be released at a different location downstream. The albedo of river water also varies with the angle of incidence of the solar radiation and the quantity of suspended particles. Therefore, intense rain events, resulting in large storm water inputs to the river, will not only increase flow rates but also the level of suspended particles and, thereby, change the albedo on a daily and yearly basis. Together with radiation, evaporative heat transfer has also been shown to be important for the removal of heat from the river [12]. As the river temperature decreases due to evaporation the humidity of the surrounding area will increase and the higher temperature difference means the potential for sensible cooling of the air will also increase. Webb [12] found the evaporative heat flux varied significantly with weather conditions, increasing with high wind speeds and low humidity. Sensible heating of the river, which would directly relate to sensible cooling of the air, was found to have the greatest effects on the river temperatures in shaded areas, i.e. where there is limited impact from solar radiation. There are further interactions between the river, the river bed and the ground water.

Although the work discussed above provides evidence for the heat transfer between water sources and the environment, and methods of modelling this behaviour, they do not provide direct evidence for the provision of cooling in a complex urban environment. Furthermore, these studies tend to focus on the impacts of river rehabilitation and consider the heat transfer processes in mainly rural locations; they do not focus on the effect of specific urban forms in the river corridor and the propagation of cooling from the river into the urban environment. Therefore, there is a need to assess the microclimate effects of urban rivers in the UK in order to evaluate their effectiveness in contributing to resilience to heat waves and how the urban form affects this. This research will focus specifically on small rivers. As well as representing a substantial number of urban watercourses smaller rivers are often representative of streams potentially being targeted for deculverting, or "forgotten" watercourses whose locality faces regeneration. Historically, many urban rivers in the UK were culverted (enclosed) as a consequence of urban expansion and the pressure to gain extra land in city centres. More recently, the daylighting of urban watercourses (i.e. the exposing of rivers) is being promoted by the UK's Chartered Institute for Water and Environmental Management, who cite improvements to flood control and ecological benefits [14]; resilience to heat waves may be an added incentive. In order to aid decision making about the urban design in such areas it is necessary to develop a body of evidence for the potential such rivers have for cooling and the impact different urban forms have on maintaining and propagating this effect.

In this paper the temperature difference between an urban river, its surrounding and an urban reference site at distance from the river is examined during a spring/summer period to evaluate the potential cooling. The temperature difference is quantified based on the variation in ambient conditions and the urban form of the river corridor. Two periods with multiple consecutive days at high ambient air temperatures were also considered in more detail and used to assess the impact of the river temperature when ambient conditions were similar.

2. Methods

The study is based along the River Don, Sheffield, UK, which flows with an average flow estimated to be 4.7 m^3/s through the study site where the channel is approximately 22 m wide. The river passes through rural locations before entering the suburbs and finally the city of Sheffield. The UHI of the city has been measured as 2 °C on a spring day [15]. Measurements of temperature and humidity were taken at 12 locations that were either directly adjacent to the river or running perpendicular to the river bank at a selection of sites close to the north of the city centre (see Fig. 1). Measurements were carried out with ibuttons (Maxim, USA) mounted in 12 plate Gill solar radiations screens (Skye Instruments). These have an accuracy of ± 0.5 °C between −10 °C and 65 °C and a resolution of 0.0625 °C. The loggers were calibrated before installation and recalibrated after a period of six months. These sites were all within 150 m of the city's inner ring road. The loggers were all located at a height of 1.5 m above the ground, except at the two street sites (OStr and CStr) where they were mounted at a height of 3 m due to practical constraints (i.e. protection from damage). Measurements were downloaded every month and the internal clocks reset. An urban reference weather station (UR) (Skye Instruments, UK) was installed approximately 1.5 km from the site, at roof level, at a similar distance from the inner ring road as the study site. This monitored air temperature (°C), relative humidity (%), wind speed (m/s) and direction (°) and solar radiation levels (W/m^2). A second weather station located adjacent to the river (E2) at a height of 1.5 m monitored air temperature (°C), relative humidity (%), wind speed (m/s) and direction (°) and water temperature (°C). Further comparative wind speed assessments were made at the two street sites using a vane anemometer (LCA501, TSI) for 30 min at 1 sec resolution.

2.1. Description of monitoring locations

Distinct locations were chosen in order to assess the effect of different urban forms on the cooling effect of the river. Four different types of urban form were chosen: *enclosed* (E), *open square* (OSq), *open street* (OStr) and *closed street* (CStr). The layout of these sites are shown in Fig. 1 with the logger locations denoted by the letter code describing the type of urban form, and an individual number. Images of the sites are given in Fig. 2.

There are two enclosed sites – at E2 the adjacent building is 6 storeys high, and at E1 the building is 7 storeys high. Both sites are on opposite sides of the river, enabling the microclimate effects to be assessed with differing building orientations. At the open square site the buildings are approximately 6 storeys high to the north and south, and 10 storeys high to the west. These surround an urban, paved square, approximately 25 × 50 m with small canopied trees in planters. The open street site is at a smaller scale than the other sites, with buildings only 2 storeys high to each side of a pedestrianised street 10 m wide opening out onto the river. The closed street site is directly adjacent and identical to the open street