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Impacts of urban development on runoff event characteristics and unit hydrographs across warm and cold seasons in high latitudes

Nora Sillanpää *, Harri Koivusalo

Aalto University, School of Engineering, Department of Civil and Environmental Engineering, P.O. Box 12100, FI-00076 Aalto, Finland

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SUMMARY

The impacts of urbanization on catchment hydrology are widely studied by comparing how different urban catchments respond to storm events, but rarely by realizing long-term observations of hydrological changes during the construction process at urbanizing small catchments. In this study, the changes occurring in runoff generation were monitored in a developing catchment under construction and in two urban control catchments. As the imperviousness of the developing catchment increased from 1.5% to 37%, significant increases were observed in event runoff depths and peak flows during rainfall–runoff events. At the same time, the only statistically significant changes that were observed for the cold period runoff events were the shorter duration and smaller runoff depths. The effect of urbanization on event runoff dynamics was studied in terms of changes in the instantaneous unit hydrographs (IUH). Negative trends were detected in the gamma parameters of IUHs, which became more consistent across events and produced a sharper shape of the hydrograph as the construction works progressed. Because urban development caused the greatest relative changes in runoff during frequently occurring minor rainfall events, the study results underlined the importance of small storms in urban runoff management for maintaining the predevelopment water balance. During infrequent major rainfall events and the cold period snowmelt events the impacts of urbanization were less pronounced. The impact of urbanization on runoff was best detected based on peak flow rates, volumetric runoff coefficients, or mean runoff intensities. Control catchments were essential to distinguish the hydrological impact caused by catchment characteristics from those caused by changes in the meteorological conditions or season.

1. Introduction

Urbanization brings on considerable changes in natural catchment characteristics by increasing the amount of impervious surface area and by creating a need for efficient drainage systems. The resultant hydrological impacts include increases in runoff volumes and peak runoff rates as well as potential decreases in baseflow (e.g. Shuster et al., 2005; Dietz and Clausen, 2008; Bedan and Clausen, 2009; Schueler et al., 2009; Burns et al., 2012). The impacts of urbanization on the hydrologic cycle are often generalized as a straightforward relationship between catchment imperviousness and runoff (Shuster et al., 2005). However, literature reveal examples where the impacts of urbanization have been masked by other factors affecting runoff generation, such as weather conditions (Ferguson and Suckling, 1990), seasons (Dougherty et al., 2006b), construction works (Line et al., 2002) and natural catchment features (Burns et al., 2005).

Cheng et al. (2010) describe three general approaches to identifying the effects of urbanization on catchment hydrology: (i) upstream–downstream measurements in the same watershed, (ii) measurements before and after the changes in the same watershed, and (iii) measurements in paired or several watersheds. Most process-level studies have quantified the impacts of urbanization on runoff based on suburban catchments, where impervious surfaces cover a large percentage of the total catchment area; for this reason, additional studies are needed that compare the changes occurring in undeveloped catchments to the changes occurring in catchments with moderate suburban development (Burns et al., 2005). Shuster et al. (2005) noted that there is lack of controlled experiments that track the hydrological effects of an incremental increase in impervious area for various land use types. Similarly, Dietz and Clausen (2008) argue that much of the research has focused on comparing different catchments over limited time periods, while it would be easier to detect causality if increases in runoff during development were documented. Many earlier long-term studies of several decades in urbanizing catchments consider large watersheds up to hundreds of square

* Corresponding author. Tel.: +358 503863325.
E-mail address: nora.sillanpaa@aalto.fi (N. Sillanpää).

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kilometres (e.g. Ferguson and Suckling, 1990; Changnon et al., 1996; Beighley and Moglen, 2002; Dougherty et al., 2006a,b). These studies provide view on the aggregated hydrological impacts of urbanization but do not provide information about the exact construction process and related hydrological changes that occur in small urban catchments, in a spatial scale typical for new urban developments.

A lack of studies focusing on urban runoff generation under cold climatic conditions has been recognized by several authors (e.g. Semádeni-Davies and Bengtsson, 1999; Matheussen, 2004; Ho and Valeo, 2005; Valtanen et al., 2014). One reason for ignoring the cold conditions is that a common focus is on high intensity rainfall events that are the key contributor to flooding in urban areas (Ho and Valeo, 2005). Decreased evapotranspiration during winter months leads to large runoff generation potential at both rural and urban catchments. Runoff volumes at urban sites are enhanced by the snowmelt runoff that is generated from pervious surfaces and easily reaches paved surfaces and the urban drainage network (Taylor, 1977, 1982; Westerström, 1984; Buttle and Xu, 1988; Bengtsson and Westerström, 1992; Thorolfsson and Brandt, 1996). Despite the low intensity of winter snowmelt compared with the summer downpours, the long duration of snowmelt and the large extent of runoff contributing surfaces must be considered when designing urban drainage systems, such as retention/detention storage structures (Bengtsson and Westerström, 1992).

Previous studies have reported conflicting results regarding the type and extent of changes caused by urbanization on runoff generation under wintry conditions. A series of cold climate studies addressed the hydrological impact of urbanization in the Kawarta Heights watershed in Peterborough, Ontario, Canada (Taylor, 1977, 1982; Buttle and Xu, 1988; Buttle, 1990). Taylor (1977) by comparing seasonal variations in runoff behavior between rural (1.14 km^2) and urban sub-catchments (0.70 km^2, 38% impervious area, including also a construction site). The difference in runoff between these two catchments was the largest during the springtime in terms of both direct runoff volumes and peak flow rates. Consequently, Taylor (1977) concluded that urban development appeared to have a larger impact on runoff during snowmelt than during summer and autumn rainfall conditions. Buttle and Xu (1988) concluded that suburban development increased direct runoff during snowmelt and rain-on-snow events because of the lowered infiltration capacity of urban lawns and the disturbed soil surfaces at construction sites. Later on, however, Buttle (1990) reported that no significant increases in either event direct runoff volumes or peak flow rates were observed based on the data for individual snowmelt events from 14 years of suburban development. In a modelling study conducted in Trondheim, Norway, Matheussen (2004) concluded that the most distinct change caused by urbanization in urban runoff generation during the cold period was the earlier snowmelt and the enhanced melt rates during the early phase of the spring snowmelt. The increased number of wintertime runoff events and earlier snowmelt were also observed at two city centre catchments in Lahti, southern Finland (Valtanen et al., 2014). Furthermore, the Lahti data revealed no significant influence of urbanization on spring runoff rates.

The reviewed literature demonstrates that several knowledge gaps exist with respect to the topic of urban hydrology, including the scarce amount of hydrological data from cold climate conditions and the conflicting results about the impacts of urbanization on runoff generation under wintry conditions. The research so far has concentrated on the post-development phase of urban catchments, whereas developing areas under construction have remained rather inconspicuous. In order to respond to these research needs, the main objective of this study was to identify and quantify changes in runoff characteristics during construction works and between the warm and cold period runoff events. Specific objectives were to focus on event runoff variables such as event runoff volumes, peak flow rates, mean runoff intensities, event durations, volumetric runoff coefficients, and shape of the direct runoff hydrographs and catchment lag. It is hypothesized that urbanization changes the runoff characteristics irrespective of the source of runoff (rainfall or snowmelt) although the changes during the cold period may not be as distinct as those observed during the warm period.

2. Methods

2.1. Study catchments and monitoring

Three study catchments located within the city of Espoo in southern Finland were monitored over a period of five years from the summer of 2001 to the autumn of 2006 (Fig. 1). Finland belongs to the temperate coniferous-mixed forest zone with cold, wet winters: in southern Finland, the average annual precipitation ranges from 650 to 750 mm, the average annual temperature from 4 to more than 5 °C, and snow cover exists from November to April (Finnish Meteorological Institute, www.fmi.fi). During the winter months, road salt and sand as a gritting material were used for road safety in the study catchments.

The Saunalahdenranta (SR) study catchment underwent major construction activities during the monitoring period and it is later referred to as the developing catchment. The catchment area is characterized by rocky hillslopes with elevations ranging from 5 to 50 m above the mean sea level. In 2001, SR consisted mainly of coniferous forest, whereas by 2006 the catchment had been fully transformed into a medium-density residential area with a separate pipe sewer network for stormwater runoff (Fig. 2). The timing of the main construction phases is illustrated in Fig. 3. A summary of the changes in the total catchment area and total impervious areas (TIA) is provided in Table 1.

Simultaneous measurements were conducted at two control catchments representing developed urban areas without construction activities: Laaksolahti (LL) and Vallikallio (VK) (Fig. 1). LL is a low-density residential area of mainly detached housing (0.31 km^2 with 20% imperviousness) and VK is a medium-density residential area consisting mainly of blocks of flats (0.13 km^2 with 50% imperviousness). At LL, some of the driveways do not have asphalt paving and drainage is organized using open ditches combined with sections of separate pipe sewers and road culverts. Stormwater from rooftops is mainly conveyed to nearby lawns. At VK, all traffic-related areas have an asphalt coating. A subsurface storm sewer network covers the whole catchment area and most of the rooftops are directly connected to the storm sewers. The elevation ranges from 29 to 50 m above sea level at VK and 30 to 60 m above sea level at LL. The soils within the three study catchments consist of three soil types: (i) bedrock underlying a thin (<1 m) soil layer, (ii) till and (iii) fine-grained material such as clay in the areas at the lowest elevation (digital maps by the Geological Survey of Finland, www.gtk.fi).

In each study catchment, precipitation was recorded with tipping bucket rain gauges, adjusted for a volume resolution of 0.2 mm. The flow rates at the catchment outlets were determined based on the water depth recorded by pressure transducers. At the SR and LL, the pressure transducers were installed into a v-notch weir (90° at SR and 120° at LL) in an open ditch. The stage-discharge curves for the angles were previously presented by Kotola and Nurminen (2003). At VK, the pressure transducer was located in a sewer manhole. The flow rate was calculated using a stage-discharge curve calibrated based on on-site manual flow rate measurements as well as laboratory flume measurements. The temporal resolution of the flow and precipitation measurements