

# Urbanization alters watershed hydrology in the Piedmont of North Carolina

J. L. Boggs\* and G. Sun

USDA Forest Service, Eastern Forest Environmental Threat Assessment Center, 920 Main Campus Dr., Suite 300, Venture II, Raleigh, NC 27606, USA

## ABSTRACT

The ecohydrologic effects of urbanization that is dominated by forests clearing are not well understood in the southeastern United States. We utilized long-term monitoring data to quantify the annual water balance, stormflow characteristics, and seasonal flow patterns of an urbanized watershed (UR) (0.70 km<sup>2</sup>) and compared it to a fully forested watershed (FOR) (2.95 km<sup>2</sup>) in central North Carolina. The goal of this study was to assess how past urbanization altered watershed hydrology and to offer reference data for urban watershed planning. The mean annual discharge coefficient (discharge/precipitation) in the UR and FOR from 2000 to 2007 was 0.42 and 0.24, respectively. The UR generated about 75% more stormflow than the FOR. The UR had a lower mean evapotranspiration (ET) rate (58%) than the FOR (77%). Peakflow rates and stormflow volume of the UR were higher (e.g. 76.6 mm/day versus 5.8 mm/day for peakflow rate and 77.9 mm/day versus 7.1 mm/day for stormflow volume) than the FOR, especially during the growing season. Growing season precipitation minus discharge normalized by precipitation ( $(P - Q)/P$ ) (i.e. normalized ET  $\pm$  change in water storage) was higher in the FOR compared to the UR. Differences between the two watersheds occurred mostly during the growing season and became smaller during the dormant season. We conclude that intensive urbanization elevated watershed peakflow rates and annual discharge volumes partially due to reduction in ET during the growing season. Maintaining ET capacity of vegetation in an urbanizing watershed is important in development planning for reducing stormflow and watershed degradation. Published 2011. This article is a US Government work and is in the public domain in the USA.

KEY WORDS urban watershed; evapotranspiration (ET); discharge coefficient; North Carolina Piedmont

Received 11 October 2010; Accepted 24 December 2010

## INTRODUCTION

Water resources in urban environments are increasingly stressed in the southeastern United States due to population rise and climate change and variability (McCray and Boving, 2007; Sun *et al.*, 2008). For example, in Wake County, NC, population growth is projected to increase 148% from about 627 000 to 1 560 000 in the next 30 years (North Carolina Office of State Budget and Management, 2008). Many of the pressures on hydrology and water quality may be tied to forest loss as a consequence of urban development and sprawl (Riley, 1998; Booth *et al.*, 2001; Doll *et al.*, 2002). Although urbanization has been linked to increased flooding, decreased baseflow, low aquatic species diversity, and degraded water quality when compared to forest watersheds in general (Wolman, 1967; Leopold, 1968; Walsh *et al.*, 2001, 2005), process-based understanding of the hydrologic processes in urbanized headwater watersheds in the southeastern United States is lacking (Fisher *et al.*, 2000).

The effects of forest conversion to other landuses have been well studied in the southeastern United States (Trimble, 1974; Jackson *et al.*, 2004; Sun *et al.*, 2004) and around the world (Andreassian, 2004) where hydrologists commonly use the small 'paired watershed' approach as

the basis to quantify hydrologic response. In general, watershed manipulation experiments worldwide show that deforestation elevates water yield and reforestation decreases it (Andreassian, 2004). Reported maximum first-year hydrologic response to clear-cutting a forested watershed (FOR) in the southern Appalachians is about 400 mm/year (Swank *et al.*, 1988). However, the effects of forest cutting on peakflow rates are more variable, with most literature suggesting forest harvesting does not affect large or atypical peakflows that follow large storms (Eisenbies *et al.*, 2007). Increases in stream peakflow rates, stormflow volume, and total flow after timber harvest have been attributed to reductions in evapotranspiration (ET) and soil disturbances (Dietterick and Lynch, 1989).

Although worldwide 'paired watershed' experiments provide much of the science for modern watershed management, unfortunately these studies have limits in their ability to answer questions on the effects of urbanization on the hydrologic cycle. The primary reason is that these watershed manipulation experiments usually result in minimal impacts to forest soils except on roads and skid trails. Research has shown that peakflow from FORs may persist longer when roads and trails are present (Jones and Grant, 1996). Peakflow rates from urbanized watersheds (URs) are expected to be greater because these watersheds have been more severely impacted due to soil compaction, vegetation removal, and increases in impervious surface area (Burton and Pitt, 2002). However,

\* Correspondence to: J. L. Boggs, USDA Forest Service, Eastern Forest Environmental Threat Assessment Center, 920 Main Campus Dr., Suite 300, Venture II, Raleigh, NC 27606, USA. E-mail: jboggs@ncsu.edu

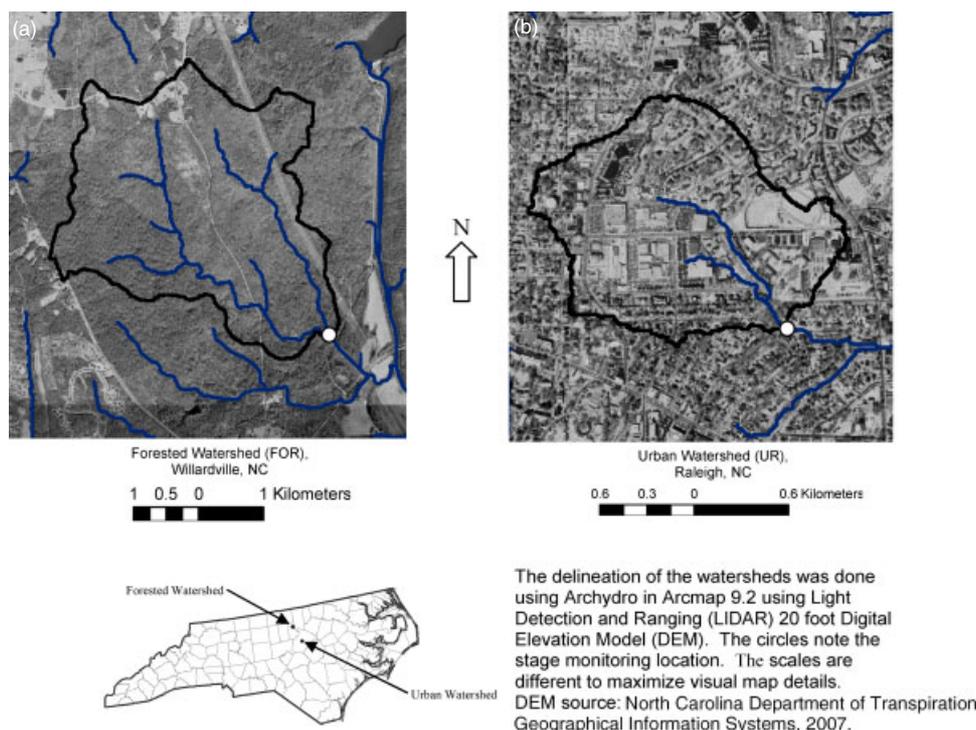


Figure 1. Maps depicting differences in land cover between the (a) forested (FOR) and (b) urbanized (UR) watershed. The FOR is located in Durham County, NC, and the UR is in Wake County, NC. The distance between the watersheds is about 56 km.

other studies show that when Best Management Practices (BMPs) are used, the hydrologic effects may be minimal. For example, the Jordan Cove urban paired watershed project found, including cul-de-sac bioretention, alternative driveway pavement treatments and roads, rain gardens, and community education and outreach maintained post-development peak runoff rate and volume at levels equal to predevelopment rates. In addition, BMPs reduced nitrogen and phosphorus exports by 65 and 40%, respectively (Dietz and Clausen, 2007; Jordan Cove Urban Watershed 319 National Monitoring Program Project Final Report, 2007). In addition, the Baltimore Long-term Ecosystem Study (<http://www.beslter.org/>) offers comprehensive studies on the effects of urbanization on watershed hydrology and water quality.

Landuse change is a global phenomenon. Understanding the hydrologic differences between natural forests and urbanized landscapes is fundamental to assessing and managing hydrology and water quality. The specific objectives of this study are (1) to compare the hydrology between an UR and FOR while highlighting components of the water balance, and (2) to explore the controls on discharge observed between the two watersheds having distinctly different landuses.

## METHODS

### *Study area and data*

Two watersheds were selected for this study; one urban dominated (Pigeon House Creek, Wake County, NC—0.70 km<sup>2</sup>), and one forest dominated (Flat River Tributary, Durham County, NC—2.95 km<sup>2</sup>) (Figure 1

and Table I). In the UR, the main stream channel is second order and has a length of 0.60 km with an elevation change of 114–98 metres above sea level (~3% gradient). In the FOR, the main stream channel is third order and has a length of 2.5 km with an elevation change of 125–82 metres above sea level (~2% gradient). According to Miller and White (1998), the available water capacity (AWC) in the UR and FOR is 8 and 14 cm, respectively, indicating that the UR has slightly less capacity to hold water compared to the FOR (Table I). The soil series on the UR are dominated by Appling and Georgeville whereas, Cecil soil series dominate the FOR (According to SSURGO 2003; 1:24 000). Raleigh belt and Carolina slate belt are the underlying geologic structures in the UR and FOR, respectively (Table I). The UR has 44% impervious cover (Homer *et al.*, 2004), with the remainder classified as open space and urban forests. The FOR is 99% forested and 1% urban with virtually no impervious cover (Homer *et al.*, 2004).

Daily rainfall and stream discharge data for the period 2000–2007 were downloaded from the USGS website (USGS, 2008). Rainfall and discharge stations for the UR are co-located whereas the closest rainfall monitoring station to the FOR discharge point is approximately 16 km away above the Dam at Falls Lake (Station 02 087 182). Stormflow (also called quickflow) and baseflow for the selected storm events were derived from a standard flow separation method using a constant slope (0.05 ft<sup>3</sup>/s/mi<sup>2</sup>/h) as described by Hewlett and Hibbert (1967). We used a total of five storms from each watershed covering different seasons (growing season, May–October and dormant season, November–April)

Table I. Watershed characteristics for the forested and urbanized watershed.

	Pigeon house creek (urban)	Flat river tributary (forest)
Watershed size (km <sup>2</sup> )	0.70	2.95
Gauging station number	208732534	208650112
Rainfall station number	208732534	2087182
Slope (%)	3	2
Elevation at gauge (m)	98	82
Latitude at gauge	35°48'25"	36°07'55"
Longitude at gauge	78°36'50"	78°50'00"
Impervious (%)	44	1
Forest and open space (%)	56	99
Soil series <sup>a</sup>	Appling (35), Georgeville (26), Wedowee (11), Goldston (8), Herdon (7), Iredell (4), Nason (4), Mayodan (2), Cartecay (2), and Tatum (1).	Cecil (95) and Mantachie (5)
Underlying geology	Raleigh belt—Metamorphic rocks consisting of injected gneiss and lineated felsic mica gneiss	Carolina slate belt—  Metamorphic rocks consisting of felsic and intermediate metavolcanic rock Intrusive rock consisting of metamorphosed granitic rock
Available water capacity (cm)	8	14
Stream length (km)	0.60	2.5

<sup>a</sup> Value in parenthesis represents percent of soil series across the watershed.

for the stormflow and baseflow separation analysis. In the study region, soil moisture is the lowest during the peak growing season when potential ET is highest, and the highest in the dormant season when potential ET is lowest (Chris Dreps, North Carolina State University, unpublished data). We computed annual watershed water balances for each watershed [ $ET = \text{Precipitation (P)} - \text{Discharge (Q)}$ ] with the assumption that the change in soil water storage was negligible over the period of our study. Because we do not have the site-specific data to estimate inflow from sewer and water main leaks and the consequent change in storage, our overall interpretation and analysis of the water balance is limited. However, change in storage is generally small in comparison to the other terms in the water balance over time. Exceptions to this occur during extreme prolonged drought periods and during periods of significant groundwater or aquifer pumping for irrigation and other commercial or municipal uses (Loaiciga, 2003). Discharge coefficients are expressed as Q/P at a storm event and annual time scale.

## RESULTS

### *Distribution of daily rainfall and streamflow*

The URs and FORs had similar range of daily rainfall (Figure 2), but the annual totals were slightly higher in the UR than in the FOR. The biggest difference in percent exceedance occurred at the lowest values (daily rainfall <10 mm/day) (Figure 2). Linear regression analysis of daily rainfall and discharge revealed an  $r^2 = 0.81$  in UR and  $r^2 = 0.14$  in the FOR (Figure 3a and b, respectively), suggesting that the UR is more responsive to rainfall at the daily scale than the FOR. Streamflow periodically

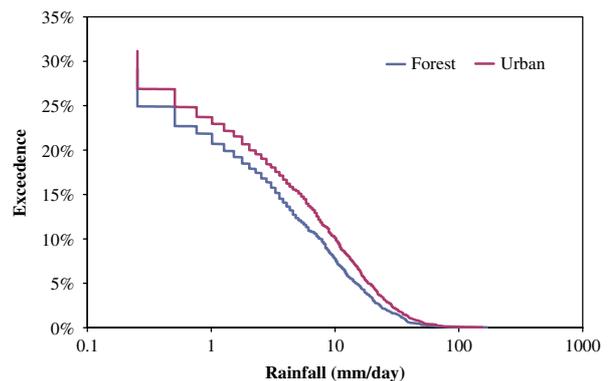


Figure 2. Percent exceedance of rainfall from January 2000 to December 2007 used to compare rainfall distribution between the urbanized and forested watershed.

ceased in the FOR while it continued in the UR, especially during the growing season (Figure 4a and b). This resulted in lower baseflow rates in the FOR compared to the UR.

On the basis of patterns of discharge across the year, there was no clear seasonal discharge pattern observed from the UR; high in-channel flow rates occurred through both the recharge period (dormant season) and low baseflow period (growing season) (Figure 4a). Discharge from the FOR revealed a pronounced seasonal pattern where ET appears to be controlling discharge amounts during the growing season (Figure 4b).

The daily flow frequency distribution provided a clear contrast of flow regimes between the two watersheds (Figure 5). The percent exceedance of daily discharge between the URs and FORs diverged greatly as discharge values decreased (Figure 5). In general, higher daily discharge exceedance classes occurred in the UR compared

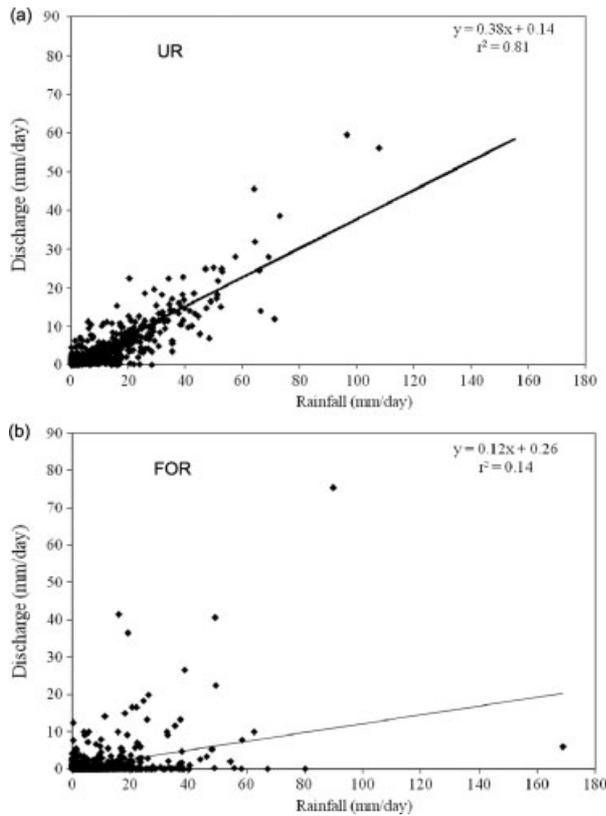


Figure 3. Scatter plot between daily discharge and rainfall from 1 January 2000 through 31 December 2007; (a) urbanized watershed, and (b) forested watershed.

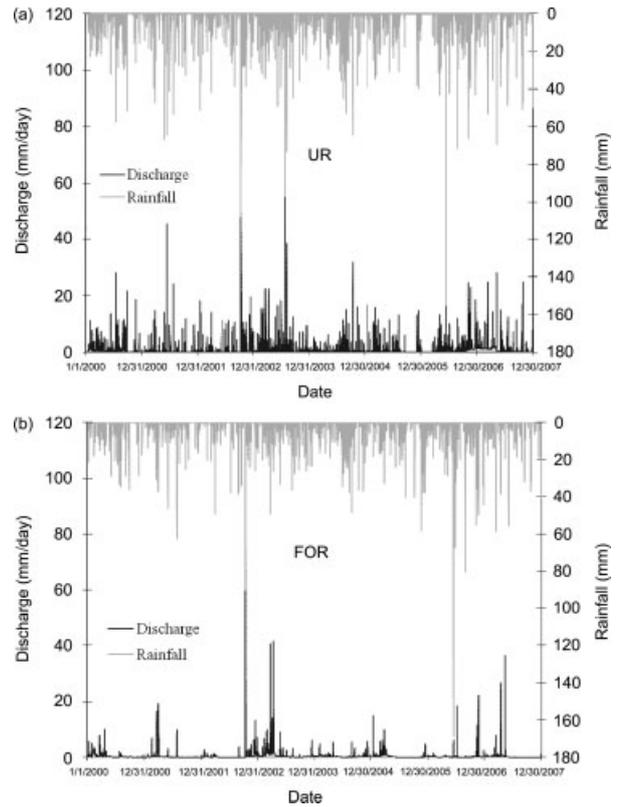


Figure 4. Relationship between daily discharge and rainfall from 1 January 2000 through 31 December 2007. (a) urban watershed, and (b) forested watershed. \*Missing data.

to the FOR. However, the range in daily discharge was larger in the FOR compared to the UR.

*Annual watershed water balance*

The discharge coefficient was lower in the FOR every year except 2003 (Figure 6) and varied from 0.32 to 0.61 in the UR with a mean value of 0.42. In contrast, the discharge coefficient in the FOR varied from 0.11 to 0.47 with a mean value of 0.24, about half the outflow generated from the UR. The UR had a lower mean annual ET rate of (603 mm/year or 58% of rainfall) than the FOR (659 mm/year or 77% of rainfall) (Figure 6). There was some slight variability in  $P - Q$  (i.e. absolute ET) with years 2001–2003 being higher in the UR.

*Seasonal discharge, peakflow, baseflow, and stormflow*

Growing season precipitation minus discharge normalized by precipitation  $(P - Q)/P$  (i.e. normalized ET  $\pm$  change in water storage) was higher in the FOR when compared to the UR for all years (Figure 7). Hereafter  $(P - Q)/P$  will be referred to as normalized ET. There was no consistent pattern in dormant season normalized ET between the FOR and UR. However, UR growing and dormant season normalized ET patterns were similar across years with UR growing season normalized ET being slightly higher. There was no distinctive pattern between FOR growing and dormant season normalized ET.

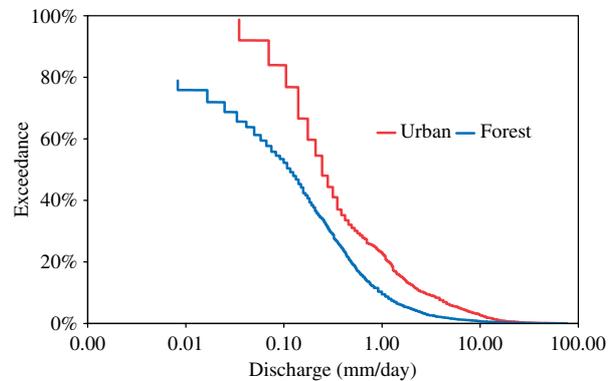


Figure 5. Percent exceedance of daily discharge from January 2000 to December 2007 used to compare discharge distribution between the urbanized and forested watershed. Percent exceedance is defined as the percent of time that a particular discharge rate occurred during the research period.

Graphical hydrograph separation analysis detailing the magnitude of stormflow and baseflow discharge generation is shown in Table II. In lieu of soil moisture data, the wet or dry antecedent moisture condition was assigned based on baseflow values during a given season and/or time of year. Data in Table II also highlight the seasonal influence on water outflow between watersheds. Stormflow volume from the UR was higher than the FOR, particularly during the growing season (e.g. 76.6 mm/day versus 5.8 mm/day for peakflow rate and 77.9 mm/day versus 7.1 mm/day for stormflow volume). Stormflow accounted for 70% or more of discharge generated in

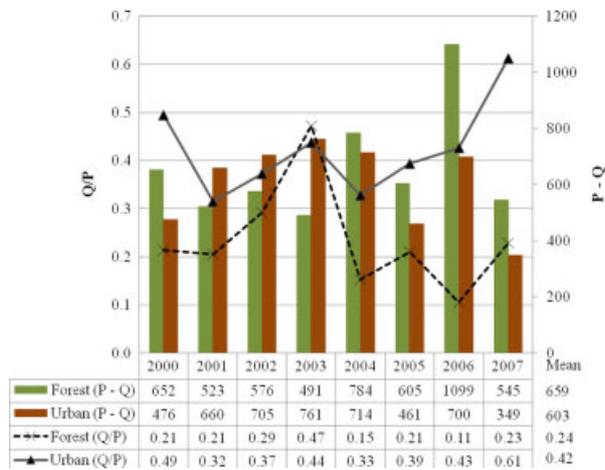


Figure 6. Annual discharge coefficient (Q/P) and precipitation minus normalized discharge (i.e. absolute evapotranspiration value) from the urbanized and forested watersheds, 2000–2007, Q = discharge, P = precipitation.

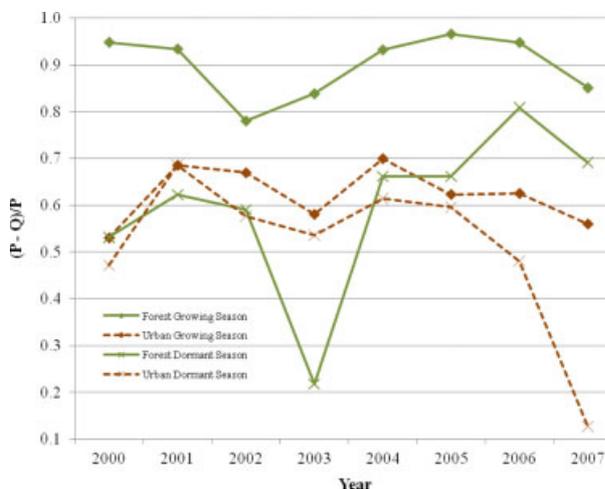


Figure 7. Growing and dormant (P-Q)/P (i.e. normalized  $\pm$  ET change in water storage) in the forest and urban watersheds, 2000–2007, Q = discharge, P = precipitation.

both watersheds. Growing season discharge coefficients from the FOR were minimal relative to the UR under wet and dry conditions, with a maximum of only 5% discharge occurring even after a large storm (169 mm). In contrast, the dormant season discharge coefficient from the FOR was similar to that of the UR, especially under high soil moisture conditions. During the growing season, peak rates were always higher in the UR compared to the FOR.

DISCUSSION

Landuse and landcover change affect all aspects of watershed hydrology from rainfall redistribution, plant transpiration, infiltration, and groundwater recharge at multiple scales. Stream discharge data from the UR and FOR were summarized in three ways that allowed us to examine annual water yield (ET and discharge/precipitation ratios), storm (peakflow rates and stormflow and baseflow volumes) and seasonal (growing versus dormant)

outflows. The cross-scale analysis allows identification of key factors controlling the hydrologic differences between the two watersheds.

Although traditional paired watershed experiments have been shown to yield good results to detect effects of landcover change (Swank *et al.*, 1988), given the distance between our forested and URs and the availability of USGS gauging stations, a paired approach was not feasible. Because we are using an unpaired watershed design, our analysis could be slightly confounded by the following factors: (1) differences in soil types, soil depth, and underlying soils and geology, and (2) differences in rainfall temporal and spatial patterns. Because the dominant drainage and permeability properties are similar between watersheds, the confounding affects created by slight soil property differences are likely minimal. In addition, the first factor becomes less important for this study because we assume most of the stormflow travels across the urban surface as overland flow and through the UR to the stream channel via culverts and pipes bypassing much of the buffer area and other pervious land cover. An examination of the second point revealed a relationship between rainfall inputs to the UR and FOR. However, the UR did receive about 17% more total rainfall over the study period. As we will discuss later, considerations for rainfall inputs alone cannot explain differences in outflow patterns. Other factors including antecedent moisture conditions, surface conditions, and the temporal patterns of ET or season are more important when examining the discharge coefficient at storm and annual time scales.

Annual water yield

Impervious surface cover has a wide range of effects on watershed hydrology from reduced infiltration, decreased water storage in the soil matrix, to peakflow rates (Schueler, 1992; Booth *et al.*, 2002; Kang and Marston, 2006). The US Environmental Protection Agency (1993a) reported that in general when impervious surface cover reaches 10–20% across a watershed stream discharge increases twofolds, 35–50% impervious cover results in a threefold increase and 75–100% impervious cover results in a fivefold increase in discharge when compared to undisturbed FORs. Wissmar *et al.* (2004) found that decreases in forest cover and increases in impervious surfaces impact discharge by producing a doubling of discharge rates compared with presettlement watershed conditions. Rose and Peters (2001) found a watershed described as 54.7% urban produced higher peakflows with a 1- to 2-day shorter recession period than watersheds defined as 13.8–0.5% urban. In this study, the annual discharge ratio in the UR that has a 44% impervious surface is on average about 75% (ranging from 6 to 290% annually) higher than the FOR. It appears the urbanization effect on annual discharge is variable, but was comparable to reported values for impervious surfaces covering 10–50% of the watershed (EPA, 1993a;

Table II. Stormflow characteristics of five storms—forest versus urban watershed.

Watershed	Wet/dry	Event duration (days)	Begin flow (mm/day)	Peak rate (mm/day)	Time to peak (days)	Stormflow (mm)	Baseflow (mm)	Event outflow (mm)	Rainfall (mm)	Discharge coefficient Outflow/rainfall	Season	Date storm started
Forest	Dry	5	0.0	1.2	4	2.5	0.1	2.6	57.2	0.04	Growing	22 July 2010
Urban	Dry	6	0.2	6.3	4	13.8	1.4	15.2	38.4	0.39	Growing	22 July 2010
Forest	Wet	7	0.2	1.2	3	2.9	1.2	4.1	74.7	0.05	Growing	30 July 2010
Urban	Wet	4	0.5	7.2	3	21.7	2.9	24.7	82.3	0.30	Growing	30 July 2010
Forest	Wet	4	0.2	5.8	2	7.1	0.6	7.7	169.4	0.05	Growing	13 June 2006
Urban	Wet	7	0.4	76.6	2	77.9	2.3	80.2	156.0	0.51	Growing	13 June 2006
Forest	Dry	6	0.1	16.4	3	23.1	0.8	23.8	52.3	0.46	Dormant	19 March 2001
Urban	Dry	5	0.2	10.8	3	21.9	0.7	22.6	64.3	0.35	Dormant	19 March 2001
Forest	Wet	6	0.9	6.5	2	12.0	4.6	16.5	35.3	0.47	Dormant	27 March 2005
Urban	Wet	9	0.2	5.8	3	16.1	0.0	16.1	35.3	0.46	Dormant	27 March 2005

Meierdiercks *et al.*, 2010). Timber harvesting activities including clear cuts in the Piedmont had similar effects on annual flow volumes, producing a 50% increase in flow in the first year (Ursic, 1978). However, unless the landscape is permanently converted from forest to urban, much of the high annual flow volume is relatively short lived especially in a managed forest the southeastern United States For example, stormflow volumes of sites having undergone conversion to pine plantations decreased by 50–83% once the trees reached 8–12 years of age (Ursic, 1985). Forests can regain their ability to moderate stormflow over time.

The large increase in streamflow due to urban development is not only related to an increase of overland flow due to impervious surfaces (Buttle, 1994) but also to a reduction in ET (Bosch and Hewlett, 1982). It is well documented that measured ET is generally high in forested areas in the southeastern United States, ranging from 50 to 90% (Sun *et al.*, 2002, 2010). These measured ET values are similar to our computed (P – Q) values. Forest ET estimates determined by an eddy covariance method near our study site ranged from 460 mm/year to 740 mm/year or 60% of precipitation (Stoy *et al.*, 2006). ET has been estimated to account for an average of 40% of the precipitation input from an urban site that is covered by ~40% impervious surfaces (Grimmond and Oke, 1999). Our study estimated that normalized ET accounted for 77% of precipitation in FORs and 58% in URs. This suggests that urbanization reduced normalized ET. However, this study did not account for water leaks from water transfer systems.

The FOR had a slightly wider discharge ratio range, 0.11–0.47, than the UR due in part to variability caused by greater fluctuations in ET (Figure 6). Our linear regression model suggests that impervious surface is one of the principle controls on discharge from the UR; that is, components of the UR, mainly imperviousness and reduced ET, cause rapid stormwater flow (Figure 3a) (Dow, 1997). Sustained baseflow is most probably due to reduced ET (Brown *et al.*, 2005). For the FOR, rainfall-discharge relations are more complex than that of the UR. Non-impervious controls (i.e. ET, infiltration, and storage) are probably the primary controls on discharge from the FOR as the relationship between rainfall and discharge is less connected (Figure 3b). Corbett *et al.* (1997) also found a wider range of discharge ratio values when comparing forest and urban watersheds, 0–56% and 20–66%, respectively. They suggested that the discharge ratio from the UR was driven by an increase in the minimum discharge ratio (higher baseflow) and not a reduced maximum discharge ratio. Research has also shown that water supply lines or sewage leaks can account for a significant amount (i.e. 100–300 mm/year) of streamflow in URs (Lerner, 1986a; Ferguson and Suckling, 1990). Our data support this assessment, where baseflow from the UR throughout each year is generally higher when compared to the FOR (Figure 4a and b). In addition, the lower intercept is smaller in the UR regression model compared to the FOR model, which

suggests that less precipitation is needed to generate discharge in that watershed (Figure 3a and b). Increased soil water storage or residence time in large FORs generally tends to produce a persistent baseflow or outflow (Dingman, 1994); however, because ET removed almost 80% of the annual rainfall input from the FOR we did not observe a persistent flow.

#### *Peakflow, stormflow, baseflow and seasonal discharge*

Although peakflow and stormflow are usually closely linked to storm size, we did not find that the differences in peakflow and stormflow between the FOR and UR were related to storm size, but rather related to seasons (Meierdiercks *et al.*, 2010). During the growing season, regardless of storm size, the discharge coefficient between the UR and FOR was always different. For example, after a large (~162 mm) storm event, the discharge coefficient was 0.51 in the UR and 0.05 in the FOR even under relatively wet antecedent moisture conditions. In addition, the discharge coefficient in the FOR was always 5% or less whereas the discharge from the UR was always greater than 30% (Table II). During the dormant season, a moderate (~60 mm) storm event under dry moisture conditions resulted in only slightly different discharge coefficients between watersheds (Table II). This smaller discharge difference could be because transpiration from the FOR is in effect turned off during the dormant season (Dunn and Mackay, 1995). Our annual seasonal data supports these storm-based data as the UR growing season normalized ET pattern is similar to the UR dormant season, suggesting a non-existent or slight seasonal influence or control on normalized ET. The FOR growing season normalized ET values, however, are higher than the those of the FOR dormant season indicating a temporal control on normalized ET (Cheng *et al.*, 2002) (Figure 7).

The seasonal variability of hydrologic responses to forest cover change found in this study was also reported by recent empirical and modeled forest hydrology studies in the coastal plain region of the southeastern United States by Sun *et al.* (2009) and Lu *et al.* (2009). Both studies support previous observations by Sun *et al.* (2000) that suggest forest cover change has the most pronounced effect during dry periods in the growing seasons when ET differences are the largest among land uses in the humid southeastern United States. Other studies with small watersheds (60–100 ha) under a patch-cut and clear-cut treatment also showed a variable increase in peakflow and lasting for 10–20 years (Thomas and Megahan, 1998) due to ET reduction and soil compaction from harvesting activities. The timber harvest treatment effect on peakflow and stormflow will, however, tend to decrease as rainfall intensity increases (Thomas and Megahan, 1998). Corbett *et al.* (1997) found that during heavy rainfall (>100 mm), discharge from a FOR was similar to a watershed covered primarily by impervious cover due to the soils becoming saturated and reducing the infiltration rate to near zero.

#### *Watershed management*

Reducing storm discharge in urban areas is a challenge that local watershed managers are constantly faced with as human population continues to grow. Conventional and more creative approaches to successfully manage peakflow, stormflow, and water quality such as optimizing spatial patterns of landuse (Tang *et al.*, 2005) and urban density (Jacob and Lopez, 2009) should be developed and implemented to serve high population areas and associated increases in living standards while maintaining ecosystem integrity.

This study showed that the FOR had a larger water retention capacity than the UR, especially during the growing season. This large retention was probably due to the high infiltration rate of undisturbed forest soils and drier soil conditions (thus higher available water storage) caused by higher ET (Kovnee, 1954; Whitehead and Robinson, 1993). When properly sized and positioned in high density development, storm water retention ponds can provide benefits that reduce stormflow and improve water quality (Jackson *et al.*, 2001; Jacob and Lopez, 2009). Detention ponds and wet/dry swales that incorporate wetland functions and urban forest features, including streamside management zones can provide both ecological and engineering benefits. For example, Sanders (1986) found that with proper urban forest planning storm discharge can be reduced by 7%. Neville (1996) found that 'heavily forested' urban environment reduced storm discharge by 26%. Careful selection of and proper placement and management of tree species in urban settings can improve rainfall infiltration into compacted subsoil by an average of 153% in the area immediately influenced by the tree's fine and coarse root system (Bartens *et al.*, 2008). In addition, with thoughtful planning we think the ET capacity of urban lands in this region could be maximized by planting trees along highway rights-of-way, in parks, open spaces, and stormwater wetlands, and clustered in multi-zone filter strips. Our study demonstrates how watershed hydrology has been modified and perhaps offers a reference for watershed development in the Piedmont region.

## CONCLUSIONS

The UR selected for this study had higher flow rates at almost all temporal scales from annual total flow, peakflow, and stormflow and baseflow volumes when compared to the FOR. We conclude that urbanization can alter watershed hydrology in the piedmont region, especially during the growing season. The primary differences between UR and FOR appear to be controlled by ET although we could not exclude the effects of other factors such as changes in soil storage, infiltration rate, and water supply infrastructure under an urbanized environment.

Watersheds under similar climatic conditions can have different hydrologic responses depending on the presence or absence of other controlling factors such as vegetation covers across the landscape. Maintaining ET, the

'biological drainage', and infiltration capacity is critical to sustaining watersheds' water storage functions. Those two factors as well as the time of year and antecedent moisture conditions should be considered in landscape design to control peak flow rates. Overland flow was likely the dominant pathway in the UR during storms while a mixture of subsurface flow, saturated subsurface stormflow, and saturated overland flow were likely the dominant pathways in the FOR. We could not exclude the hydrologic effects of recharge via water main and/or sewer leakage in the UR as reflected by the higher base-flow values when compared to the FOR. A more detailed analysis of other controlling factors including soil moisture regimes and soil physical properties in the source area in both watersheds is warranted and could further explain some of the observed outflow patterns and variability.

Traditional forest hydrology research that focused on FORs is shifting towards understanding the watershed hydrologic processes in the urban–rural interface and will play a role in understanding permanent alterations in hydrologic regimes due to forest cover changes following urbanization (Cuo *et al.*, 2008; Gash *et al.*, 2008). This study demonstrated the complexity of seasonal watershed hydrologic responses to human disturbances.

#### ACKNOWLEDGEMENTS

This work was funded by the USDA Forest Service Eastern Forest Environmental Threat Assessment Center. We would like to thank Erika Cohen for her assistance with estimating impervious surface in the urban watershed. Hydrology data used in the project were obtained from the US Geological Survey.

#### REFERENCES

- Andreassian V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology* **291**: 1–27. DOI: 10.1016/j.jhydrol.2003.12.015.
- Bartens J, Day SD, Harris JR, Dove JE, Wynn TM. 2008. Can urban tree roots improve infiltration through compacted subsoils for stormwater management? *Journal of Environmental Quality* **37**: 2048–2057. DOI: 10.2134/jeq2008.0117.
- Booth DB, Hartley D, Jackson R. 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. *Journal of the American Water Resources Association* **38**: 835–845. DOI: 10.1111/j.1752-1688.2002.tb01000.x.
- Booth DB, Karr JR, Schauman S, Konard CP, Morley SA, Larson MG, Henshaw PC, Nelson JE, Burges SJ. 2001. Urban stream rehabilitation in the Pacific Northwest. *Washington Water Resources* **12**: 1–11.
- Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**: 3–23. DOI: 10.1016/0022-1694(82)90117-2.
- Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**: 28–61.
- Burton GA, Pitt RE. 2002. *Stormwater Effects Handbook. A Toolbox for Watershed Managers, Scientists, and Engineers*. Lewis Publishers: Boca Raton, FL: 929.
- Buttle JM. 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. *Progress in Physical Geography* **18**(1): 16–41. DOI: 10.1177/030913339401800102.
- Cheng JD, Lin LL, Lu HS. 2002. Influences of forests on water flows from headwater watersheds in Taiwan. *Forest Ecology and Management* **165**: 11–28. DOI: 10.1016/S0378-1127(01)00626-0.
- Corbett CW, Wahl M, Porter DE, Edwards D, Moise C. 1997. Nonpoint source runoff modeling a comparison of a forested watershed and an urban watershed on the South Carolina coast. *Journal of Experimental Marine Biology and Ecology* **213**: 133–149. DOI: 10.1016/S0022-0981(97)00013-0.
- Cuo L, Lettenmaier DP, Mattheussen BV, Storck P, Wiley M. 2008. Hydrologic prediction for urban watersheds with the Distributed Hydrology-Soil-Vegetation Model. *Hydrological Processes* **22**: 4205–4213. DOI: 10.1002/hyp.7023.
- Dietterick BC, Lynch JA. 1989. *Proceedings of the Symposium on Headwaters Hydrology*. American Water Resources Association: Bethesda, MA; 473–485.
- Dietz ME, Clausen JC. 2007. Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management* **97**: 560–566. DOI: 10.1016/j.jenvman.2007.03.026.
- Dingman SL. 1994. *Introduction to Hydrologic Science and Basic Concepts in Physical Hydrology*. Macmillan Publishing Company: New York; 1–26.
- Doll BA, Wis-Frederick DE, Buckner CM, Wilkerson SD, Harman WA, Smith RE, Spooner J. 2002. Hydraulic geometry relationships for urban streams throughout the piedmont of North Carolina. *Journal of the American Water Resources Association* **38**(3): 641–651. DOI: 10.1111/j.1752-1688.2002.tb00986.x.
- Dow CL. 1997. *Long-term trends in annual watershed evaporation and Bowen ratio due to urbanization in the eastern United States*. PhD Dissertation, Penn State University, University Park, PA; 145.
- Dunn SM, Mackay R. 1995. Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. *Journal of Hydrology* **171**: 49–73. DOI: 10.1016/0022-1694(95)02733-6.
- Eisenbies MH, Aust WM, Burger JA, Adam MB. 2007. Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians—A review. *Forest Ecology and Management* **242**: 77–98. DOI: 10.1016/j.foreco.2007.01.051.
- Environmental Protection Agency. 1993a. Guidance specifying management measures for sources of nonpoint source pollution in coastal waters. United States Environmental Protection Agency #840-B-92-002. Washington, DC: USEPA Office of Water.
- Ferguson BK, Suckling PW. 1990. Changing rainfall-runoff relationships in the urbanizing Peachtree Creek watershed, Atlanta, Georgia. *Water Resources Bulletin* **26**(2): 313–322. DOI: 10.1111/j.1752-1688.1990.tb01374.x.
- Fisher DS, Steiner JL, Endale DM, Stuedemann JA, Schomberg HH, Franzluebber AJ, Wilkinson SR. 2000. The relationship of land use practices to surface water quality in the Upper Oconee Watershed of Georgia. *Forest Ecology and Management* **128**: 39–48. DOI: 10.1016/S0378-1127(99)00270-4.
- Gash JHC, Rosier PTW, Ragab R. 2008. A note on estimating urban roof runoff with a forest evaporation model. *Hydrological Processes* **22**: 1230–1233. DOI: 10.1002/hyp.6683.
- Grimmond CSB, Oke TR. 1999. Evapotranspiration rates in urban areas. Impacts of Urban Growth on Surface Water and Groundwater Quality. Proceedings of IUGG 99 Symposium HS5, Birmingham. IASH Publ. no. 259.
- Hewlett JD, Hibbert AR. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. Paper Presented at International Symposium on Forest Hydrology, PA State University, University Park. 275–290.
- Homer C, Huang C, Yang L, Wylie B, Coan M. 2004. Development of a 2001 National Landcover Database for the United States. *Photogrammetric Engineering and Remote Sensing* **70**(7): 829–840.
- Jackson CR, Burges S, Liang X, Leytham M, Whiting K, Horner R, Beyerlein D, Hartley D, Crawford C, Johnson B. 2001. Simplified continuous hydrologic modeling for drainage design and analysis. In *The Influence of Land Use on the Hydrologic-Geomorphic Responses of Watersheds*, Wigmosta M (ed.). American Geophysical Union Monograph: Washington, DC; 39–58.
- Jackson CR, Sun G, Amatya D, Swank WT, Riedel M, Patric J, Williams T, Vose JM, Trettin C, Aust WM, Beasley RS, Williston H, Ice GG. 2004. Fifty years of forest hydrology in the southeast. In *A Century of Forested and Wildland Watershed Lessons*, Ice GG, Stednick JD (eds). The Society of American Foresters: Bethesda, MD; 33–112, Chapter 3.
- Jacob JS, Lopez R. 2009. Is denser greener? An evaluation of higher density development as an urban stormwater-quality best management

- practice. *Journal of the American Water Resources Association* **45**(3): 687–701. DOI: 10.1111/j.1752-1688.2009.00316.x.
- Jones JA, Grant GE. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research* **32**: 959–974. DOI: 10.1029/95WR03493.
- Jordan Cove Urban Watershed 319 National Monitoring Program Project Final Report. J.C. Clausen. 2007. Dept. of Natural Resources Management and Engineering, College of Agriculture and Natural Resources, University of Connecticut, Storrs.
- Kang RS, Marston RA. 2006. Geomorphic effects of rural-to-urban land use conversion on three streams in the Central Redbed Plains of Oklahoma. *Geomorphology* **79**: 488–506. DOI: 10.1016/j.geomorph.2006.06.034.
- Kovnee JL. 1954. Evapotranspiration in forest stands of the Southern Appalachian Mountains. *Georgian Mineral News Letter* **7**(4): 80–85.
- Leopold LB. 1968. *Hydrology for Urban Planning—A Guidebook on the Hydrologic Effects of Urban Landuse*. Circular 554, U.S. Geologic Survey, Reston, VA.
- Lerner DN. 1986a. Leaking pipes recharge groundwater. *Ground Water* **24**(5): 654–662. DOI: 10.1111/j.1745-6584.1986.tb03714.x.
- Loaiciga HA. 2003. Climate change and ground water. *Annals of the Association of American Geographers* **93**(1): 30–41.
- Lu J, Sun G, McNulty SG, Comerford NB. 2009. Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA. *Wetlands* **29**(3): 826–836. DOI: 10.1672/07-162.1.
- McCray JE, Boving TB. 2007. Introduction: urban watershed hydrology. *Journal of the American Water Resources Association* **43**(4): 839–840. DOI: 10.1111/j.1752-1688.2007.00068.x.
- Meierdiercks KL, Smith JA, Baeck ML, Miller AJ. 2010. Heterogeneity of hydrologic response in urban watersheds. *Journal of the American Water Resources Association* **46**(6): 1–17. DOI: 10.1111/j.1752-1688.2010.00487.x.
- Miller DA, White RA. 1998. A conterminous United States multi-layer soil characteristics data set for regional climate and hydrology modeling. *Earth Interactions* **2**(2): 1–26. DOI: 10.1175/1087-3562(1998)002<0001:ACUSMS>2.3.CO;2.
- Neville LR. 1996. *Urban watershed management: the role of vegetation*. PhD Dissertation, SUNY, College of Environmental Science and Forestry, Syracuse, NY.
- North Carolina Department of Transportation Geographical Information Systems. 2007. <http://www.ncdot.org/it/gis/>. (3 November 2008).
- North Carolina Office of State Budget and Management. 2008. <http://www.osbm.state.nc.us>. (3 November 2008).
- Riley AL. 1998. *Restoring Streams in Cities: A Guide for Planners, Policy Makers, and Citizens*. Island Press: Washington, DC; 448.
- Rose S, Peters NE. 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* **15**: 1411–1457. DOI: 10.1002/hyp.218.
- Sanders RA. 1986. Urban vegetation impacts on the hydrology of Dayton, Ohio. *Urban Ecology* **9**: 361–376.
- Schueler TR. 1992. Mitigating the adverse impacts of urbanization on streams: a comprehensive strategy for local governments. In Kumble P, Schueler T (eds). *Watershed Restoration Sourcebook*, Publication #92701 of the Metropolitan Washington Council of Governments: 21–31.
- Stoy P, Katul GG, Siqueira MBS, Juang JY, Novick KA, McCarthy HR, Oishi AC, Uebelherr JM, Kim H-S, Oren R. 2006. Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US. *Global Change Biology* **12**: 2115–2135.
- SSURGO (Soil Survey Geographic Database), Natural Resources Conservation Service. 2003. <http://soildatamart.nrcs.usda.gov/>. (3 November 2008).
- Sun G, Amatya DM, Skaggs RW, Swift LW Jr, Shepard JP, Riekerk H. 2002. A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US. *Journal of Hydrology* **263**(1–4): 92–104. DOI: 10.1016/S0022-1694(02)00064-1.
- Sun G, Riedel M, Jackson R, Kolka R, Amatya D, Shepard J. 2004. Influences of management of Southern forests on water quantity and quality. Gen. Tech. Rep. SRS-75. U.S. Department of Agriculture, Forest Service, Southern Research Station: Asheville, NC; 195–234, Chapter 19.
- Sun G, Riekerk H, Kornhak LV. 2000. Ground-water-table rise after forest harvesting on cypress-pine flatwoods in Florida. *Wetlands* **20**: 101–112. DOI: 10.1672/0277-5212(2000)020[0101:GWTRAF]2.0.CO;2.
- Sun G, McNulty SG, Moore Myers JA, Cohen EC. 2008. Impacts of multiple stresses on water demand and supply across the Southeastern United States. *Journal of American Water Resources Association* **44**(6): 1441–1457. DOI: 10.1111/j.1752-1688.2008.00250.x.
- Sun G, Noormets A, Gavazzi M, McNulty SG, Chen J, Domec J-C, King J, Amatya DM, Skaggs RW. 2010. Energy and water balances of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA. *Forest Ecology and Management* In press. DOI: 10.1016/j.foreco.2009.09.016.
- Swank WT, Swift LW, Douglass JE. 1988. Streamflow changes associated with forest cutting, species conversions, and natural disturbances. In *Forest Hydrology and Ecology at Coweeta*, Swank WT, Crossley DA Jr (eds). Springer-Verlag: New York; 297–312.
- Tang Z, Engel BA, Lim KJ, Pijanowski BC, Habor J. 2005. Minimizing the impact of urbanization on long term runoff. *Journal of the American Water Resources Association* **41**(6): 1347–1359. DOI: 10.1111/j.1752-1688.2005.tb03804.x.
- Thomas RB, Megahan WF. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: a second opinion. *Water Resources Research* **34**: 3393–3403. DOI: 10.1016/S0022-1694(00)00231-6.
- Trimble SW. 1974. *Man-Induced Soil Erosion on the Southern Piedmont, 1700–1970*. Soil Conservation Society of America: Ankeny, IA.
- United States Geological Survey (USGS). 2008. <http://waterdata.usgs.gov/nwis>. (30 September 2008).
- Ursic SJ. 1978. Effect of harvesting systems on water quality and supply. In *Complete Tree Utilization of Southern Pine, Proceedings of a Symposium*. McMillin CW (ed.). Forest Products Research Society: New Orleans, LA; 103–107.
- Ursic SJ. 1985. Hydrologic effects of complete and conventional harvest of loblolly pine biomass. In *Proceedings of the Third Biennial Silvicultural Research Conference*, General Technical Report SO-54, Shoulders E (ed.). USDA Forest Service: Atlanta, GA; 565–572.
- Walsh CJ, Roy AH, Feminella JW, Cottingham PE, Groffman PM. 2005. The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society* **24**: 706–723. DOI: 10.1899/0887-3593(2005)024[0706:TUSSCK]2.0.CO;2.
- Walsh CJ, Sharpe AK, Breen PF, Sonneman JA. 2001. Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities. *Freshwater Biology* **46**: 535–551. DOI: 10.1046/j.1365-2427.2001.00690.x.
- Whitehead PG, Robinson M. 1993. Experimental basin studies: an international and historical perspective of forest impacts. *Journal of Hydrology* **145**: 217–230. DOI: 10.1016/0022-1694(93)90055-E.
- Wissmar RC, Raymond TK, Logsdon MG. 2004. Effects of changing forest and impervious land covers on discharge characteristics of watersheds. *Environmental Management* **34**(1): 91–98. DOI: 10.1007/s00267-004-0224-5.
- Wolman MG. 1967. A cycle of sedimentation and erosion in urban river channels. *Geografisks Annaler* **49a**: 385–395.