Link between Impervious Cover and Base Flow in the White Clay Creek Wild and Scenic Watershed in Delaware

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Abstract: Field measurements indicate a correlation between increased impervious cover and decreased stream base flow in and near the White Clay Creek Wild and Scenic River watershed near Newark, Del. A stream base flow monitoring network was established in 19 watersheds near the University of Delaware campus. The watersheds have land uses varying from heavily forested to highly urbanized with impervious cover ranging from 3 to 44%. Using geographic information system land use mapping, watershed impervious cover was estimated based on the ratio of pavement and roof area for each land cover condition. Stream base flows were calculated using the continuity equation ($Q=vA$) from velocity and channel cross-section area measurements recorded on 5 days during 2006 and 2007. Results from all five events indicate increased watershed impervious cover correlates with decreased stream base flows. For the five events, the coefficients of determination (R^2) based on linear regression of impervious cover and base flow data are 0.33, 0.35, 0.32, 0.46, and 0.58; evidence of fair to reasonably good correlation. Increased watershed imperviousness can result in dwindling drinking water and aquatic resource flows especially during drought periods. Water resource protection area ordinances, recharge augmentation, and pavement reduction techniques are available to reduce the impacts of impervious cover on watershed hydrology.

DOI: 10.1061/(ASCE)1084-0699(2009)14:4(324)

CE Database subject headings: Base flow; Infiltration; Watersheds; Hydrology; Droughts.

Introduction

Hydrology is the study of water quantity and quality circulated between the earth and the atmosphere. Thornthwaite and Mather (1957) defined the hydrologic cycle by the water budget equation as

$$P = R + I + \mathrm{ET} - \Delta S$$

where P=precipitation; R=runoff that flows overland to a waterway; I=infiltration to the groundwater table as the source of dry-weather base flow in streams and deeper aquifers; ET =evaporation directly to the atmosphere plus transpiration by plants; and ΔS=change in moisture storage in surface water, groundwater, and/or soil.

Water resources engineers and planners are interested in the runoff and infiltration components of the hydrologic cycle. Runoff estimates are required to design hydraulic structures such as storm sewers, culverts, and storm water basins. Infiltration data are necessary to design groundwater facilities like septic systems and recharge basins.

In addition to precipitation patterns, soil type, and land cover, the amount of impervious cover in a watershed is a primary predictor of runoff and infiltration. Impervious cover is the area of pavement and roof area that accompanies urban and suburban development.

Water budget theory holds that as impervious cover increases in a watershed, runoff increases and infiltration declines. As watersheds become more urbanized, added impervious cover can lead to more frequent and intense flood flows. Decreased infiltration caused by impervious cover lowers the groundwater table, the source of dry-weather stream base flows, and can lead to dwindling water supplies during drought.

Water budget formulas indicate that increased impervious cover from urban development in watersheds leads to reduced groundwater recharge or infiltration. A U.S. Environmental Protection Agency (1993) water budget model indicates that natural ground cover with no impervious cover can infiltrate up to 50% of total precipitation while infiltration declines to 35% of precipitation for developed areas with 35–50% impervious cover. The curve number method (Table 1) indicates that runoff increases and infiltration and other interception losses decrease with increasing impervious cover (USDA 1997). For 5.1 cm (2.0 in.) of precipitation, assuming hydrologic Group B soils, infiltration and other interception losses decline from 4.9 cm (1.9 in.) for open space (0% impervious) to 0.5 cm (0.2 in.) for parking lots (98% impervious).

Many jurisdictions strive to protect the quality and quantity of ground and surface water supplies by setting maximum impervious cover criteria for new development. The New Castle County, Delaware Dept. of Planning (1997) water resource protection area ordinance sets an impervious cover threshold of 20% on new development in recharge, wellhead, limestone aquifer, and reser-

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Note. Discussion open until September 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on February 7, 2008; approved on August 7, 2008. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 14, No. 4, April 1, 2009. ©ASCE, ISSN 1084-0699/2009/4-324–334/$25.00.

Table 1. Impervious Cover, Runoff, and Infiltration by Curve Number (CN) Method

Land cover (Soil Group B)	Imp. (%)	CN	Precip. (cm)	Runoff (cm)	Infiltr. (cm)
Open space	0	61	5.1	0.2	4.9
Residential low	12	65	5.1	0.4	4.7
Residential med.	25	70	5.1	0.6	4.5
Residential high	38	75	5.1	1.0	4.1
Apartments	65	85	5.1	2.0	3.1
Commercial	85	92	5.1	3.0	2.1
Pavement	100	98	5.1	4.5	0.6

voir watershed areas. For instance, a new 10 ha (25 acre) subdivision is limited to 2 ha of new pavement and roof area on the parcel. Further research on the link between impervious cover, infiltration, and base flow is sought to understand the hydrologic basis for water resource protection ordinances.

Objectives and Approach

The objective of this research is to examine the relationship between impervious cover and stream base flow in 19 watersheds in and near the White Clay Creek Wild and Scenic River watershed near Newark, Del. A stream base flow monitoring network was established at 14 watersheds near the University of Delaware campus. USGS stream gauge data provided supplemental base flow measurements along five streams in the Christina River Basin; the Brandywine, Red Clay, White Clay, Christina, and Shellpot Creeks. Geographic information system (GIS) mapping derived impervious cover estimates for watersheds ranging from highly forested (0–10% impervious) to highly urbanized (over 40% impervious). University of Delaware field crews estimated dry-weather base flows using stream velocity and cross-section area measurements recorded on 5 days during 2006 and 2007. Stream base flow data were plotted against watershed impervious cover for each sampling event to examine for correlation using linear regression line of best fit techniques.

Study Area

The study area is the White Clay Creek watershed, part of the Christina River Basin in northern Delaware, situated midway between Philadelphia and Baltimore along the mid-Atlantic coast in the United States. The White Clay Creek drains 265 km^2 (102 mi.^2) and flows from headwaters in Chester County, Pennsylvania and downstream through Newark, Del. before joining the Christina River (Fig. 1). The watershed is divided by the fall line, the head of navigation which splits the hilly, rocky Piedmont physiographic province to the north from the flat, sandy Coastal Plain to the south. The stream monitoring stations are situated at or above the fall line in the Piedmont province. The White Clay Creek and tributaries flow through or near the University of Delaware campus which provides convenient access by student field crews to the stream monitoring sites. In 2000, the President and Congress declared 306 km (190 mi.) of the White Clay Creek and tributaries as a national wild and scenic river, now one of only two rivers in the United States designated on a watershed basis instead of a river segment basis.

Literature Review

Many studies dating to the late 1960s suggest that increased impervious cover in watersheds leads to altered runoff patterns and reduced groundwater recharge available for dry-weather stream base flow. Several recent studies suggest base flows may remain unchanged or even increase as watersheds become more urbanized due to factors such as leakage from water supply piping or imports of water into the basin. Table 2 summarizes a literature review of impervious cover and base flow studies.

1960s. A guide book using data from the Brandywine Creek in Pennsylvania (just upstream from Delaware) asserted that urbanization is the most forceful of land use changes that affect the hydrology of a watershed (Leopold 1968). Leopold wrote that: "increased imperviousness has the effect of increasing flood peaks during storm periods and decreased low flows between storms."

1970s. In Philadelphia watersheds, stream base flow declined steadily until watershed imperviousness reached 40–50% (Hammer 1973). A United States Fish and Wildlife Service study concluded that stream habitat for fish reach a degraded condition when base flow drops to 30% of average when imperviousness exceeds 45% of the watershed (Tennant 1976). A synthesis of research in the Canon's Brook watershed in England found that decreased base flow is likely to occur as a result of urbanization (Hollis 1976). Klein (1979) conducted a linear regression study of 27 watersheds in the Piedmont province of Maryland and found that stream base flow diminishes with increased watershed imperviousness as follows:

Impervious cover	Stream base flow	
(%)	($\text{m}^3/\text{s}/\text{km}^2$)	($\text{ft}^3/\text{s}/\text{mi.}^2$)
10	0.0066	0.60
30	0.0045	0.41
50	0.0025	0.23

1980s. Stream base flows along six urbanized streams in Long Island, New York were reduced to 20–85% of total stream flow due to construction of sewers and impermeable cover (Simmons and Reynolds 1982). Base flow along streams with undeveloped watersheds usually account for 90–95% of total stream flow.

1990s. Along the Peachtree Creek near Atlanta, flows declined as the watershed evolved from less urbanized to more urbanized. Ferguson and Suckling (1990) wrote: ". . . declining low flows

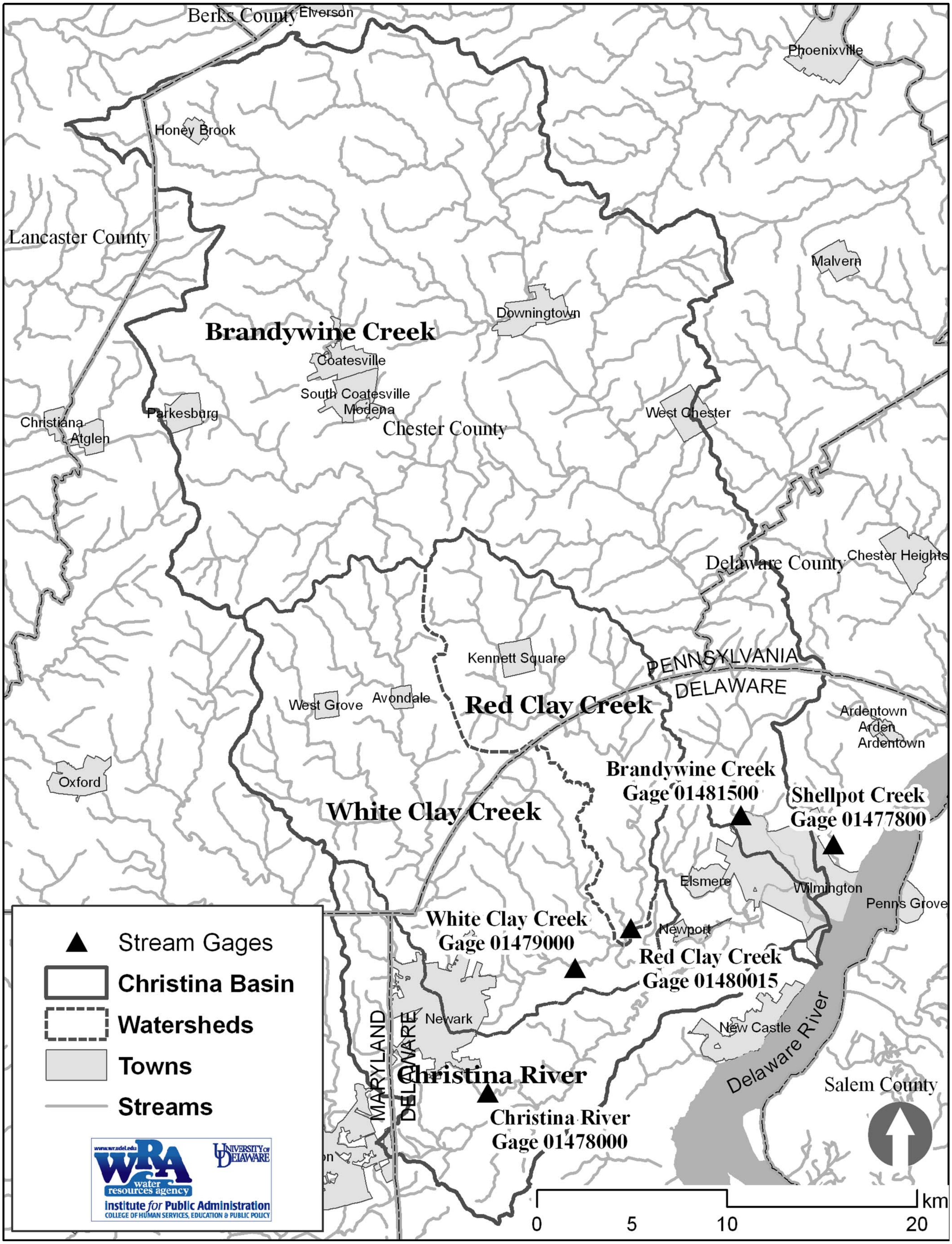

Fig. 1. Location map of Christina Basin monitoring stations (used with permission)

Table 2. Literature Review of Watershed Impervious Cover and Base Flow Studies

Date	Author(s)	Watershed	Area	Summary of findings
1968	Leopold	Brandywine	Southeastern Pa.	Imperviousness increases flood peaks and decreases low flows
1973	Hammer	Schuylkill	Philadelphia, Pa.	Base flow declined until watershed impervious reached 40–50%
1975	Tennant	—	—	Fish suitability declines when watershed imperviousness exceeds 45%
1976	Hollis	Canon's Brook	England	Decreased base flow is likely to occur as a result of urbanization
1979	Klein	Chesapeake	Maryland	As watershed imperviousness increases, stream base flow diminishes
1982	Simmons, Reynolds	South Shore	Long Island, N.Y.	Base flows along six urbanized streams reduced to 20–85% of total flow
1990	Ferguson, Suckling	Peachtree Creek	Atlanta	Low flows declined as the watershed evolved from less to more urbanized
1992	Spinello, Simmons	South Shore	Long Island, N.Y.	1976–1985, base flow reduced to 14–88% of average in urbanized watersheds
1997	Scorca	East Meadow	Long Island, N.Y.	By 1970's, base flow decreased by 70% from predevelopment before 1953
2000	Brun and Band	Gwynns Falls	Baltimore, Md.	Runoff ratio changes dramatically when watershed impervious exceeds 20%
2000	Finkenbine, Atwater	English Bay	Vancouver, B.C.	Summer base flow extremely low in streams where impervious > 20–40%
2001	Wang, Lyons, Kanehl	Fox River	Southeastern Wis.	Impervious of 8–12% is threshold associated with sharp decline in base flow
2002	Jennings, Jarnagin	Accotink Creek	Virginia	Change in stream flow occurred between 13% (1963) and 21% (1971) impervious
2002	Meyer		Illinois	Base flows increase with urbanization from water system and sewer leakage
2002	Konrad and Booth	Puget Sound	Washington	Low flows increase in urban/suburban and decrease in suburban/2 rural streams
2005	Brandes et al.	Delaware River	New Jersey, Pennsylvania	Increases in impervious to 7–21% may not result in reductions in base flow
2005	Rogers and DeFee	White Oak	Houston	With increased impervious, flood/drought potential doubled three times 1980–2000
2005	Walsh.	—	—	Reduced base flow from impervious counteracted by water supply leaks

can be adequately explained by urban hydrologic theory, which focuses on the effects of urban impervious surfaces upon direct runoff and infiltration." Low flows in dry years declined with increased urbanization because of reduction of water stored in the subsurface due to deflection of precipitation from recharge and removal of water from the watershed by evapotranspiration. To restore base flows, they recommended that storm water management should include infiltration approaches to force runoff into the soil.

Hydrograph separation techniques for ten gauged streams on the South Shore of Long Island, New York indicated base flow averaged between 14 and 88% of annual stream discharge from 1976 to 1985 in urbanized watersheds, down from 95% of annual discharge during 1948–1952, a period when watershed development was minimal (Spinello and Simmons 1992). Base flow decreases were due to lowering of the water table as a result of urbanization including more impermeable area and routing of storm and sanitary sewers. A study from Olympia, Wash. (City of Olympia 1996) indicated increases in impervious cover resulted in decreased infiltration (recharge) and increased runoff. By the late 1970s, base flows in the developed East Meadow Brook along the South Shore of Long Island, New York decreased by 65–70% compared to the predevelopment period before 1953 (Scorca 1997). Prior to 1953, base flow in the undeveloped watershed was about 95% of total stream flow. By the 1970s, after development during the post-World War II building boom, base flow declined to 65% of total stream flow.

2000s. A hydrologic study in the Gwynns Falls watershed near Baltimore affirmed the existence of a threshold by concluding that the runoff ratio changes dramatically when watershed impervious cover exceeds 20% (Brun and Band 2000). A study of 11 Vancouver watersheds indicated summer base flow was extremely low in streams where impervious cover exceeded 20% (Finkenbine et al. 2000). Increased impervious cover in the watersheds caused declines in summer base flow due to decreased groundwater recharge. Research along 47 southeastern Wisconsin streams found that base flow declined significantly when watershed imperviousness exceeded a threshold range of 8–12% (Wang et al. 2001). In the Accotink Creek watershed in Virginia, Jennings, and Jarnagin (2002) concluded that "a statistically significant change in stream flow response occurred between the 13% (1963) and 21% (1971) impervious surface coverage."

An article by the Center for Watershed Protection (2003) concluded that urbanization causes increased impervious cover in a watershed whereby "... dry weather flow in streams may actually decrease because less groundwater recharge is available ...."

An Illinois State Water Survey conceptual model of urban watersheds in Illinois indicated base flows actually increased with more urbanization due to leakage from water supply systems or sanitary sewers, lawn watering, and car washing (Meyer 2002).

Konrad and Booth (2002) studied hydrologic trends in ten urban, suburban, and rural watersheds in the Puget Sound basin of western Washington and concluded that "trends in the 7 day low flow were mixed, increasing in one urban stream and one suburban stream, and decreasing in one suburban and two rural streams." The authors concluded that changes in infiltration and recharge due to urban development are not influenced by low wet season base flow. Instead, base flow may actually increase in urbanizing watersheds due to water line and sanitary sewer leaks, interbasin water withdrawals, and groundwater pumping to outside the watershed.

Brandes et al. (2005) examined ten watersheds in New Jersey and Pennsylvania in the Delaware River Basin where impervious coverage ranged from 7 to 21% and concluded that "…increases in impervious area may not result in measurable reductions in base flow at the watershed scale." Only one of the ten watersheds detected decreased base flow trends and a few of the watersheds recorded increased base flow over time. The loss of recharge due to increased impervious cover may have been offset by water imports into the basins such as wastewater discharges and leaking sanitary sewers which artificially replenish the groundwater table and base flows. Two of the ten watersheds exceeded 15% impervious cover and only one watershed exceeded 20% impervious, thresholds where one is more likely to observe base flow reductions due to urbanization.

Walsh et al. (2005) concluded that "urbanization does not affect instream base flow among urban areas in the world." Reduced base flow from increased catchment impervious may occur but may be counteracted by water supply and wastewater pipe leaks and water imports from outside the watershed.

In the White Oak Bayou watershed near Houston, the number of days below expected flow declined from 1948 to 2000, a trend associated with human activity (Rogers and DeFee 2005). As impervious cover increased from 10% in 1972 to 30% by 2000, the potential for flooding and drought doubled three times. The study suggested when urban development reaches 25% of the watershed, the potential for floods and droughts increases exponentially.

Methods

We selected 14 watersheds draining to the White Clay Creek near the University of Delaware campus in Newark, Del. to measure dry-weather base flow (Fig. 2). Since the streams were near the University of Delaware, crews were able to visit all of the sites in 1 day to measure base flow and minimize variances due to weather and precipitation changes from 1 day to the next. We supplemented the network and included five USGS stream gauges in the Christina River Basin making a total of 19 base flow monitoring stations available for analysis. The watersheds were selected to have a wide variance in impervious cover ranging from 3 to 44% with land uses ranging from heavily forested to highly urbanized.

Using Arc Map GIS, we calculated land use area in the watersheds of the 14 stream monitoring sites and five USGS stream gauge stations in the Christina River Basin (Table 3). The State of Delaware Planning Office provided 2002 land use data interpreted from aerial photography which was updated to 2006 by the University of Delaware, Water Resources Agency.

We estimated the composite impervious cover in each watershed using the "Delaware Method" formula as

$$\mathrm{IC_{TOT}} = [\mathrm{IC_1(LU_1)} + \mathrm{IC_2(LU_2)} + \ \ldots\ . \mathrm{IC}_i(\mathrm{LU}_i)]/\mathrm{DA_{TOT}}$$

where $\mathrm{IC_{TOT}}$=total impervious cover of the watershed (%); $\mathrm{IC_1}$, $\mathrm{IC_2}$, IC_i=representative impervious cover of each land use (%); $\mathrm{LU_1}$, $\mathrm{LU_2}$, LU_i=area of each land use in the watershed; and $\mathrm{DA_{TOT}}$=total drainage area of the watershed.

We calculated dry-weather base flow by measuring stream velocity (v) and cross-section area (A) at each monitoring site and then plugging into the continuity equation of hydraulics where: $Q=vA$. Student field crews performed base flow measurements on May 2, May 26, and August 9, 2006; and September 6 and October 8, 2007. We avoided day to day weather and precipitation variances by measuring base flows at all 19 sites on the same day. We attempted to minimize groundwater recharge differences due to geology and soils as all of the watersheds are situated in the Piedmont physiographic province. Dry-weather base flow patterns were confirmed by conducting monitoring at least 7 days after the last rain event and examining for near-horizontal, recession limbs of hydrographs at the White Clay Creek at Newark USGS stream gauge No. 01478650 on each monitoring date.

We estimated stream velocity using a propeller-type current meter manufactured by Geopacks of London. We calculated the mean number of propeller revolutions per unit time from three trials and calculated velocity by the following formula as provided by the manufacturer:

$$v = (0.000854)(N)(60)/(T) + (0.05)(3.28)$$

where v=velocity; N=number of revolutions of the meter; and T=time for the meter to spin the counted number of revolutions.

Along several small streams, base flow became too low to measure with the current meter as the propeller blades were not fully submerged and got caught on the channel bottom. When flow depth was too shallow to use the current meter, we calculated velocity using the floating object method where $v=t/L$; and t=time for a floating object such as a cork to flow distance, L.

We field surveyed stream cross-section area by measuring the depth of flow from the water surface to the channel bottom at even intervals measured horizontally across the stream.

We calculated base flow using the continuity equation of hydraulics where $Q=vA$. For instance, we estimated the base flow in Middle Run on May 26, 2006 as $Q_{W7}=(0.44\ \mathrm{m/s})\ (0.27\ \mathrm{m}^2) = 0.12\ \mathrm{m}^3/\mathrm{s}$. To account for differences in watershed area, we calculated unit base flow by dividing base flow by the drainage area. For Middle Run, the unit base flow recorded on May 26, 2006 was $Q/\mathrm{DA}=(0.12\ \mathrm{m}^3/\mathrm{s})/(10.1\ \mathrm{km}^2)=0.012\ \mathrm{m}^3/\mathrm{s}/\mathrm{km}^2$.

Results

Table 4 summarizes typical base flow measurements for May 2, 2006. For statistical analysis, we prepared scatter plots by graphing stream base flow (BF) on the vertical axis and watershed impervious cover (IC) on the horizontal axis. Correlations between base flow and watershed impervious are described by the coefficient of determination (R^2) and linear regression straight line of best fit ($\mathrm{BF}=m(\mathrm{IC})+b$) where m=slope ($\mathrm{m}^3/\mathrm{s}/\mathrm{km}^2/\%$ impervious) and b=constant. The closer R^2 is to 1.0, the better the

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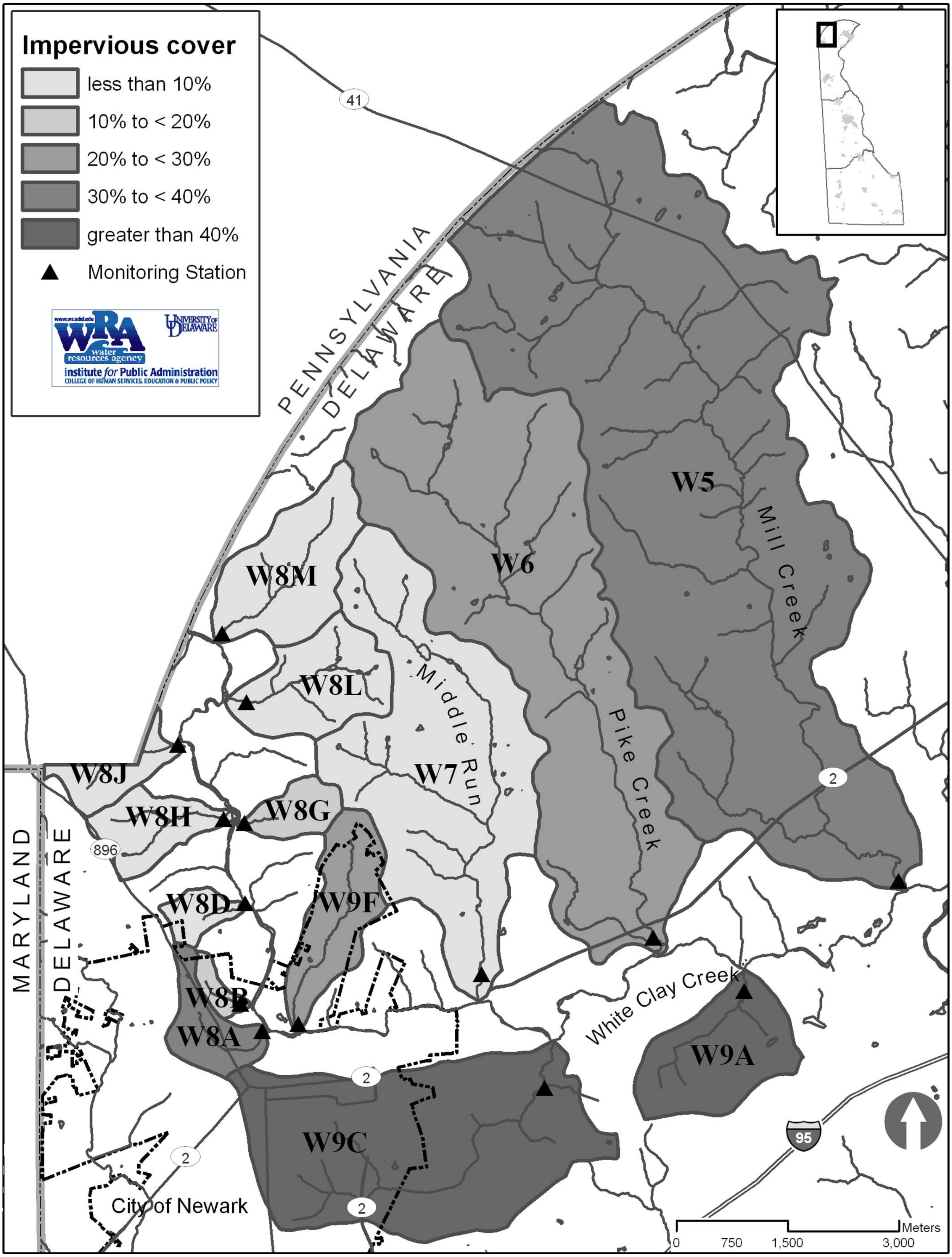

Fig. 2. Base flow monitoring stations in the White Clay Creek watershed

Table 3. Land Use and Impervious Cover of Stream Base Flow Monitoring Watersheds in Delaware

			Watershed				
ID	Stream	Imp. (%)	(km^2)	(mi.^2)	Urban (%)	Agr. (%)	Forest (%)
W5	Mill Creek	34.2	33.6	12.5	71	4	25
W6	Pike Creek	29.8	17.1	6.6	66	7	27
W7	Middle Run	9.3	10.1	3.9	24	41	35
W8A	Blue Hen Cr.	31.8	1.0	0.4	57	0	43
W8B	Fairfield	18.0	0.3	0.1	49	1	50
W8D	Old Trestle	5.3	0.5	0.2	12	23	65
W8G	Footbridge	14.6	0.8	0.3	17	9	74
W8H	Wedgewood	4.7	1.3	0.5	5	33	62
W8J	Nature Center	4.6	0.8	0.3	14	10	76
W8L	Lamborn	2.8	2.3	0.9	4	32	64
W8M	Corner Ketch	8.0	2.9	1.1	16	24	60
W9A	Harmony	43.8	2.6	1.0	87	5	8
W9C	Cool Run	41.2	9.3	3.6	80	10	10
W9F	Jenny's Run	28.3	2.1	0.8	61	13	26
BWW	Brandywine	13.4	828	319	23	37	40
RCS	Red Clay	17.3	140	54	33	30	37
WCS	White Clay	16.1	264	102	27	31	43
CHR	Christina	21.5	54	21	45	27	28
SHP	Shellpot	41.0	19.3	7.5	77	2	20

line of fit. An R^2 value above 0.3 would indicate fair correlation between variables and R^2 values above 0.5 would indicate reasonably good correlation. Table 5 provides summary statistics of the base flow monitoring results such as R^2, slope of the line of best fit; and mean, minimum, and maximum base flow

May 2, 2006. We conducted the first round of base flow monitoring on May 2, 2006, 8 days after the previous rainfall event of April 25 which deposited 0.30 cm (0.12 in.) at the University of Delaware rain gauge in Newark, Del. The maximum temperature on May 2 was 24.7°C (76.4°F). Linear regression $[\text{BF} = -0.0588(\text{IC}) + 0.0298]$ and $R^2 = 0.33$ indicates a negative correlation between increased watershed impervious cover and decreased stream base flow (Fig. 3). Base flows ranged from 0.003 $\text{m}^3/\text{s}/\text{km}^2$ for a watershed with 41% impervious cover to 0.049 $\text{m}^3/\text{s}/\text{km}^2$ with 4.6% impervious cover.

May 26, 2006. We conducted the second round of base flow monitoring on May 26, 2006, 7 days after the previous rainfall event of May 19 which deposited 0.23 cm (0.09 in.) at the University of Delaware rain gauge in Newark. The maximum temperature on May 26 was 26.4°C (79.6°F). Fig. 4 indicates base

Table 4. Stream Base Flow Measurements in Delaware on May 2, 2006

ID	Stream	Imp. (%)	DA (km^2)	v (m/s)	A (m^2)	$Q = vA$ (m^3/s)	Q/DA ($\text{m}^3/\text{s}/\text{km}^2$)	Q/DA ($\text{ft}^3/\text{s}/\text{mi.}^2$)
W5	Mill Creek	34.2	33.57	0.27	1.37	0.3770	0.0113	1.03
W6	Pike Creek	29.8	17.11	0.22	1.52	0.3284	0.0193	1.76
W7	Middle Run	9.3	10.11	0.16	1.03	0.1664	0.0166	1.51
W8A	Blue Hen Cr.	31.8	1.04	0.09	0.11	0.0096	0.0093	0.85
W8B	Fairfield Run	18.0	0.26	0.21	0.03	0.0056	0.0217	1.97
W8D	Old Trestle	5.3	0.47	0.18	0.06	0.0113	0.0245	2.22
W8G	Footbridge	14.6	0.75	0.07	0.33	0.0219	0.0294	2.67
W8H	Wedgewood	4.7	1.27	0.47	0.15	0.0690	0.0546	4.97
W8J	Nature Center	4.6	0.80	0.20	0.19	0.0393	0.0488	4.44
W8L	Lamborn Run	2.8	2.33	0.11	0.33	0.0357	0.0154	1.40
W8M	Corner Ketch	8.0	2.85	0.19	0.27	0.0523	0.0185	1.68
W9A	Harmony Run	43.8	2.59	0.06	0.27	0.0173	0.0067	0.61
W9C	Cool Run	41.2	9.33	0.09	1.14	0.1041	0.0112	1.02
W9F	Jenny's Run	28.3	2.07	0.13	0.29	0.0379	0.0184	1.67
BWW	Brandywine	13.4	828.20	—	—	9.3517	0.0114	1.03
RCS	Red Clay	17.3	140.08	—	—	1.1902	0.0085	0.78
WCS	White Clay	16.1	264.06	—	—	1.3886	0.0053	0.48
CHR	Christina	21.5	54.54	—	—	0.3401	0.0063	0.57
SHP	Shellpot Cr.	41.0	19.34	—	—	0.0567	0.0029	0.26

Table 5. Summary Statistics of Impervious Cover and Base Flow Correlation for Delaware Watersheds

Date	R^2	Slope ($m^3/s/km^2/\%$ imp.)	Median base flow ($m^3/s/km^2$)	Median base flow ($ft^3/s/mi.^2$)	Maximum base flow ($m^3/s/km^2$)	Maximum base flow ($ft^3/s/mi.^2$)	Minimum base flow ($m^3/s/km^2$)	Minimum base flow ($ft^3/s/mi.^2$)
May 2, 2006	0.33	−0.0588	0.0179	1.63	0.0488	4.44	0.0029	0.26
May 26, 2006	0.35	−0.0350	0.0116	1.06	0.0342	3.11	0.0025	0.23
August 9, 2006	0.32	−0.0263	0.0080	0.74	0.0256	2.33	0.0009	0.08
September 6, 2007	0.46	−0.0060	0.0026	0.24	0.0048	0.44	0.0008	0.07
October 8, 2007	0.58	−0.0078	0.0025	0.23	0.0058	0.53	0.0004	0.04
Five events	0.34	−0.0238	0.0074	0.67	0.0258	2.34	0.0009	0.08

flow ranged from 0.003 to 0.034 $m^3/s/km^2$ for an impervious area ranging from 41 to 4.6%. Linear regression [BF =−0.035(IC)+0.0186] and $R^2=0.35$ indicates stream base flow declined with increased watershed imperviousness and the correlation was about the same as observed on May 2, 2006.

August 9, 2006. After waiting over the summer for the streams to recede back to base flow conditions, we conducted the third round of base flow monitoring on August 9, 2006, 11 days after the previous rainfall event of July 28 which deposited 1.22 cm (0.48 in.) at the University of Delaware rain gauge in Newark. The maximum temperature on August 9 was 30.3°C (86.5°F), warmer than the sampling events in May 2006. Fig. 5 indicates base flow ranged from 0.001 to 0.026 $m^3/s/km^2$, lower than flows recorded earlier in the water year during May 2006. Linear regression [BF=−0.0263(IC)+0.0137] and $R^2=0.32$ indicates a correlation where stream base flow declines with increased watershed imperviousness similar to that observed during the May 2006 events.

September 6, 2007. We resumed the fourth round of base flow monitoring, 15 days after the previous rainfall event of August 21 which deposited 1.83 cm (0.72 in.) at the University of Delaware rain gauge in Newark. The maximum temperature on September 6 was 31.2°C (88.1°F). Fig. 6 indicates base flow ranged from 0.0008 $m^3/s/km^2$ (41% impervious) to 0.0048 $m^3/s/km^2$ (9.3% impervious). These were the lowest recorded base flows, reflecting late summer conditions. Linear regression [BF=−0.006(IC)+0.0039] and $R^2=0.46$ indicate a stronger correlation between increased watershed imperviousness and decreased base flow than observed during the three events in 2006.

October 8, 2007. We conducted the fifth round of base flow monitoring on October 8, 2007, 16 days after the previous rainfall event of September 22 which deposited 0.61 cm (0.24 in.) at the University of Delaware rain gauge in Newark. The maximum temperature on October 8 was 31.3°C (88.4°F). Fig. 7 indicates base flow ranged from 0.0004 to 0.0058 $m^3/s/km^2$ for impervious cover ranging from 41 to 9.3%. Linear regression line [BF=−0.0078(IC)+0.004] and $R^2=0.58$ suggests good correlation (the strongest of the five events) between increased watershed impervious and decreased stream base flow.

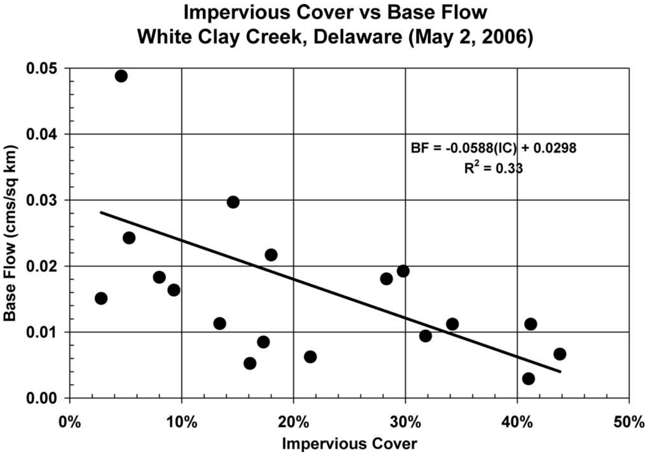

Fig. 3. Impervious cover and base flow observed on May 2, 2006

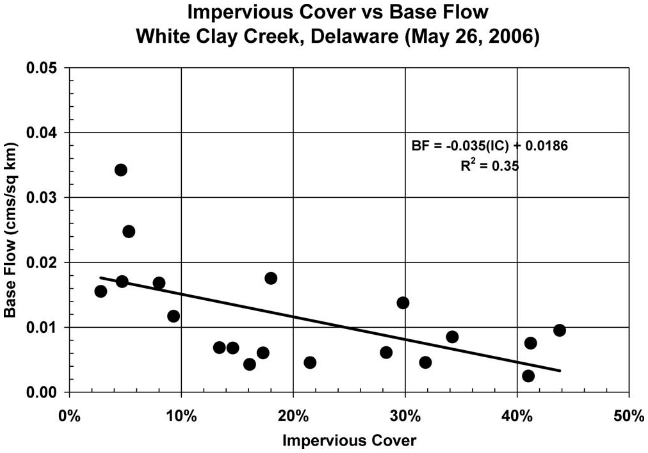

Fig. 4. Impervious cover and base flow observed on May 26, 2006

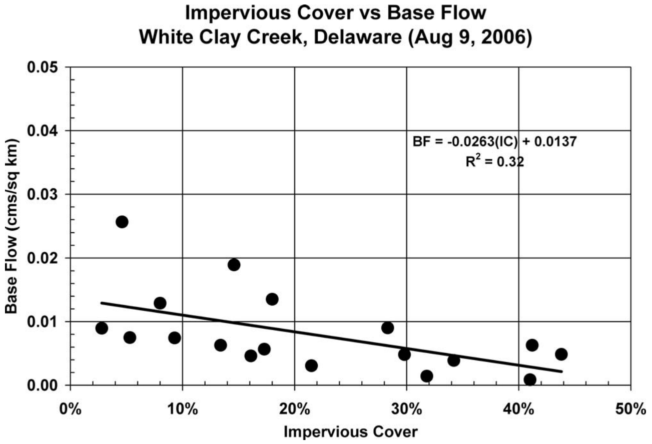

Fig. 5. Impervious cover and base flow observed on August 9, 2006

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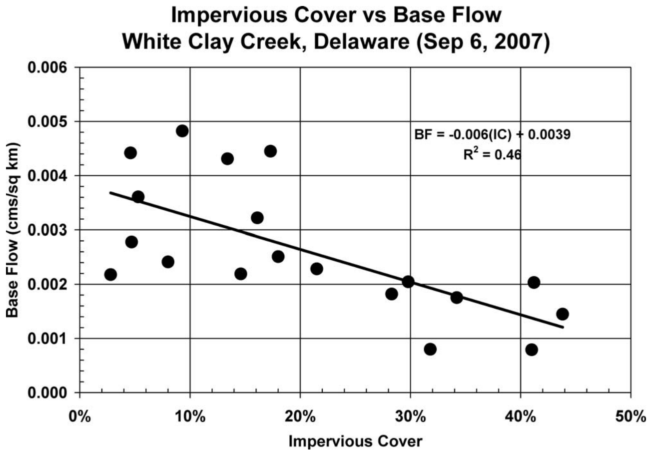

Fig. 6. Impervious cover and base flow observed on September 6, 2007

Median of 5 Events. Fig. 8 plots the median of base flows recorded on May 2, May 26, and August 9, 2006; and September 6 and October 8, 2007 versus watershed impervious cover. Linear regression line of best fit [BF=−0.0238(IC)+0.0123] with slope of −0.0238 $m^3/s/km^2/\%$ imp and $R^2=0.34$ confirms a negative correlation between increasing watershed impervious cover and decreased dry weather base flow.

Discussion

We observed consistent correlation between increased watershed impervious cover and decreased dry weather base flow during all five monitoring events in 2006 and 2007. The coefficients of determination (R^2) for the five events are 0.33, 0.35, 0.32, 0.46, and 0.58 indicating reasonably fair to good correlation. All five of the events recorded negative slopes (−0.0588, −0.0350, −0.0263, −0.0060, and −0.0078 $m^3/s/km^2/\%$ imp) for the linear equation of best fit indicating negative correlation between impervious cover and stream base flow.

Seasonal differences between impervious cover and base flow were somewhat apparent as late season results were better correlated than early season results. The highest R^2 values (0.46 and 0.58) were observed in late summer and fall on September 6 and October 8, 2007. Base flows were higher earlier in the water year in the spring than in late summer or early fall. Median base flows during May 2, May 26, and August 2006 and September 6 and October 8, 2007 were 0.0179, 0.0116, 0.0080, 0.0026, and 0.0025 $m^3/s/km^2$, respectively.

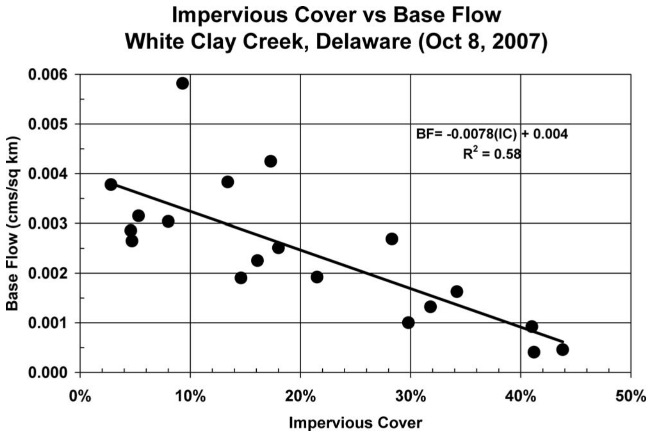

Fig. 7. Impervious cover and base flow observed on October 8, 2007

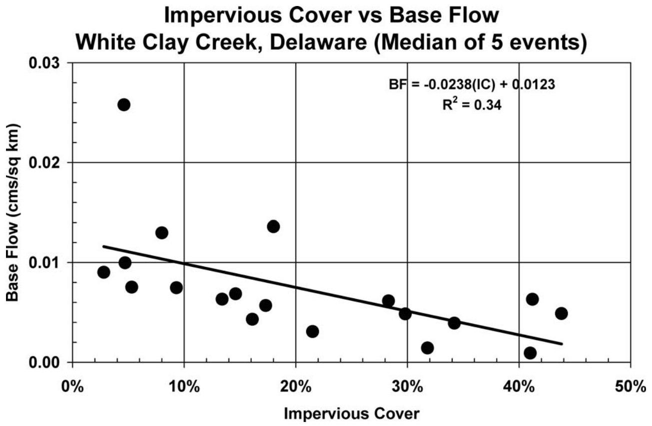

Fig. 8. Impervious cover and median base flow observed for five events in 2006 and 2007

By selecting monitoring stations in the same watershed (White Clay Creek and the Christina Basin), and the same physiographic province (Piedmont) we attempted to minimize variances in base flow due to differing hydrology, geology, and soils. The sites are underlain by the Wissahickon Schist, Gneiss, and Cockeysville Marble formations in the hilly, rocky Piedmont. The monitoring site watersheds share similar soils in the Glenelg, Manor, Chester, and Elsinboro-Delanco soil associations.

Other land use factors such as forest cover may influence the amount of base flow in a stream. Booth et al. (2002) observed that the amount of forest cover in a watershed impacts stream flow. We conducted a linear regression analysis of base flow versus forest cover at the 19 monitoring sites and found a reasonable correlation for the monitoring events conducted earlier in the season when flows were higher on May 2, May 26, and August, 2006 (R^2=0.46, 0.39, and 0.36) but found a poor correlation later in the season when flows were lower on September 6 and October 8, 2007 0 (R^2=0.14 and 0.19). We founded that base flow and forest cover was better correlated when base flows were higher, which typically occurs earlier in the water year (Fig. 9). High evapo-

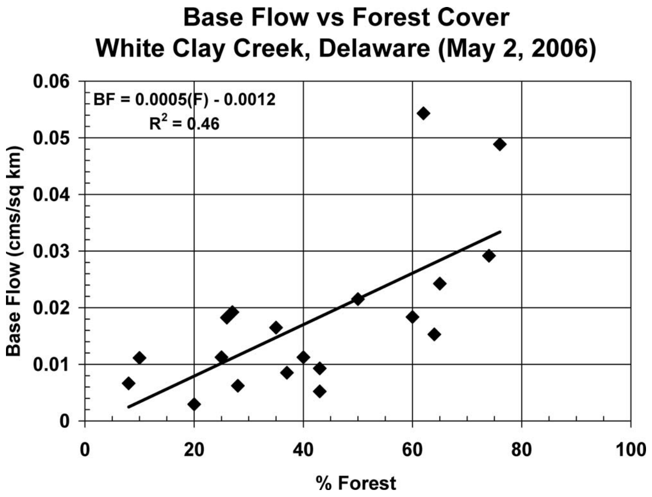

Fig. 9. Forest cover and base flow observed during May 2, 2006

transpiration rates in highly forested watersheds during the hot, late summer months may explain this poor late season correlation.

We evaluated whether the size of the watershed may affect the base flow - impervious cover relationship. All of the mostly forested watersheds with less than 10% impervious and high base flows also have drainage areas less than 13 km^2 (5 mi.^2). Yet several large watersheds such as the Brandywine Creek and White Clay Creek also have low impervious cover and high base flows. Small watersheds such as the Shellpot Creek and Harmony Run have high impervious cover with low base flows. While we did not find an apparent relationship between watershed size and base flows, we did observe that due to development and fragmentation of forests and open space in the urbanized Mid-Atlantic, it was difficult to find stream monitoring stations that drain large watersheds with low impervious cover.

Other researchers have concluded that leaking water systems can offset loss of recharge due to increasing impervious cover, and in some cases, may increase base flows in urbanizing watersheds. The watersheds in the White Clay Creek monitoring network with more than 5% urban/suburban land are served by public water systems with estimated unaccounted for water losses of about 10%, so we expect that some leakage is occurring into the groundwater. On the other hand, groundwater in the watersheds is also intercepted by a regional sanitary sewer system which is frequently rehabilitated to reduce high infiltration and inflow (I & I) rates. Leakage from the water supply system may be occurring, and it may be offset to some degree by interception of groundwater by the sanitary sewer system as I & I.

Policy Implications

Our research in the White Clay Creek watershed of the Christina Basin in northern Delaware indicates urbanized watersheds with higher amounts of impervious cover tend to have decreased base flows. To mitigate loss of recharge and base flow, we recommend that governments consider water resource protection area ordinances that set impervious cover thresholds on new development in sensitive watersheds, wellhead, and recharge areas.

The New Castle County, Delaware water resource protection area (WRPA) ordinance limits the amount of impervious cover (such as roof and pavement) to 20% or new development in surface water, recharge, and wellhead areas. WRPAs are defined as limestone aquifers, reservoir watersheds, wellhead areas, and recharge areas. Impervious cover thresholds are concepts that seek to balance a right to realize economic development of land with protection of water resources by minimizing loss of recharge and protecting the quality and quantity of water supplies in WRPAs (Kauffman et al. 2004).

New development in New Castle County WRPAs may exceed the 20% impervious cover threshold, but not exceed 50% impervious, provided the applicant submits a climatic water budget and installs infiltration facilities to augment recharge. The water budget must document that postdevelopment recharge will be no less than predevelopment recharge when computed on an annual basis. The applicant is required to offset the loss of recharge due to increased impervious cover by constructing recharge facilities that convey relatively pure rooftop runoff for infiltration to groundwater.

Local governments are urged to protect ground and surface waters in WRPAs through a recommended source water protection hierarchy (ranked in order of preference): (1) preserve WRPAs as open space and parks by acquisition or conservation easement; (2) limit impervious cover of new development to 20% by right within WRPAs; (3) allow impervious cover of new development to exceed 20% within WRPAs (but no more than 50% impervious) provided the applicant develops recharge facilities that directly infiltrate rooftop runoff; and (4) allow impervious cover of development to exceed 20% within WRPAs (but less than 50% impervious) provided the applicant develops recharge facilities that infiltrate runoff from forested and grassed surfaces with pretreatment.

Progressive WRPA ordinances incorporate the following impervious cover reduction strategies to minimize total pavement and roof area in the watersheds:
- Narrower residential roads;
- Smaller turn-around and cul-de-sac radii;
- Smaller parking stalls;
- Angled one-way parking;
- Smaller front yard setbacks;
- Disconnect rooftop runoff to splash onto lawns;
- Remove existing impervious surfaces;
- Shorter road lengths;
- Permeable paving for spill over parking areas;
- Smaller parking demand ratios;
- Clustered subdivisions with open space;
- Shared parking and driveways;
- Reforest along riparian streams; and
- Acquire open space and conservation easements.

Conclusions

During each of five monitoring events in 2006 and 2007 at 19 stations in and near the White Clay Creek Wild and Scenic River watershed in Delaware, we observed that increased watershed impervious correlates with decreased base flow. For the five events, the coefficients of determination (R^2) based on linear regression of impervious cover and base flow data are 0.33, 0.35, 0.32, 0.46, and 0.58, evidence of fair to good correlation. We attribute decreased base flow in the highly urbanized, high impervious cover watersheds to loss of permeable recharge areas covered by roof and pavement. Water supply leakage into the groundwater may be occurring but is offset by byproducts of urbanization such as storm sewers and sanitary sewers that intercept and lower the groundwater table resulting in less base flow in the streams. Urbanization and its byproducts are reducing groundwater recharge as the source of base flow in streams in and near the White Clay Creek watershed in northern Delaware. Increased watershed imperviousness can result in dwindling drinking water and aquatic resource flows, especially during drought periods. Water resource protection area ordinances, recharge augmentation, and pavement reduction techniques are available to reduce the impacts of impervious cover on watershed hydrology.

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