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Effects of suburban development on runoff generation in the Croton River basin, New York, USA

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Abstract

The effects of impervious area, septic leach-field effluent, and a riparian wetland on runoff generation were studied in three small (0.38–0.56 km^2) headwater catchments that represent a range of suburban development (high density residential, medium density residential, and undeveloped) within the Croton River basin, 70 km north of New York City. Precipitation, stream discharge, and groundwater levels were monitored at 10–30 min intervals for 1 year, and stream water and groundwater samples were collected biweekly for δ^{18}O, NO_3^-, and SO_4^{2-} analysis for more than 2 years during an overlapping period in 2000–2002. Data from 27 storms confirmed that peak magnitudes increased and recession time decreased with increasing development, but lags in peak arrival and peak discharge/mean discharge were greatest in the medium density residential catchment, which contains a wetland in which storm runoff is retained before entering the stream. Baseflow during a dry period from Aug. 2001–Feb. 2002 was greatest in the high-density residential catchment, presumably from the discharge of septic effluent through the shallow groundwater system and into the stream. In contrast, moderate flows during a wet period from Mar.–Aug. 2002 were greatest in the undeveloped catchment, possibly as a result of greater subsurface storage or greater hydraulic conductivity at this site. The mean residence time of baseflow was about 30 weeks at all three catchments, indicating that human influence was insufficient to greatly affect the groundwater recharge and discharge properties that determine catchment residence time. These results suggest that while suburban development and its associated impervious surfaces and storm drains accelerate the transport of storm runoff into streams, the combined effects of remnant natural landscape features such as wetlands and human alterations such as deep groundwater supply and septic systems can change the expected effects of human development on storm runoff and groundwater recharge.

Keywords: Hydrology; Runoff; Groundwater; Suburban development; Wetland

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1. Introduction

Urbanization is a pervasive global trend. Nearly, half the world's population now resides in urban areas, and that percentage is expected to increase to 60% by the year 2030 (McGee, 2001). In the United States, 80% of the population now lives in urban metropolitan areas (US Census Bureau, 1999), and a dominant demographic trend is the growth of suburban areas into previously undisturbed forests, shrublands, and deserts (Katz and Bradley, 1999). Maintaining an adequate water supply and protecting water quality in suburban areas are growing problems whose solutions will require extensive effort and research.

The effects of suburban development has been characterized in several studies; increased flood frequencies in areas with impervious surfaces were reported in the late 1960s and early 1970s (Leopold, 1968; Seaburn, 1969; Anderson, 1970). More recent studies have focused on the effects of engineered aspects of catchments, (e.g. detention basins, riparian buffers and septic systems) on runoff volume and water quality (Robertson et al., 1991; Griffin, 1995; Chin and Gregory, 2001; Booth et al., 2002). The effects of suburban development on runoff characteristics are widely acknowledged to include (relative to the undisturbed pre-development condition): (1) decreased low flow and groundwater recharge, (2) increased surface runoff in annual streamflow, (3) increased magnitude of peak runoff, (4) decreased lag time between rainfall and runoff response, (5) increased rate of hydrograph rise and recession, and (6) decreased mean residence time of streamflow (Hirsch et al., 1990; McCuen, 1998; Rose and Peters, 2001). Most process-level studies have quantitatively documented these effects in suburban catchments in which impervious surfaces represent a large percentage of the total drainage area; but additional studies are needed that compare these effects in catchments with moderate suburban development to those in undeveloped catchments.

Impervious areas such as paved roads and roofs increase the rate of surface water runoff through storm sewers resulting in decreased groundwater recharge. Yet some suburban landscape features, such as lawns, parks, golf courses, and woodlands provide groundwater recharge rates similar to those that existed prior to development (Lerner, 2002). Another feature in many suburban areas is domestic septic systems that discharge to shallow groundwater, whereas other areas have sanitary sewers that transport treated domestic wastewater directly to surface waters (Hirsch et al., 1990).

The quantity and quality of surface runoff are of great concern in the Croton River Watershed of southeastern New York, a water supply area for New York City. This region has experienced extensive suburban development during the past 50 years resulting in large increases in impervious area. However, wooded and undeveloped land remains, and impervious area, generally, does not exceed 15% of the total watershed area (Center for Watershed Protection, 2001). Runoff processes within this region likely retain some characteristics from the era prior to European settlement when forest and wetland covered nearly the entire landscape (Schueler, 1987), however, more than 80,000 domestic septic systems in the watershed could potentially increase groundwater recharge and baseflow through discharge from leach fields (Heisig, 2000; Sherlock et al., 2002). Little is known about the net effect of these suburban features on baseflow, groundwater recharge, and stormflow generation in suburban settings that represent a broad range of development intensities.

This paper presents results of a study of the effects of suburban development on baseflow and runoff processes in three small catchments of similar size, geomorphology, and physiographic characteristics in the Croton River basin (Fig. 1). The three catchments represent a gradient of suburban conditions from forested (undeveloped) to medium and high density residential development. The study entailed (1) measurement of rainfall amount, stream discharge, and groundwater levels at wells within each catchment, and (2) calculation of mean residence time of stream water from ^{18}O measurements in precipitation and baseflow from each of the three catchments. Our working hypothesis was that suburban development and its associated impermeable surfaces would increase runoff peaks and accelerate the hydrograph rise and recession during stormflow events, and also decrease the groundwater recharge rate and mean residence time.

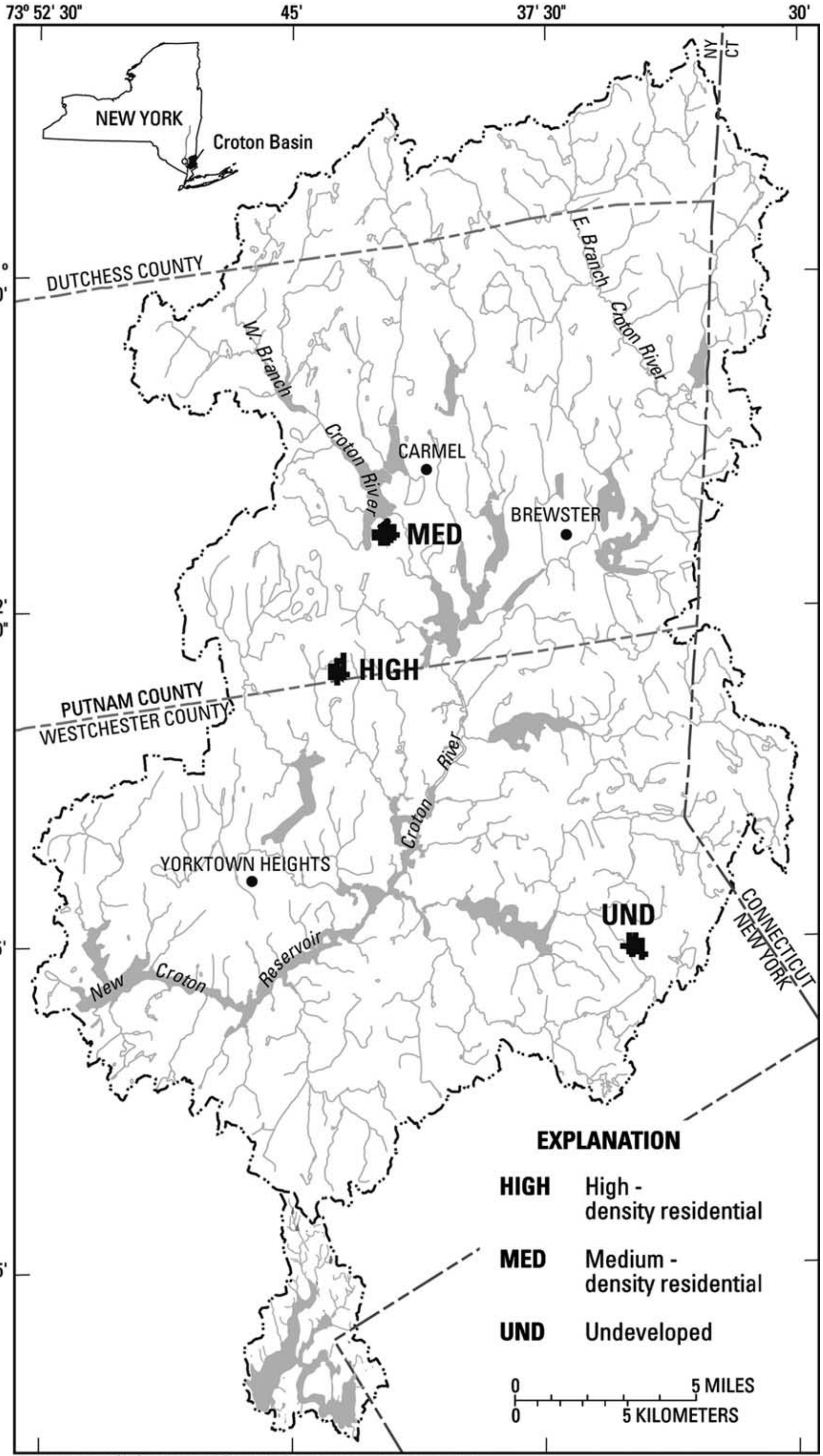


Fig. 1. Location of the three study catchments within the Croton River basin in southeastern New York.

1.1. Study area

The 971-km^2 Croton River basin in southern New York State (Fig. 1) consists of 12 reservoirs that supply 492 million L of water per day to New York City and upstate communities equivalent to about 10% of the City's water supply (Galusha, 2002). The Croton basin encompasses parts of Dutchess, Putnam and Westchester Counties in New York, and part of the State of Connecticut. The basin had a total population of 189,912 in 2000 (Moffett et al., 2003).

The Croton basin is largely underlain by Precambrian sedimentary and igneous rock of the New England Upland province; elevations range from 200 to 500 m above sea level. Soils are developed on glacial till and are medium to moderately textured and generally well drained. The Croton basin is 56.7% forested, 25.0% residential land, 7.4% agricultural land, 4.1% commercial land, 5.7% lakes and reservoirs, and 0.8% undeveloped land (Linsey et al., 1999). Mean annual precipitation is 1299 mm, and mean annual temperature is 9.9 °C at Yorktown Heights, New York in the southern part of the Croton basin at an elevation of 204 m (1971–2000 mean; Northeast Regional Climate Center; climod.nrcc.cornell.edu). During the principal winter of the study, 2001–2002, total snowfall was only 368 mm, compared to a 30-year mean of 960 mm at Yorktown Heights. The dry winter with a mean temperature that was 3.4 °C above normal at Yorktown Heights combined to provide little snowmelt to streams in the late winter/early spring of 2002.

Each of the three catchments selected for study represents a different degree of development (Linsey et al., 1999). One is undeveloped and has second growth forest cover (UND), and the other two are dominated by suburban residential development (Fig. 2). A US National or global standard does not exist for classifying urban or residential land use based on population or housing density (Hitt, 1994). Both of the developed catchments in this study would be classified as 'high density residential' according to criteria developed by the US Geological Survey's National Water-Quality Assessment (Hitt, 1994), however, we have classified these catchments as medium density residential (MED, 1.6 houses/ha) and high-density residential (HIGH, 2.8 houses/ha) to distinguish them. Pertinent characteristics of the three catchments are given in Table 1.

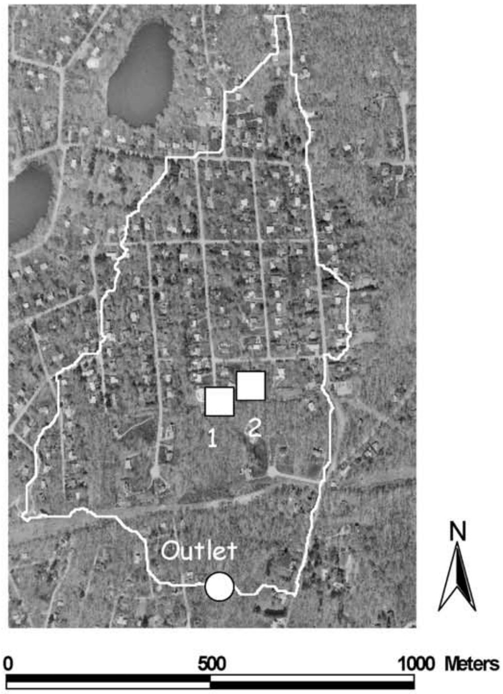
The developed catchments consist primarily of single family detached homes that are supplied by local groundwater. All houses in the HIGH catchment and about one-third of those in the MED catchment have individual wells, but the other two-thirds of the homes in MED are supplied by four nearby wells that pump and store water in an above-ground tank for later distribution. All wells in this area are cased through unconsolidated till or alluvium, are finished in fractured bedrock, and have an average depth of 120 m (Linsey et al., 1999). All houses in the two developed catchments have septic systems with leach fields. Runoff from roads and other impervious surfaces flows through storm drains to culverts that empty into the study streams.

The locations of residential areas relative to the storm-drain network and stream in HIGH are different from those in MED. The residences form a grid-like standard housing layout (Arnold and Gibbons, 1996) throughout the HIGH catchment (Fig. 2A), whereas residences in the MED catchment form a cluster-housing layout in the upper northern part that borders a headwater wetland to the south through which stormwater flows before entering the stream (Fig. 2B). The regular housing layout at HIGH, with a row of properties in direct contact with the principal stream, implies more direct delivery of septic wastewater from leach fields to the shallow groundwater system and to the stream, whereas wastewater from leach fields at MED discharges water through the headwater wetland, which flows into a stream at the lower end of the catchment.

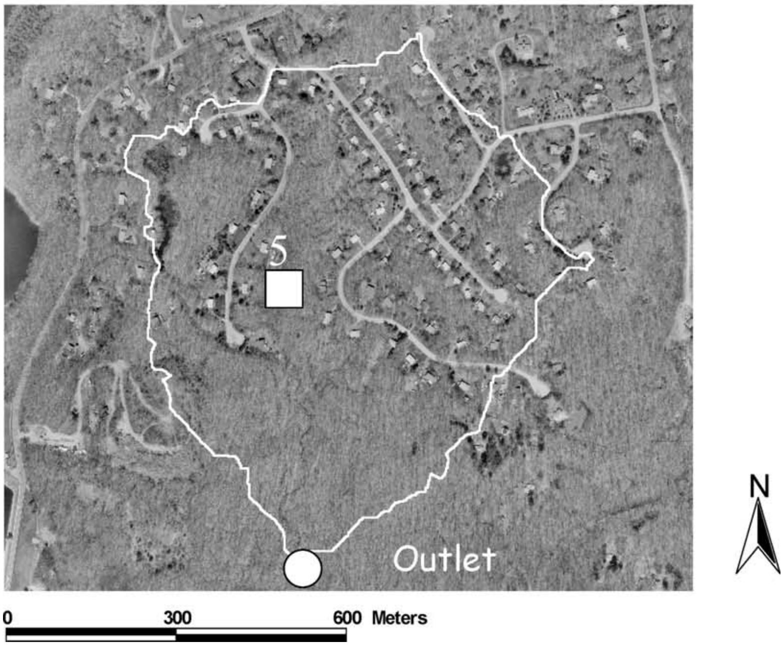
2. Methods

2.1. Field monitoring and data collection

All three streams were sampled weekly or biweekly during baseflow conditions (at least three rain-free days prior to sampling) for chemistry and isotope analyses from Mar. 2000–Aug. 2002; all other hydrological and meteorological measurements occurred from Aug. 2001–Aug. 2002. Air temperature was measured by an automated system in each catchment that provided mean values every 10 min, and precipitation amount was summed over the same



A. HIGH



B. MED

Fig. 2. Aerial photographs of the (A) HIGH catchment, and the (B) MED catchment, showing locations of outlet stream gage and selected monitoring wells discussed in text.

Table 1
Characteristics of the three study catchments

Catchment characteristic	Undeveloped (UND)	Medium density residential (MED)	High density residential (HIGH)
Drainage area (km^2)	0.38	0.45	0.56
Elevation range (m)	87	90	105
Mean slope (%)	18.3	15.6	13.6
Housing density (no/ha)	0	1.6	2.8
Total impervious area (% of catchment area)	0	6.2	11.1
Connected impervious area (% of catchment area)	0	5.0	5.8

10-min interval. Data are analyzed for a dry (Aug. 2001–Feb. 2002) and wet period (Mar.–Aug. 2002); precipitation was 374 mm during the dry period, 39% below the 30-year mean value in the region, and 666 mm during the wet period, within 2% of the 30-year mean value (Yorktown Heights, 1971–2000 mean, http://climod.nrcc.cornell.edu).

Stream discharge in each catchment was measured at a 120° v-notch weir, where stage was recorded every 10 min with a pressure transducer/data logger system, and converted to discharge through a rating curve. Discharge measurements were made occasionally by volumetric and current meter methods, and largely confirmed the theoretical stage—discharge relation for each weir.

Discharge from septic systems was estimated by assuming a per-capita-water-consumption rate of 326 L/d, which is the mean domestic consumption for Putnam County (Solley et al., 1998), and a mean of 2.92 persons per household (http://factfinder/census.gov) in the Town of Carmel in which the developed catchments are located.

Groundwater levels were monitored in four wells (HIGH-1, HIGH-2, MED-5, and UND-4) at 30-min intervals with capacitance rods (Fig. 2). Wells were constructed of 50 mm diameter PVC. Each well was installed by digging a hole about twice the diameter of the pipe with a power auger to the soil/bedrock interface, inserting a capped PVC pipe to the bottom of the hole, backfilling the entire screen length with quartz sand, and adding bentonite just below land surface in the unscreened interval to prevent infiltration along the pipe. Wells were first developed by pumping out several well volumes until visibly clear water was recharging the well. The four wells discussed in this paper were installed at depths ranging from 2000 to 3000 mm below land surface, with a 400–500 mm unscreened length that begins at the surface, and was then screened to the bottom. Groundwater was sampled biweekly for $\delta^{18}O$ analysis by running tubing down to the well bottom, pumping out in excess of one tube volume (0.5 L), and then collecting the sample. Care was taken to remove all air bubbles from the tubing prior to sampling.

Stream water was sampled weekly or biweekly for $\delta^{18}O$, NO_3^-, and SO_4^{2-} analysis from Mar. 2000–Aug. 2002 at all three catchment outlets, and precipitation was sampled weekly or biweekly for $\delta^{18}O$ analysis during the same period at a suburban site in Brewster, in the central part of the Croton River basin (Fig. 1). Additionally, groundwater samples were collected from 25 domestic wells in catchment HIGH during May 2002 and analyzed for $\delta^{18}O$. These samples were collected by opening the tap on the cold water storage tank at each house and filling the bottle; therefore these samples were not run through a water softening system prior to sampling.

All samples for $\delta^{18}O$ analysis were collected in 20-ml glass vials with polyethylene-lined caps that seal to prevent evaporation. Analysis of $\delta^{18}O$ was by mass spectrometry using an automated version of the CO_2–H_2O equilibration technique (Epstein and Mayeda, 1953) at the US Geological Survey laboratory in Menlo Park, California. Values are reported in per mil units (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW) with a precision of 0.05‰. Nitrate and SO_4^{2-} concentrations were analyzed by ion chromatography at the State University of New York College of Environmental Science and Forestry according to a method described in Shepard et al. (1989).

2.2. Data analysis and modeling

Twenty-seven storms between Aug. 2001 and Aug. 2002 were selected for analysis. A storm was defined as (1) measured rainfall greater than 2.5 mm followed by no rainfall for at least 3 h, and (2) an increase in stream discharge at HIGH of at least 30% above the pre-event value within 3 h. The time elapsed between the centroid (time at which half of the rainfall for the storm was reached) of the storm and the discharge peak was defined as the lag time for the event (Viessman et al., 1989). A distinct break in slope on the recession limb of the HIGH catchment hydrograph about 3 h after the peak indicated the cessation of runoff from impervious areas and a transition to baseflow recession. Thus, 3-h recession constants were calculated for all 27 storms in each catchment, through the linear reservoir hydrograph-recession equation

$$Q_t = Q_0\,\mathrm{e}^{-kt} \tag{1}$$

where Q_0 is the discharge at time $t=0$, Q_t is discharge at a later time t, and k is the recession coefficient, expressed in inverse time. For $t=3$ h, this coefficient is

$$k_3 = 8\ln\left(\frac{Q_3}{Q_\mathrm{p}}\right) \tag{2}$$

where Q_3 is the discharge 3 h after the peak discharge Q_p, and k_3 is the 3-h recession constant expressed in inverse days. The 3 h time point after the runoff peak was considered the end (t_e) of the runoff event at HIGH. The absence of a similar break in the slope of the recession curves for the two other catchments resulted from a more gradual cessation of stormflow. Thus, the end of the runoff event t_e (hours) in the MED and UND catchments were estimated from the 3-h recession constants k_3 and the catchment area A as

$$t_\mathrm{e} = 3\frac{k_3^\mathrm{HIGH}A}{k_3A^\mathrm{HIGH}} \tag{3}$$

where k_3^HIGH and A^HIGH are the 3-h recession constants and the catchment area, respectively, at the HIGH catchment. This inverse time and area weighting approach accommodates the differing shapes of the storm hydrographs in the two less developed catchments. The hydrograph for each storm was normalized as the relative runoff height, in mm, above the straight line connecting the beginning and the end (t_e) of each storm.

Annual evapotranspiration ET (mm) was calculated from the empirical formula of Turc (1954) and Pike (1964)

$$\mathrm{ET} = \frac{P}{\sqrt{0.9 + \left(\frac{P}{L}\right)^2}} \tag{4}$$

with

$$L = 300 + 25T + 0.05T^3 \tag{5}$$

where P is total annual precipitation (mm), and T is mean annual temperature (°C).

A master combined recession curve was generated for each site based on daily runoff hydrographs by MRCtools (Lamb and Beven, 1997). Precipitation-free runoff recessions with durations longer than 10 days were automatically selected for each watershed. An integral master recession curve was obtained by superposition of all recession curves with durations of at least 10 rain-free days. The master recession curve has an exponential form identical to Eq. 1, where Q_t and Q_0 are daily discharge rates, t is time in days, and the recession constant k expresses the rate of depletion of the groundwater dynamic storage (1/days). An exponential fit of the master recession curve was used to obtain the recession constant k, and the dynamic storage volume was calculated as

$$V_\mathrm{m} = \frac{Q_0}{k} \tag{6}$$

where Q_0 is the discharge at the beginning of groundwater drainage (top of the master recession curve), and V_m is the transient storage (‘dynamic volume’) of water that would be discharged during a recession from full groundwater storage if no additional recharge entered the catchment (Vitvar et al., 2002).

Baseflow residence time in the aquifer was calculated through a convolution integral approach (Maloszewski et al., 1992; McGuire et al., 2002) that describes the transformation of an ^{18}O input (precipitation concentration C_in) into an ^{18}O output (stream concentration C_out) within a continuous flow system. For conservative tracers such as ^{18}O, this expression takes the form of a convolution integral with a system response function

$$C_\mathrm{out}(t) = \int_0^\infty C_\mathrm{in}(t-T)g(T)\mathrm{d}T \tag{7}$$

where the function $g(T)$ characterizes a model of the type of water mixing, and t and T are chronological and residence time, respectively. The δ^{18}O values of precipitation samples from Brewster were used as the input and were adjusted according to precipitation amount. The δ^{18}O values of stream water were used as the output, and only values indicative of baseflow conditions were included by selecting from the biweekly samples that were collected at least 3 days after a storm as defined above. The mean residence time was estimated from assumed flowpath distributions, such as the exponential and advection–dispersion distribution that have commonly been applied in catchment studies (Maloszewski et al., 1992; McGuire et al., 2002; Vitvar et al., 2002).

3. Results and discussion

The following section addresses the effects of: (1) impervious area on hydrograph peaks and recessions, (2) a wetland in the MED catchment on hydrograph peak lags and shape, and (3) septic discharge in the HIGH catchment on low flow. We also discuss runoff differences among the catchments during a wet period and the residence time of baseflow in each catchment.

3.1. Effects of impervious area

Mean peak discharges for the 27 storms progressively increased with increasing development from 3.3 mm/d at UND and 4.7 mm/d at MED to 9.9 mm/d at HIGH (Fig. 3A). Similarly, mean 3-h recession constants for these storms increased as development increased from 4.0/d at UND and 5.3/d at MED to 9.7/d at HIGH (Fig. 3B). In both cases, the greatest increase was from MED to HIGH, indicating that storm runoff characteristics were not linearly related to housing density. A Kruskal-Wallis one way analysis of variance on ranks for data that fail a test for normality combined with a Tukey test for all pairwise comparisons indicated that the peak discharges and the 3-h recession constants were significantly different ($p < 0.05$) among the catchments and that the values at HIGH were greater than those at either MED or UND, however, the differences between MED and UND were not significant. The increase of discharge peaks with increasing development and impervious area exceeds that observed in several past studies on the basis of annual discharge (Hirsch et al., 1990), daily discharge (Rose and Peters, 2001), and hourly discharge (Brezonik and Stadelmann, 2002; Burges et al., 1998). These studies report peak discharge increases of about 80% in urban catchments with 50% impervious area (Rose and Peters, 2001) and increases of about 50% in urban catchments with 30% impervious area (Burges et al., 1998), whereas a 300% increase was observed in the HIGH catchment, which has an impervious area of only 11.1%, and a 42% increase was observed in the MED catchment, which has an impervious area of only 6.2%.

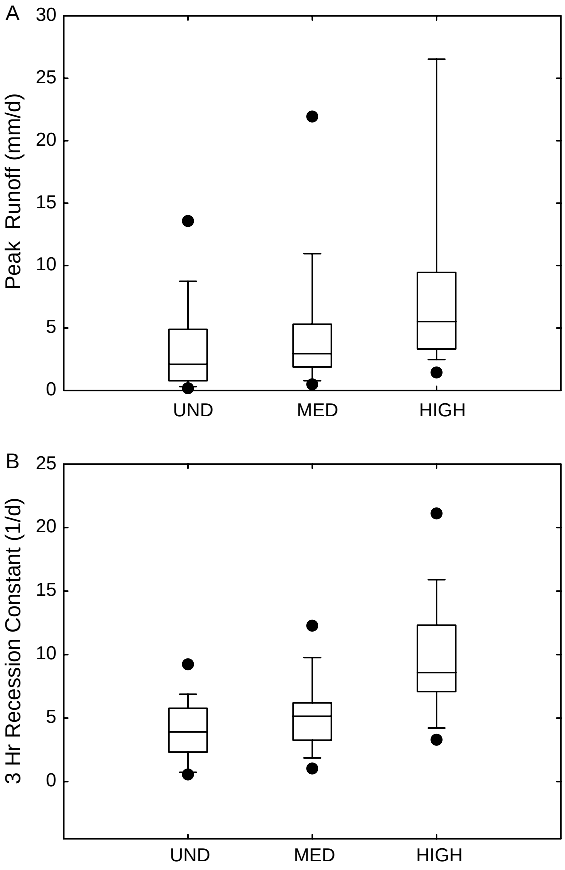


Fig. 3. Box and whisker plots of (A) peak runoff, and (B) 3-h recession constants in the three study catchments for 27 storms during 2001–02. The maximum peak runoff value of 49.4 mm/d is not shown in Fig. 3A for the HIGH catchment.

Peak runoff in the Croton catchments increased with maximum rainfall intensity. The relation, however, was strongest and the slope steepest at the HIGH catchment ($r^2 = 0.70$, slope = 0.06, $p < 0.05$), decreased with decreasing development (MED $r^2 = 0.22$, slope = 0.02, $p < 0.05$), and was weakest with the lowest slope at UND

($r^2 = 0.19$, slope $= 0.006$, $p < 0.05$). These relations are consistent with a previous study in which Stumm and Ku (1997) reported a strong relation between peak precipitation and runoff ($r^2 = 0.75$) for 62 storms in a suburban catchment on Long Island, New York (30% impervious area). These results suggest that the relation between peak runoff and peak precipitation rate strengthens as the percentage of impervious area increases, which is the basis for the Rational Method that is used to predict peak discharge in urban catchments based on rainfall intensity (Viessman et al., 1989).

3.2. Effects of a headwater wetland

The headwater wetland in the MED catchment is believed to predate development. The wetland lies below (south of) the clustered residential area; thus, all stormwater drainage and septic leachate moves through the wetland before entering the stream (Fig. 2b). The effects of this wetland on stormflow retention (Fig. 4A), the stormflow hydrograph shape (Fig. 4B), and the generation of baseflow were examined. A Kruskall-Wallis analysis of variance on ranks for data that fail a test for normality combined with a Tukey test for all pairwise multiple comparisons confirmed ($p < 0.05$) that the event lag times were shortest at HIGH (median value $= 30$ min), longer at UND (80 min), and longest at MED (120 min). The ratios of peak discharge to event mean discharge were significantly different among the three catchments ($p < 0.05$, same statistical tests used for lag time data), greater at HIGH (median value $= 3.7$) than the other two catchments, but not significantly different between UND (2.7) and MED (2.6). The headwater wetland in MED delayed storm runoff peaks and broadened the stormflow hydrograph relative to the HIGH catchment producing a hydrograph shape, peak flow and 3-h recession that could not be statistically distinguished from the UND catchment. The lag times at HIGH rarely exceeded 90 min, and the few negative values indicate that in some instances the peak discharge preceded the centroid of the storm. The standard deviation of the lag times at HIGH was 26 min, lower than the values of 40 min at UND and 47 min at MED-an additional indication that surface runoff from impervious areas was the dominant flow component in HIGH, and therefore, lag times showed less seasonal variation than runoff at the other two sites, which must rely to a greater extent on pre-storm groundwater levels.

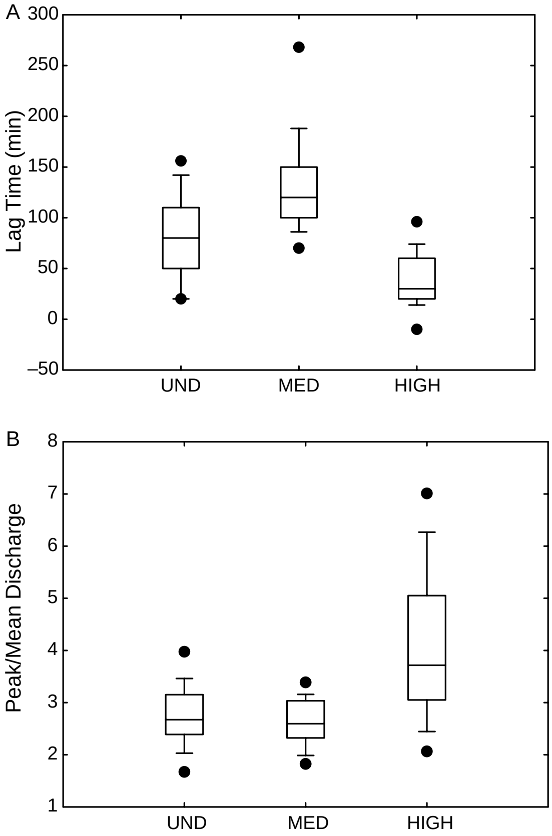


Fig. 4. Box and whisker plots of (A) peak lag time, and (B) peak/mean discharge in the three study catchments for 27 storms during 2001–2002.

The effects of wetland groundwater storage in MED are further demonstrated by the relation between pre-storm well levels in the wetland and lag times when groundwater storage was low. Well MED-5 (Fig. 2b) was located in the wetland, and overall, showed levels that were not related to lag time because other factors such as rainfall amount, intensity, and duration likely influenced lag times (Fig. 5A). However, a strong inverse relation between pre-storm groundwater level and lag time was evident ($r^2 = 0.93$, $p < 0.01$) when those levels were > 200 mm below land surface, indicating that when conditions were especially dry,

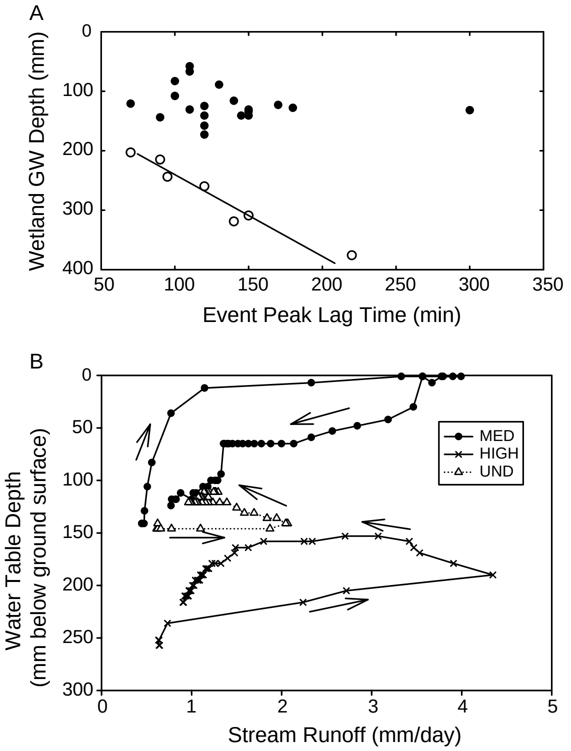


Fig. 5. (A). Peak lag time and wetland water table depth (MED-5), and (B). Stream runoff and groundwater level at a riparian well in each of the three study catchments during a rain storm on April 25, 2002. The wells used in this figure are shown in Fig. 2, except for well UND-1, which is not shown.

retention in the wetland was the dominant factor controlling lag time.

The dynamics of the water table in the wetland and stream runoff in the MED catchment provides additional evidence that storage and release of groundwater from the wetland controls the timing of stream runoff peaks during storms. The hydrograph of a typical storm on April 25, 2002 shows clockwise hysteresis that indicates a change in the relation between stream runoff and well levels in MED-5 from the rising limb to the falling limb of the hydrograph (Fig. 5B). Groundwater levels first increased with little increase in stream runoff, which confirms the effects of rapid discharge to the wetland from storm drains within the residential area. Once groundwater levels rose close to the land surface, stream runoff then increased while well levels remained fairly steady and close to the surface. Peak runoff occurred only after a time lag from the initial peak in groundwater levels. In contrast, stream runoff and shallow groundwater levels in the riparian areas of HIGH (HIGH-1) and UND (UND-4), generally, showed counterclockwise hysteresis (Fig. 5B). Stream runoff increased and peaked with only small increases in groundwater levels. Groundwater levels increased at a greater rate and magnitude on the hydrograph recession. The pattern demonstrated in Fig. 5B for the April 25, 2002 storm was dominant throughout the storms that were monitored in the three catchments. In the wetland at the MED catchment, 70% of the 27 storms monitored showed clockwise hysteresis, 19% showed counterclockwise hysteresis, and 11% showed neither pattern clearly. In contrast, 85% of storms in the HIGH catchment and 67% of storms in the UND catchment showed counterclockwise hysteresis as demonstrated in Fig. 5B. The wetland in the MED catchment receives rapid runoff of storm discharge from upgradient impermeable areas, which initially stores much of this runoff, as evidenced by the rapid rise of the water table without a similar rise in the stream runoff response. Once the water table in the wetland rises close to the surface, water is then transported through the shallow wetland soil or over the surface. The effects of the wetland are sufficient enough that stream runoff peaks are somewhat greater and recessions somewhat more rapid (Fig. 3), but not significantly different than those in the UND catchment.

3.3. *Effects of discharge from septic leach fields*

Stream baseflow from the MED and HIGH catchments was expected to reflect the contribution of residential septic leach fields (Heisig, 2000). Data collected during the dry period (Aug. 2001–Feb. 2002) of the study indicates that runoff in HIGH at baseflow was about 0.25 mm/d greater than at the UND and MED catchments (Fig. 6A). Estimated daily septic-discharge was 952 L per house, equivalent to runoff values of 0.25 mm/d in HIGH, and 0.14 mm/d in MED. Thus, the estimated increased groundwater discharge from septic systems in HIGH was equivalent to the observed increase in low baseflow runoff relative to UND. No similar enhancement of runoff was observed during low baseflow in MED, however,

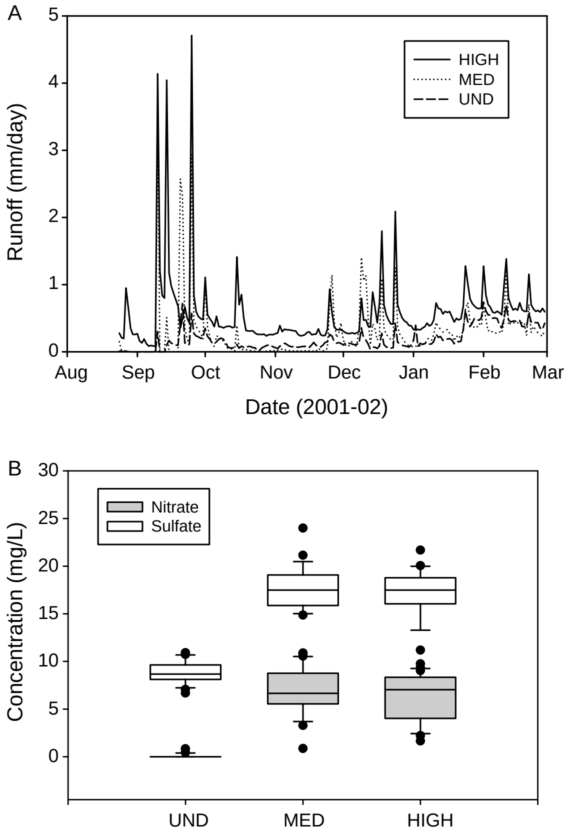


Fig. 6. (A) Stream runoff during a dry period, Aug. 2001–Feb. 2002 at the three study catchments, and (B) box and whisker plots of NO_3^- and SO_4^{2-} concentrations in stream water at the three study catchments during the entire study period, Aug. 2001–Aug. 2002.

because: (1) this catchment has a lower housing and septic system density than HIGH, (2) septic discharge must first pass through the wetland, where much of the potential runoff is likely stored and/or removed by soil and vegetation, and (3) observation suggests that the MED stream loses a small amount of water through the streambed just upstream of the weir, which would be most significant at low flow. Points 2 and 3 above are further supported by the calculated water balance for MED which shows low annual runoff of 211 mm/year, compared to values of 316 and 272 at HIGH and UND, respectively, and an amount (139 mm) that cannot be accounted for in the water balance (Table 2).

Nitrate and SO_4^{2-} concentrations at baseflow in HIGH and MED are elevated relative to UND (Fig. 6B), which further indicates the likely presence of septic effluent in these streams as shown by previous studies in the Croton Watershed and in similar suburban settings (Robertson et al., 1991; Heisig, 2000), though other sources such as lawn fertilizer may contribute to elevated concentrations as well. Evidence of increased baseflow from septic leach field effluent at HIGH is also consistent with the findings of Sherlock et al. (2002), who documented downward vertical flow from septic leach fields in the soil towards the water table during rain storms in a residential area near the Croton River basin. Their results indicated a fairly long groundwater residence time in the soil C horizon and eventual transport to the water table, where down slope flow of groundwater could then contribute to stream baseflow.

The master recession method was applied to daily discharge data (Fig. 7) and recession constants k were calculated according to Eq. (1) (Table 3). Exponential regressions of high statistical significance ($r^2 > 0.96$, $p < 0.01$) were fit to the data from each catchment. This approach provides insight into long-term recession, characteristic of extended periods of 10 days or longer without substantial precipitation (Lamb and Beven, 1997). The results indicate that recession was

Table 2
Water balance for the three study catchments during Aug. 2001–Aug. 2002

Water balance quantity all values (mm/year)	Undeveloped (UND)	Medium density residential (MED)	High density residential (HIGH)
Precipitation	870	919	907
Total input (precipitation + estimated septic input)	870	974	998
Evapotranspiration	580	624	644
Runoff	272	211	316
Unaccounted difference	18	139	38

Evapotranspiration was calculated from Eqs. (4) and (5).

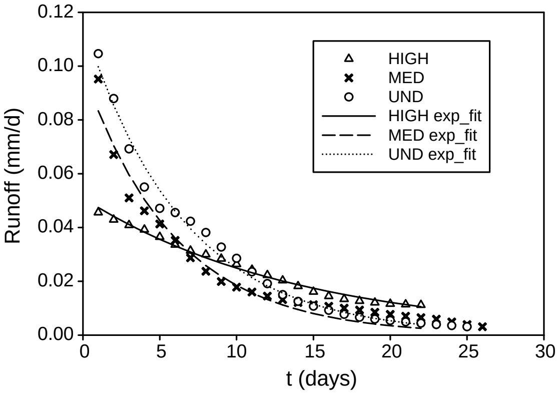


Fig. 7. Master recession curves of daily discharge for all three study catchments with exponential regression fits.

fastest in the UND catchment ($k=0.13/d$), slowest in the HIGH catchment ($k=0.06/d$), and intermediate in the MED catchment ($k=0.1/d$). Thus, recession at the event time scale was fastest in the developed catchment (Fig. 3B), whereas at the seasonal scale, recession was fastest in the UND catchment. The results of this analysis are consistent with greater sustainability of runoff with increasing residential development and septic system density as these catchments experience long periods of drying.

Oxygen isotope data collected from residential wells and two shallow wells in catchment HIGH during the dry period of Aug. 2001–Feb. 2002 were also consistent with the influence of septic runoff in shallow groundwater and stream water (Fig. 8). First, the 25 residential wells sampled in catchment HIGH have a similar distribution of δ^{18}O values (Kruskall-Wallis Analysis of Variance on Ranks, $p>0.05$) as those of well HIGH-1, which is located in a riparian area just down gradient from a residential septic leach field. Well HIGH-2, located upslope from HIGH-1 near the hillslope/riparian transition and not directly down slope from a septic leach field, however, has δ^{18}O values that are greater than those of the septic-influenced well and the residential wells ($p<0.05$) suggesting this groundwater has a different origin and transport history. The stream at HIGH has a median δ^{18}O value that is intermediate between those of wells HIGH-1 and -2 and a distribution of ranks that is statistically indistinguishable ($p>0.05$) from these wells suggesting that both of these groundwater 'types' may be contributing to streamflow during this relatively dry period. Alone, these δ^{18}O data do not provide definitive proof of the presence of a 'deep' septic signal in shallow groundwater and streamflow, but are consistent with the elevated low flow, higher NO_3^- and SO_4^{2-} concentrations, and slower recession during dry periods in the septic-influenced catchments as discussed above. Together, these data provide strong evidence that septic runoff increases low flow in the HIGH catchment.

3.4. Runoff differences during a wet period

Whereas, the analyses of hydrologic data reported thus far show the likely effects on stream runoff of: (1) rapid surface runoff over impermeable surfaces during storms and (2) septic discharge to the shallow groundwater/surface water system during dry periods, low flow runoff patterns in the study catchments during a wet period from Mar.–Aug. 2002 appear to be unrelated to residential development, and may reflect natural differences in storage and transmissivity among the catchments.

Daily duration curves show differences between runoff among the catchments during the dry and wet study periods (Fig. 9). Data from the Aug. 2001–Feb. 2002 dry period show the previously discussed higher flows during storms in the 1–10% flow exceedance range at HIGH and MED relative to UND, and also the higher low flows at HIGH than MED and UND, which are most pronounced in

Table 3
Some quantities calculated for the study catchments as part of the master recession analysis.

Quantities calculated from master recession analysis	Undeveloped (UND)	Medium density residential (MED)	High density residential (HIGH)
Q_0 Initial baseflow (mm/d)	2.79	2.35	1.22
k Linear storage coefficient (1/d)	0.15	0.16	0.07
V_d Dynamic storage (mm)	18	15	17

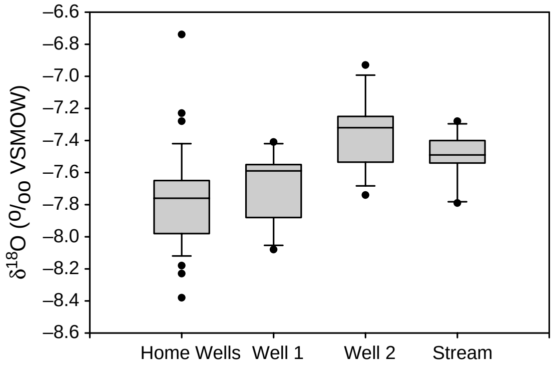


Fig. 8. δ^{18}O values for samples collected in catchment HIGH during the dry period, Aug. 2001–Feb. 2002 in home wells, Well 1, Well 2, and the Stream.

the 90–99% flow exceedance range (Fig. 9A). In contrast, flow duration curves from the Mar.–Aug. 2002 wet period show less difference between the three catchments in the 1–2% flow exceedance range than during the dry period, and higher flow at UND than the other two catchments in the 4–55% flow exceedance range (Fig. 9B). At values $>70\%$ flow exceedance, however, the HIGH catchment shows progressively greater flow than the other catchments, similar to that observed during the dry period. These data indicate that the effects of impermeable surfaces on storm flow are less pronounced during wet conditions when groundwater levels are closer to land surface, and even the UND catchment is poised for rapid runoff of incoming precipitation. Higher baseflow was evident at HIGH relative to the other catchments during both the wet and dry periods whenever stream runoff decreased to <1 mm/d. The higher runoff values in UND than those at HIGH and MED at moderate flows during wet conditions may not only indicate greater potential groundwater storage at UND, but may also be a reflection of other factors such as greater saturated hydraulic conductivity at shallow depths in UND, which is consistent with the possible impacts of compaction in disturbed soils. Determining the reasons for these higher moderate flows at UND would require a more detailed analysis of the thickness and permeability of shallow aquifer materials in these catchments.

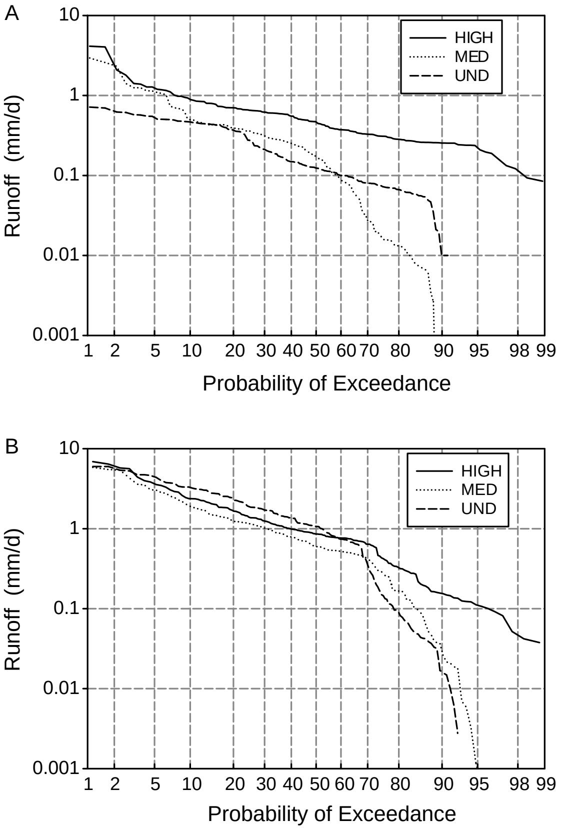


Fig. 9. Daily discharge-duration curves for the three catchments: (A) dry period (Aug. 2001–Feb. 2002), and (B) wet period (Mar.–Aug. 2002).

3.5. Catchment residence times

The measured and simulated δ^{18}O values for baseflow during 2000–2001 are plotted in Fig. 10. A dispersion model based on the δ^{18}O values of precipitation was fit to the data for each catchment. The best-fit simulations ($r^2=0.40$) were achieved with an advection–dispersion distribution with the parameter $D/vx=0.5$ and an exponential-piston flow distribution with parameter $\eta=1.1$, respectively. Flow models similar to these have been applied successfully in many small catchments (<2 km^2), and either model can be viewed as a reasonable representation of these Croton study catchments (McGuire et al., 2002; Vitvar et al., 2002). These models indicate a mean residence time of about 30 weeks for baseflow in each catchment, similar to values of 6 months–1 year that have been

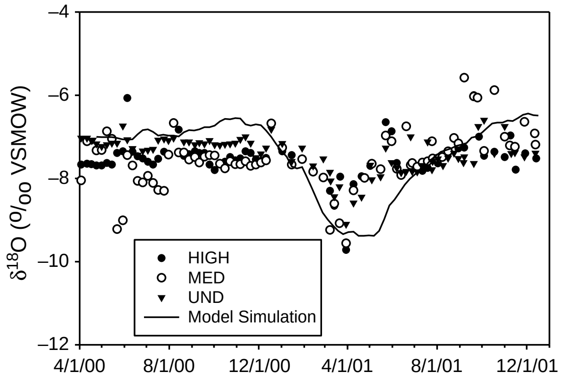


Fig. 10. Measured δ^{18}O values in baseflow samples from Apr. 2000 to Jan. 2002, and a best-fit simulation of an advection–dispersion model with a mean residence time of about 30 weeks (parameters given in text).

measured in other small catchments (McGuire et al., 2002; Vitvar et al., 2002). That the seasonal patterns in δ^{18}O values in all three catchments could be fit by the same flow models with the same residence time was surprising and might be partly explained by two factors. First, the mean δ^{18}O value of water from the sampled domestic wells in the HIGH catchment was about −7.7‰ (Fig. 8), which is similar to the mean δ^{18}O value for baseflow; therefore, the presence of septic effluent likely muted the expected variation in streamwater δ^{18}O values at this catchment. Second, application of Eq. (6) to the master recession analysis indicates that differences in the dynamic subsurface storage volumes between the catchments are small (V_d at HIGH = 17 mm, at MED = 15 mm and at UND = 18 mm, Table 3). Overall, the lack of measurable differences in the mean residence time of water among these three catchments suggests that human alteration of the landscape studied here is not great enough to significantly affect this variable that integrates aspects of groundwater recharge, discharge, and subsurface water storage.

4. Summary and conclusions

The effects of impervious area, a headwater wetland, and septic leach field discharge on stormflow runoff, baseflow generation, and groundwater recharge/discharge were compared on an episodic and seasonal basis in three catchments representing a gradient from undeveloped to high-density residential suburban development. The results indicate that some aspects of stream runoff appear to be affected by human development whereas other aspects appear unaffected. During storms, peak flows generally increased and recession times generally decreased with increasing development. Storage in a wetland in the MED catchment, however, increased lags in runoff peaks and broadened stormflow hydrographs relative to what was expected for the intensity of development within the catchment. Consequently, none of the storm flow measures examined in MED could be statistically distinguished from those in UND. The pumping of deep groundwater from fractured bedrock and discharge via septic systems to shallow groundwater increased low streamflow by about 0.25 mm/d in the HIGH catchment relative to the UND catchment, although a similar increase was not observed in the MED catchment. The effects of development on stream runoff were less evident during a wet period of the study than they were during a dry period, and the UND catchment showed greater runoff at moderate flows when conditions were wet, possibly due to greater storage and/or hydraulic conductivity in shallower parts of the shallow groundwater reservoir in UND that controls baseflow during these conditions. Overall, there was little difference in the dynamic storage among these three catchments, and therefore, all three showed similar mean residence times of about 30 weeks. These results show that suburban development through impermeable surfaces/storm drains and groundwater pumping/septic systems affects both high flow and low flow stream runoff, yet has little affect on other aspects of runoff such as residence time and moderate flow when conditions are wet, which are influenced by groundwater recharge and discharge.

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