Hydrology of channelized and natural headwater streams

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Abstract Understanding hydrology of channelized and natural headwater streams is paramount for maintaining ecosystem function and natural flow regimes. Two channelized and two natural headwater streams located in Upper Big Walnut Creek (UBWC) watershed in Ohio, USA, were instrumented to facilitate measurement, characterization and comparison of hydrology to the accepted paradigm for headwater hydrology. Data were collected at 10-min intervals from 1 January 2005 to 31 December 2006. Differences in flow magnitudes (average, low and high) were generally greater ($P < 0.05$) in the channelized streams. Frequency of zero discharge and out-of-bank discharge was significantly greater in the natural streams. Zero discharge occurred in summer and out-of-bank flows occurred in winter. Rate of change variables indicated that channelized streams respond more quickly to rainfall, have significantly greater peak flows, and have slower recession times. In contrast, natural streams tend to be more "flashy". The findings were generally consistent with the accepted paradigm for headwater hydrology and attributed to stream type, presence of subsurface drainage, potential connection to groundwater, and differences in riparian vegetation. The design and installation of management practices that influence hydrology should consider the potential impacts of altering stream hydrology. Management practices such as water-table management have the potential and show promise in altering the hydrology of channelized streams to resemble the hydrology of natural streams.

Key words peak flow; drainage; discharge; watershed; low flow; magnitude; frequency

Hydrologie de cours d'eau recalibrés et naturels de tête de bassin

Résumé La compréhension de l'hydrologie des cours d'eau, recalibrés et naturels, de tête de bassin est déterminante pour maintenir les fonctions écosystémiques ainsi que les régimes naturels d'écoulement. Deux cours d'eau, de tête de bassin, naturels et deux recalibrés situés dans le bassin versant du Big Walnut Creek supérieur dans l'Ohio, Etats-Unis, ont été instrumentés pour faciliter la mesure, la caractérisation et la comparaison hydrologiques par rapport au paradigme consensuel de l'hydrologie des têtes de bassin. Les données ont été acquises à pas de temps de 10 minutes du 1er Janvier 2005 au 31 Décembre 2006. Les différences dans la magnitude de l'écoulement (moyen, faible et fort) sont généralement plus importantes ($P < 0.05$) dans les cours d'eau recalibrés. Les fréquences d'assèchement et de crue inondante sont significativement plus importantes dans les cours d'eau naturels. Des assèchements se sont produits en été et des crues inondantes ont eu lieu en hiver. Les taux de variation montrent que les cours d'eau recalibrés répondent plus rapidement à la pluie, ont des pics de débit significativement supérieurs, et présentent des récessions plus lentes. Les cours d'eau naturels tendent quant à eux à avoir un comportement plus de type "éclair". Les résultats sont dans l'ensemble cohérents avec le paradigme généralement accepté de l'hydrologie des têtes de bassin, et sont liés au type de cours d'eau, à la présence de drainage de subsurface, aux connections potentielles avec la nappe souterraine, et aux différences de végétation riparienne. Le dimensionnement et la mise en œuvre de pratiques de gestion ayant un effet sur l'hydrologie devraient tenir compte des impacts modificateurs de l'hydrologie du cours d'eau. Les pratiques de gestion telles que la gestion de nappe ont un potentiel prometteur pour modifier l'hydrologie des cours d'eau recalibrés dans un sens qui la fait ressembler à l'hydrologie des cours d'eau naturels.

Mots clefs pic de débit ; drainage ; débit ; bassin versant ; étiage ; magnitude ; fréquence

INTRODUCTION

Headwater streams are distinct lotic ecosystems that provide habitat for unique biological communities and serve as sites for biogeochemical processing of nutrients and other chemical constituents (Meyer *et al*., 2007; Richardson & Danehy, 2007). Headwater streams are the interface between terrestrial and riverine ecosystems, providing hydrological connectivity (Freeman *et al*., 2007) between uplands and downstream waters. Headwater streams have been defined as streams having either a stream order (Strahler, 1957) less than three (Vannote *et al*., 1980; Freeman *et al*., 2007), riparian widths equal to or less than 10 m (Peterson *et al*., 2001), or drainage areas less than 1 km^2 (Gomi *et al*., 2002). Thus, headwater streams comprise from two-thirds (Leopold *et al*., 1964; Freeman *et al*., 2007) to more than 80% (Sidle *et al*., 2000; Gomi *et*

al., 2002; Seitzinger *et al*., 2002; Naiman *et al*., 2005) of the total stream length of watersheds worldwide.

Headwater streams may be classified as perennial or intermittent, dependent upon discharge throughout the year. The geomorphology of headwater streams may be characterized as channelized or natural. Here, stream channelization is defined by deepening and widening of natural swales or existing streams to remove water from agricultural fields and to receive discharge from subsurface tiles, whereas a natural stream has been able to develop under more natural conditions. Over 3.2×10^6 km of stream channels in the USA have been modified (Schoof, 1980), many of those to facilitate conveyance of subsurface tile drainage waters. Subsurface tile drainage is a common practice used to facilitate rapid conveyance of drainage waters for optimal agricultural crop production. The upper midwest USA accounts for 58% of the corn and 70% of the soybean production in the USA (Kovacic *et al*., 2006). Thirty-seven percent of all the cropland in the midwest and cornbelt states is tile-drained (Fausey *et al*., 1995; Zucker & Brown, 1998), leading to significant amounts of channelization; and 25% of the waterways in Illinois have been channelized (Mattingly *et al*., 1993).

One defining characteristic of headwater streams is their hydrology. Hydrology is a structuring force in headwater streams as it influences the riparian vegetation, instream biota and the biogeochemical processing. Yet, the availability and quantification of hydrological parameters from channelized and natural headwater streams, needed to formulate any strong conclusions about the impacts of channelization, is scant (Rhoads & Herricks, 1996).

In general, headwater stream discharges are greatest during the winter and early spring when thawing and snowmelt occur and when evapotranspiration is at its lowest. Conversely, discharges are least during the summer (Rheinhardt *et al*., 1999). In contrast, Rhoads & Herricks (1996) used a 42-year hydrological record for the Kaskaskia River at Bondville, Illinois to show that the greatest amount of discharge was measured during the spring, and the least amount in the autumn. In that study, substantial variations in annual flow patterns were observed. Flow variability has also been shown to be inversely related to watershed size: as watershed size decreases the variability in flow increases (Horwitz, 1978). Sparse data from studies conducted at a range of locations with varying climates suggest that channelization alters the natural flow regime, resulting in changes to response variables such as magnitude, frequency and rate of change. The most significant impacts of channelization are realized in headwater streams (Frothingham *et al*., 2002).

Mean discharge in natural streams will generally be less than that from channelized streams (Essery & Wilcock, 1990; Brooks *et al*., 2003). Existing information on the effects of channelization on low flow is contradictory. Swales (1982) suggested that channelization further pronounces the extremes of discharge (i.e. low flows are further reduced and high flows are increased). Similarly, Allan & Flecker (1993) suggest that channelization will further reduce summer baseflows. In contrast, Williams & Hynes (1977) indicate that channelization often results in streams that intersect groundwater, increasing the discharge during summer low-flow periods. Supporting that theory, Astrom *et al*. (2001) present data from two ditched streams in Finland and note an increase in discharge during low-flow periods. Flow duration curves for streams in Ireland indicate increases in both low and high flows following channelization (Essery & Wilcock, 1990). In channelized streams, peak discharges are generally greater compared to natural sinuous channels (Simpson *et al*., 1982; Poff *et al*., 1997; Moussa *et al*., 2002), although Astrom *et al*. (2001) suggest that reductions in peak discharge from two channelized ditches in Finland resulted from a levelling effect. Magner *et al*. (2004) suggested that channelization and tile drainage resulted in increased peak discharges ranging from 17 to greater than 300% in a Minnesota headwater system, while a literature review by Brookes (1988) indicated that 90–190% increases in peak discharges occurred following straightening of the Boyd River in Iowa. Similarly, Gorman & Karr (1987) reported four-fold increases in peak discharges for a channelized stream containing 90% tile drainage, compared to a natural stream containing approx. 20% tile drainage. Natural sinuous channels are characterized by smaller peak discharges compared to channelized streams (Shields & Cooper, 1994; Rheinhardt *et al*., 1999; Brooks *et al*., 2003; Powell *et al*., 2007).

Frequency of flooding (defined here as flows exceeding top of bank or bankfull capacity) and periods of zero flow are also influenced by channelization. In general, natural sinuous channels are more prone to overbank flooding (Shields & Cooper, 1994; Rheinhardt *et al*., 1999; Brooks *et al*., 2003; Powell *et al*., 2007). As a result of channelization, frequency of flooding or bankfull exceedence is dampened (Poff *et al*., 1997; Royer *et al*., 2004; Schaller *et al*., 2004). In contrast, Simpson *et al*. (1982), in a review of other studies, documented frequent periods of zero flow in natural streams compared to continuous flow in channelized streams. During the summer months, there is a high probability that natural streams will totally dry up (Rheinhardt *et al*., 1999). Poff *et al*. (1997) classified streams with greater than 10 days of zero discharge as intermittent runoff or intermittent flashy streams.

Headwater streams tend to be more "flashy" than larger rivers (Baker *et al*., 2004). Channelization and tile drainage, characteristic of low-gradient midwestern USA streams, also affect the response of the stream to rainfall inputs and tend to produce "flashy" streams (Royer *et al*., 2004; Schaller *et al*., 2004). Hydrographs of flashy streams are generally characterized by rapidly rising limbs, followed by gradually sloping recession limbs and extended baseflow recession times (Rhoads & Herricks, 1996). Time to peak discharge in channelized systems occurs more quickly compared to natural sinuous channels (Simpson *et al*., 1982; Poff *et al*., 1997; Moussa *et al*., 2002). Similar findings on time to peak discharge have been reported from simulation studies (Dunn & Mackay, 1996).

Biogeochemical processing, habitat structure and species diversity are all driven by the hydrology associated with headwater streams, yet comprehensive hydrological assessments on channelized and natural headwater streams are minimal. These assessments are needed to specifically understand how hydrology differs between channelized and natural headwater streams. Understanding the similarity and differences in hydrology between first-order channelized and natural headwater streams is critical for watershed planning and management, as well as the design and implementation of conservation practices.

The accepted paradigm for headwater streams suggests that natural sinuous channels, when compared to channelized streams, are characterized by: (a) smaller discharges, (b) greater extremes with respect to drought and flooding, and (c) slower response to rainfall but longer time of flow (Shields & Cooper, 1994). To validate this paradigm, more detailed headwater hydrology studies across an array of locations are required. Thus, the objective of this study was to quantify and characterize the hydrology of channelized and natural headwater streams within the Upper Big Walnut Creek (UBWC) watershed in Ohio, USA, and compare and contrast those findings to the stated paradigm for headwater hydrology.

METHODS

Study sites

The study sites are headwater streams located in the Upper Big Walnut Creek watershed (UBWC), Ohio. The UBWC watershed is an 11-digit watershed (HUC 05060001-130) located in central Ohio (latitudes 40°06′00″–40°32′30″; longitudes 82°56′00″–82°42′00″; Fig. 1). Understanding the headwater hydrology in this watershed is important because UBWC is one of 14 benchmark watersheds being studied as part of the US Department of Agriculture (USDA) Conservation Effects Assessment Project – Watershed Assessment Study (Richardson *et al*., 2008). Additionally, the findings from this study should be transferable to other headwater streams in cool humid climates. The watershed area is 492 km^2 and contains 467 km of perennial and intermittent streams that drain into Hoover Reservoir. Headwater streams (first- and second-order streams) in this watershed account for approximately 84% of all the streams in the watershed. Headwater streams in the UBWC watershed are a combination of low-gradient channelized and natural streams having perennial and intermittent flows. The streams convey drainage waters from upland agricultural, urban and industrial areas to higher-order streams that eventually converge into the Hoover Reservoir.

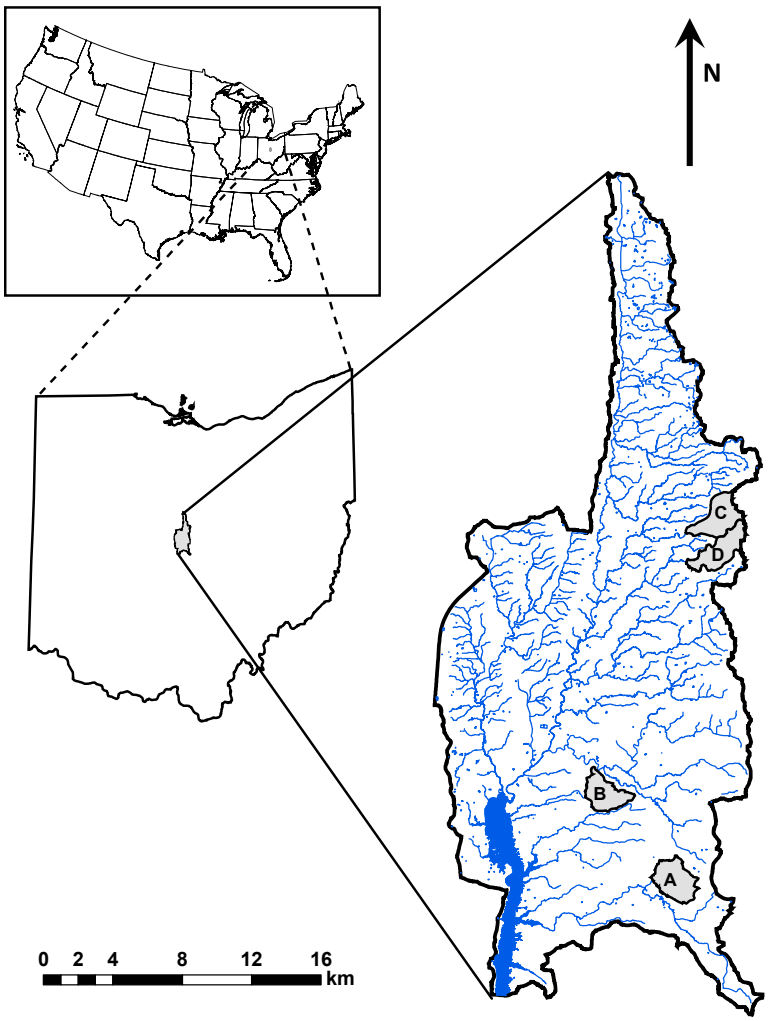

Fig. 1 Upper Big Walnut Creek watershed and locations of channelized streams (A and B) and natural streams (C and D).

The UBWC is located in the humid continental-hot summer climatic region of the USA. The climate provides for approximately 160 growing days at a base temperature (temperature at which development ceases) of 0°C, generally lasting from late April to early to mid-October. Normal daily temperatures range from an average minimum of –9.6°C in January to an average maximum of 33.9°C in July. Thunderstorms during the spring and summer produce short-duration, intense rainfalls. Moisture in the form of frozen precipitation or snow averages 500 mm annually and occurs primarily in the winter months (December–March). The 30-year normal rainfall recorded near the southwest portion of the watershed was 985 mm. Monthly distribution of rainfall exhibits a bimodal distribution with a primary peak in late spring and early summer and a secondary peak in late autumn and early winter. Soils in the watershed are clayey, poorly drained, and consist primarily of Bennington-Pewamo-Cardington soil association (60%) and the Centerburg-Bennington soil association (20%).

Two channelized (A and B) and two natural (C and D) headwater watersheds ranging in size from 389 to 454 ha were identified and instrumented for this study (Fig. 1). Each watershed was selected based on qualitative assessments of watershed size, agronomic practices, land use, topography and dominant hydrological processes (Table 1). The channelized watersheds are dominated by minimal relief and large, systematic tile-drained fields, while the natural watersheds are characterized by smaller, more sloping fields and natural surface drainage. The channelized watersheds are representative of eastern midwest tile-drained watersheds and the natural water-

Table 1 Basin characteristics between channelized and natural pairs of headwater basins within the Upper Big Walnut Creek, Ohio, USA.

	Channelized: A	B	Natural: C	D
Size and shape characteristics:				
Drainage area (ha)	454	389	439	428
Mean basin slope (degrees)	0.24	0.29	0.41	0.42
Relief (m)	15.8	19.2	41.1	50.4
Total channel length (m)	677	1000	10212	6950
Surface drainage density (m ha^{-2})	1.5	2.6	23.3	16.2
Elongation (-)	0.77	0.68	0.59	0.52
Circularity (-)	0.59	0.54	0.52	0.37
Land-use classification:				
Urban (%)	0.1	0.1	0.2	0.1
Agriculture (%)	95.3	88.9	72.3	64.9
Shrub/scrub (%)	0.0	0.1	0.4	0.8
Wooded (%)	4.5	10.4	26.6	33.3
Wetland (%)	0.1	0.3	0.4	0.9
*Soil characteristics**:				
Amanda (%)	0.0	0.0	15.5	7.0
Bennington (%)	47.3	52.9	13.0	32.3
Centerburg (%)	6.5	0.9	0.0	0.0
Cardington (%)	0.0	0.0	53.2	36.7
Pewamo (%)	46.2	46.2	2.5	10.9

* **Soil taxonomy for each soil type:** Amanda: fine-loamy, mixed, mesic typic Hapludalfs; Bennington: fine, illitic, mesic aeric Epiaqualfs; Centerburg: fine-loamy, mixed, mesic aquic Hapludalfs; Cardington: fine, illitic, mesic aquic Hapludalfs; Pewamo: fine, mixed, mesic typic Argiaquolls.

sheds better represent natural drained systems. The dominant land use in each watershed was row-crop agriculture. Both channelized watersheds contained riparian zones, consisting mostly of herbaceous riparian vegetation and exhibit the straightened, over-enlarged, trapezoidal channel shape typical of agricultural drainage ditches in the midwestern USA. Both natural watersheds possessed forested riparian zones with sinuous channels and cross-sectional areas that would be expected (Urban & Rhoads, 2003) in the absence of channelization (Table 2). Channel length and thus surface drainage density (Table 1) was greater in the natural watersheds compared to the channelized watersheds (Fig. 2).

Table 2 Means (SD) of geomorphology characteristics*, channel roughness, and calculated discharge capacities from headwater streams and ditches within the Upper Big Walnut Creek watershed, 2005. Mean values in bold rows are significantly different ($P < 0.10$).

	Streams	Ditches	Difference (%)
Top bank width (m)	**4.05 (1.20)**	**8.91 (0.58)**	120
Bankfull wetted perimeter (m)	**4.61 (1.32)**	**9.88 (0.48)**	114
Thalweg depth (m)	**0.77 (0.24)**	**1.71 (0.25)**	122
Cross-section area (m^2)	**2.12 (1.24)**	**8.04 (1.48)**	279
Width-to-depth ratio	9.79 (1.26)	9.52 (3.19)	–3
Number of large woody debris	**2.00 (0.00)**	**0.00 (0.00)**	–100
Sinuosity	1.52 (0.18)	1.14 (0.20)	–25
Gradient	–0.42 (0.10)	–0.15 (0.08)	–64
Channel roughness †	0.045	0.095	111
Bankfull discharge ‡ (m^3 s^{-1})	**9.15 (7.71)**	**56.40 (3.11)**	516

* Obtained from measurements along six cross-sections in a 125-m reach located within 30 m of the flume.

† Channel roughness value was calculated using Cowan (1956) and represents roughness value used within stream types.

‡ Bankfull discharge was determined as the product of mean channel cross sectional area and mean velocity calculated as described in Manning (1895).

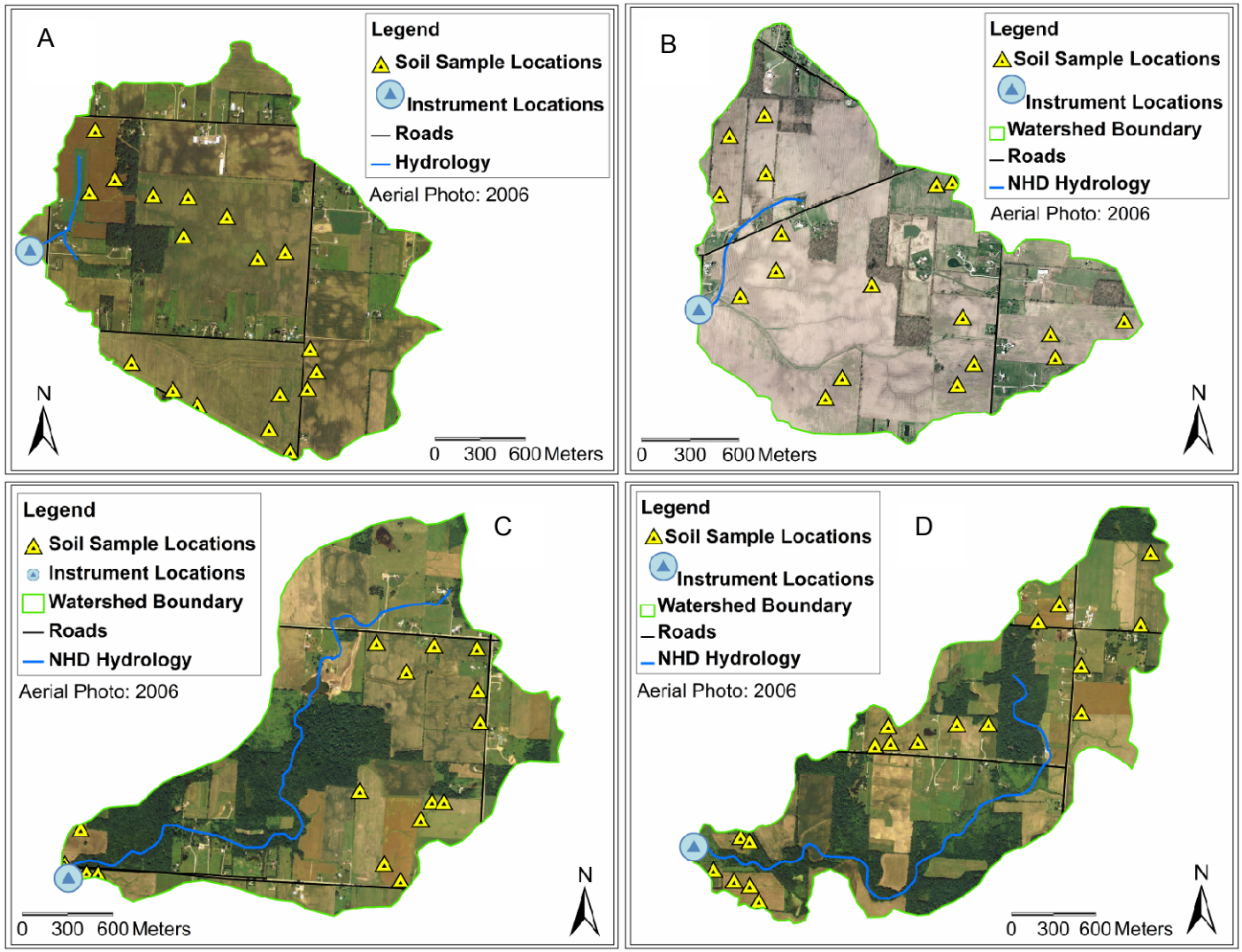

Fig. 2 Schematic of the four experimental basins (A–D) with streams, instrument locations, and soil sampling sites.

Data collection

Hydrology measurements were collected at the outlet of each headwater watershed from 1 January 2005 to 31 December 2006. The outlet of each headwater watershed was instrumented with a 2.4 m (8 ft) Parshall flume and an Isco 4230 bubbler for recording stage. Stage was recorded at 10-min intervals. Flume submergence or tailwater was a frequent occurrence because of the low gradient within the study streams. Thus, an Isco 2150 area velocity sensor was positioned in the centre of flow at the throat of the flume to measure mean velocities during the submergence periods. Discharge was calculated by developing a stage–discharge relationship for each flume using the stage and velocity measurements. The measured 10-min discharge values were aggregated to daily values for statistical analysis. Precipitation was measured with Isco 674 tipping bucket raingauges located adjacent to the flumes and recorded simultaneously with stage.

Hydrological indices and statistical analysis

Available hydrological data can generally be classified under one of five components: magnitude, frequency, duration, timing and rate of change (Poff *et al*., 1997). Magnitude data include indices such as central tendency flows, low flows and high flows, as well as peak flows. Frequency identifies a number of occurrences that a defined threshold is exceeded, while duration describes the length of time for each occurrence. Timing refers to the temporal cycles or periods often noticed with hydrological data. These patterns are usually seasonal (Simpson *et al*., 1982). Rate of change provides an indication of how a stream responds to a rainfall event (slowly or rapidly) and how long discharge from that event might be realized. While different from flashiness, rate of change indices, such as time to peak discharge and time to recession, also provide some insight into stream flashiness (Baker *et al*., 2004).

Sixteen hydrology indices representing a subset of the hydrological indices recommended by Olden & Poff (2002) were selected for this study to enable characterization of the magnitude, frequency, timing and rate of change of hydrology in channelized and natural headwater streams. The 16 variables were selected because they represent some of the most commonly used variables in describing hydrology, permitting direct comparison to similar studies. Nine magnitude indices (mean daily discharge, median daily discharge, minimum daily discharge, 10th, 25th, 75th and 90th percentile, maximum daily discharge and event peak discharge); two frequency indices (number of days of zero discharge and of bankfull discharge exceeded); and five rate-of-change indices (time to peak discharge, time-to-peak-discharge index, time to recession, time-to-recession index, and the Richards-Baker flashiness index, Baker *et al*., 2004) were calculated and investigated for a two-year period (Table 3). Daily values for the magnitude and frequency variables were summarized by month, resulting in 24 values for each variable from each basin. Timing and rate-of-change variables were calculated based on the measured 10-min records and were also summarized by month. Monthly values of precipitation were also calculated to assist with the interpretation of the hydrological responses and the potential influence of precipitation.

A three-factor analysis of variance (ANOVA) was conducted to detect differences in hydrology and precipitation between stream types (i.e. channelized and natural), among months, and between years on the hydrological indices. The SNK test was used for post-ANOVA comparison of differences in means. Only the results from the effects of stream type, the two-factor interaction effect of stream type × month, and the three-factor interaction effect of stream type × month × year were reported. The influence of temporal variation on hydrology is important; but the selective reporting of the results permits focus on the most important results for addressing the objective, and accounts for the potential influence of month or year on the effect of stream type. The assumptions of normality and equal variance were not met despite $\log x+1$ transformation. The three-factor ANOVA was conducted with rank-transformed values because a non-parametric analogue to the three-factor ANOVA was not available. Rank transformation is commonly recommended in these situations and its use with a parametric test results is the equivalent of a non-parametric three-factor ANOVA (Conover, 1999). All statistical analyses were conducted using SigmaStat 3.1 for Windows (Systat Software, 2004) and a significance level of $P < 0.05$.

Table 3 Calculation methods for monthly hydrological response variables used for this study.

Response variable	Formula
Magnitude:	
Average flows	
Mean daily discharge (m^3/s)	$\frac{1}{n}\sum_{j=1}^{n} Q_j$ where $Q_j = \sum_{i=10}^{1440} Q_i$
50th percentile of daily discharge (m^3/s)	median(Q_j; for $j = 1, \ldots, n$)
Low flows	
Minimum daily discharge (m^3/s)	minimum (Q_j ; for $j = 1, \ldots, n$)
10th percentile of daily discharge (m^3/s)	10th percentile (Q_j ; for $j = 1,\ldots, n$)
25th percentile of daily discharge (m^3/s)	25th percentile (Q_j ; for $j = 1,\ldots, n$)
High flows	
75th percentile of daily discharge (m^3/s)	75th percentile (Q_j ; for $j = 1,\ldots, n$)
90th percentile of daily discharge (m^3/s)	90th percentile (Q_j ; for $j = 1,\ldots, n$)
Maximum daily discharge (m^3/s)	maximum (Q_j ; for $j = 1,\ldots, n$)
Peak event discharge (m^3/s)	maximum (Q_{ij} ; for $i = 10$, 1440 and $j = 1,\ldots,$ # events)
Frequency:	
Number of days with zero discharge (days)	count ($Q_j = 0$)
Days discharge capacity is exceeded (days)	count ($Q_j \geq$ bankfull capacity)
Rate of change:	
Mean event time to peak discharge (min)	$\frac{1}{\#\text{events}} \sum_{i=1}^{\#\text{events}} t_{peak(i)}$
Mean time-to-peak index (-)	$\frac{1}{\#\text{events}} \sum_{i=1}^{\#\text{events}} \frac{t_{p(i)}}{\text{hydrograph duration}(i)}$
Mean event recession time (min)	$\frac{1}{\#\text{events}} \sum_{i=1}^{\#\text{events}} t_{recession(i)}$
Mean recession index (-)	$\frac{1}{\#\text{events}} \sum_{i=1}^{\#\text{events}} \frac{t_{recession(i)}}{\text{hydrograph duration}(i)}$
Richards-Baker flashiness index	$\frac{\sum_{i=1}^{y} \lvert q_i - q_{i-1} \rvert}{\sum_{i=1}^{y} q_i}$

n: number of days in month; Q_{ij}: discharge per time i, for event j; Q_j : daily discharge for day j;
y: time step of the hydrological record; and q_i: discharge for time step i.

RESULTS

Mean annual precipitation within the natural watersheds (928 mm in 2005; 988 mm in 2006) was greater than the channelized watersheds (830 mm in 2005; 908 mm in 2006). A significant ($P < 0.05$) three-way interaction effect (stream type × month × year) on precipitation was observed and indicated that the two-factor effect (stream type × month) differed among years. No difference in precipitation occurred between stream types during any month of 2005 (Table 4). Conversely, in 2006 precipitation was greater within the natural watersheds compared to the channelized watersheds in January, May and July 2006.

Fourteen of 16 response variables indicated an effect of stream type or an interaction effect (Table 5). Only 25th percentile of discharge exhibited a significant effect of stream type without any significant higher-order interaction effects (Table 5). Nine response variables (i.e. mean daily discharge, minimum daily discharge, 10th and 75th percentile discharge, mean peak discharge, frequency of zero discharge, Richards-Baker flashiness index, mean time to peak, and mean

Table 4 Mean monthly precipitation (standard deviation) results from three-factor ANOVA (stream type × month × year). Values in bold rows are significantly different ($P < 0.05$).

Time period	Natural streams (mm)	Channelized streams (mm)
2005	79.9 (51.3)	72.4 (55.8)
Jan 2006	**87.2 (1.0)**	**62.7 (0.0)**
May 2006	**115.6 (0.0)**	**72.3 (12.4)**
July 2006	**253.0 (4.7)**	**101.5 (14.9)**

Table 5 Values of *P* from three-factor ANOVA conducted to determine the effect of stream type (ST), month (MO) and year (YR) on the hydrology of channelized and natural headwater streams in the Upper Big Walnut Creek basin, Ohio, 2005–2006. Bold values are those < 0.05.

Response variable	ST	ST × MO	ST × MO × YR
Magnitude:			
Average flows			
Mean daily discharge (m^3/s)	**0.041**	**0.004**	0.185
50th percentile of daily discharge (m^3/s)	0.289	0.283	0.832
Low flows			
Minimum daily discharge (m^3/s)	**<0.001**	**0.049**	0.861
10th percentile of daily discharge (m^3/s)	**0.008**	**0.044**	0.853
25th percentile of daily discharge (m^3/s)	**0.020**	0.141	0.910
High flows			
75th percentile of daily discharge (m^3/s)	0.549	**0.002**	0.161
90th percentile of daily discharge (m^3/s)	0.878	0.086	0.454
Maximum daily discharge (m^3/s)	**0.008**	**<0.001**	0.002
Mean peak discharge (m^3/s)	**0.039**	**0.004**	0.114
Frequency:			
Frequency discharge = 0 (days)	**<0.001**	**<0.001**	0.882
Frequency discharge > bankfull (days)	**<0.001**	0.301	0.042
Rate of change:			
Richards-Baker flashiness index	0.840	**0.004**	0.257
Mean time to peak (min)	0.317	**0.045**	0.300
Mean time-to-peak index (-)	**<0.001**	**0.013**	0.048
Mean time to recession (min)	0.082	0.065	0.120
Mean recession index (-)	**0.001**	**0.016**	0.682

recession time) exhibited a significant two-factor interaction effect (stream type × month) (Table 5). Additionally, maximum daily discharge, frequency of above-bankfull discharge and mean time-to-peak index exhibited significant three-factor effects (Table 5).

Magnitude variables

Mean daily discharge in channelized streams (0.070 m^3/s) was significantly less ($P < 0.05$) than mean daily discharge in natural streams (0.075 m^3/s). Mean daily discharge by month ranged from 0.0007 to 0.314 m^3/s in the channelized streams and from 0.001 to 0.486 m^3/s in the natural streams (Fig. 3). The greatest mean daily discharge was observed in January 2005 for channelized and natural streams. The minimum mean daily discharge rate was observed during July 2005 for the channelized streams, while the minimum mean daily discharge was recorded during August and September 2006 for the natural streams (Fig. 4). Mean daily discharge was greater ($P < 0.05$) in natural streams compared to channelized streams in July, but was greater ($P < 0.05$) in channelized streams compared to natural streams in August and September (Fig. 4; Table 5). No differences in mean daily discharge occurred between stream types during the other months.

Median daily discharge by month ranged from 0.0 to 0.071 m^3/s in the channelized streams and 0.0 to 0.295 m^3/s in the natural streams. Median monthly discharge was 0.024 m^3/s for

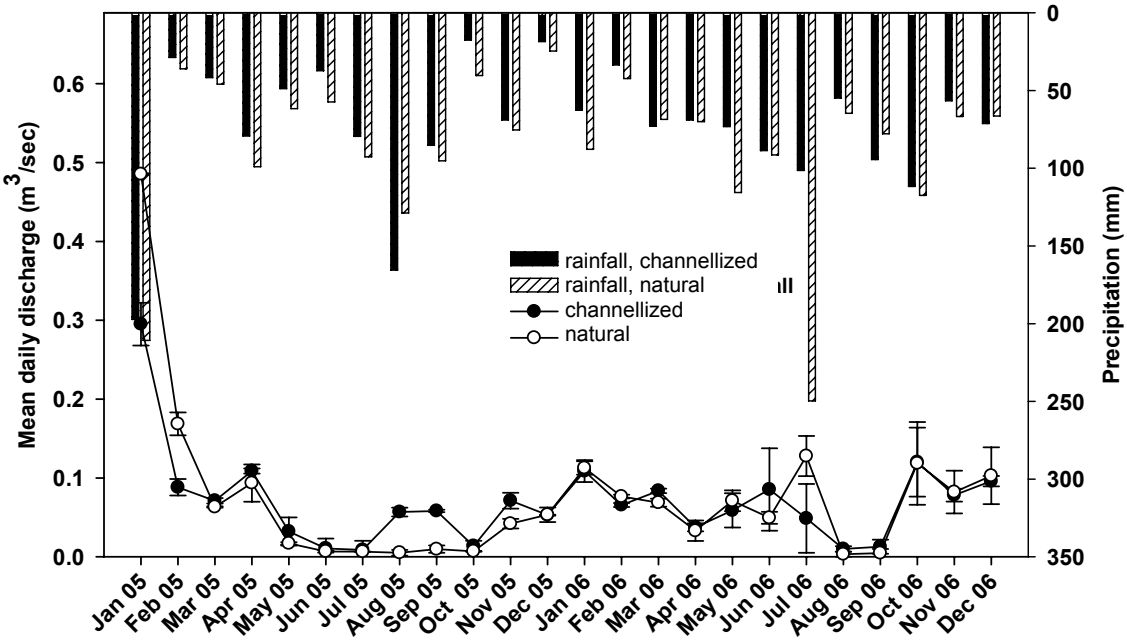

Fig. 3 Mean daily discharge and rainfall for two channelized and two natural streams in Upper Big Walnut Creek basin in Ohio, for the period January 2005–December 2006.

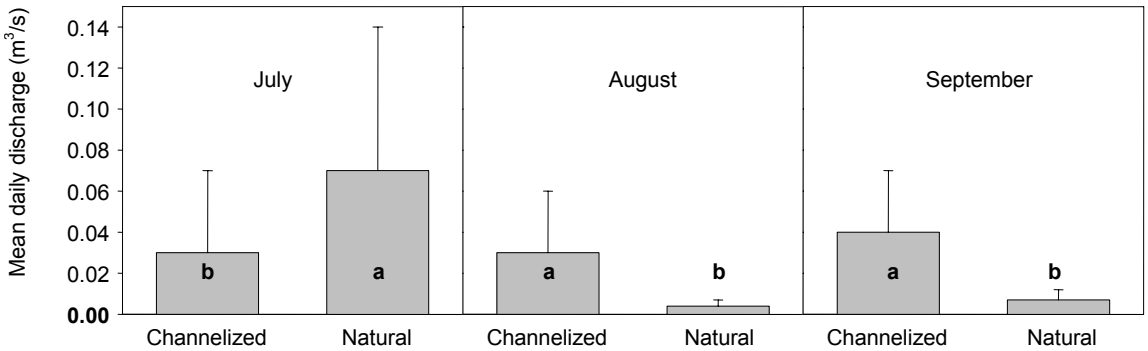

Fig. 4 Mean and standard deviation of daily discharge in channelized and natural headwater streams in the Upper Big Walnut Creek basin in July, August and September. Differences in this response variable only occurred during these three months in both 2005 and 2006.

the channelized streams and 0.035 m^3/s for the natural streams. Median discharge did not exhibit a significant effect of stream type, stream type × month, or stream type × month × year.

Minimum daily discharge was significantly greater ($P < 0.05$) in the channelized streams (0.0104 m^3/s) compared to the natural streams (0.0098 m^3/s). Measurements for the 10th and 25th percentile discharge were significantly less ($P < 0.05$) in the channelized streams than the natural streams. Minimum daily discharge and 10th percentile discharge exhibited a significant ($P < 0.05$) two-factor interaction effect (Table 5; Fig. 5). Minimum daily discharge was greater ($P < 0.05$) in channelized than natural streams in June and July; no differences between stream types occurred in the other months (Fig. 5). The 10th percentile discharge was greater ($P < 0.05$) in channelized *vs* natural streams in June; no differences occurred in other months (Fig. 5). The 25th percentile flows in the channelized streams were significantly ($P < 0.05$) less than those of the natural streams. No two- or three-factor interaction effects were noted with the 25th percentile discharges.

Maximum mean daily discharge in the channelized streams (0.56 m^3/s) was significantly greater ($P < 0.05$) than maximum mean daily discharge in the natural streams (0.50 m^3/s). The

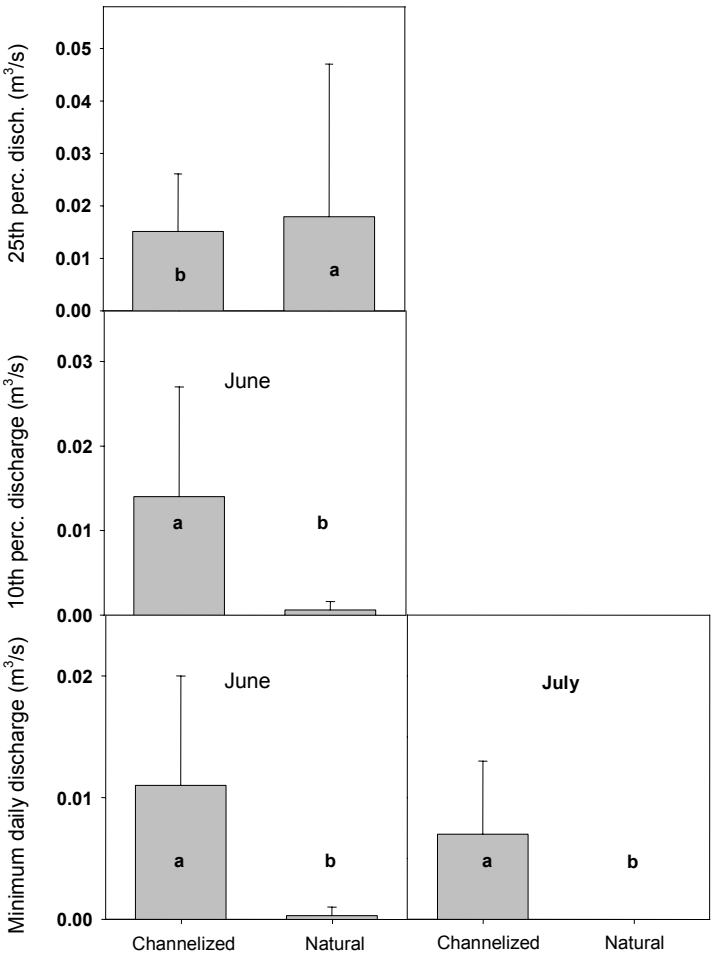

Fig. 5 Mean and standard deviation of low-flow response variables in channelized and natural headwater streams in the Upper Big Walnut Creek basin.

75th percentile discharge was greater ($P < 0.05$) in natural streams compared to channelized streams in July, but in September the opposite trend occurred (Fig. 6). A significant ($P < 0.05$) three-factor interaction effect was observed for maximum daily discharge which indicates that the interaction effect of stream type × month was significant in 2005, but not 2006. Maximum daily discharge was greater ($P < 0.05$) in channelized streams than natural streams in August and September 2005 (Fig. 6); no differences between stream types occurred during the other months of 2005 or 2006.

Mean monthly peak discharge in channelized streams was 0.51 m^3/s compared to 0.44 m^3/s in natural streams. Maximum mean monthly peak discharge for both stream types was measured in January 2005. Maximum mean monthly peak discharge in the channelized streams was 1.98 m^3/s compared to 2.25 m^3/s in the natural streams. Significant ($P < 0.05$) differences in mean monthly peak discharges were observed in April, July, August, September and November (Table 5; Fig. 6). Monthly mean event peak discharge was significantly ($P < 0.05$) greater in the channelized streams in April, August, September and November compared to the natural streams. However, peak discharge in July was greater ($P < 0.0$) in the natural streams compared to the channelized streams (Fig. 6).

Frequency variables

Mean annual number of days with zero discharge occurred more often in natural streams (87.5 days) compared to channelized streams (8 days). Significant ($P < 0.05$) differences between stream

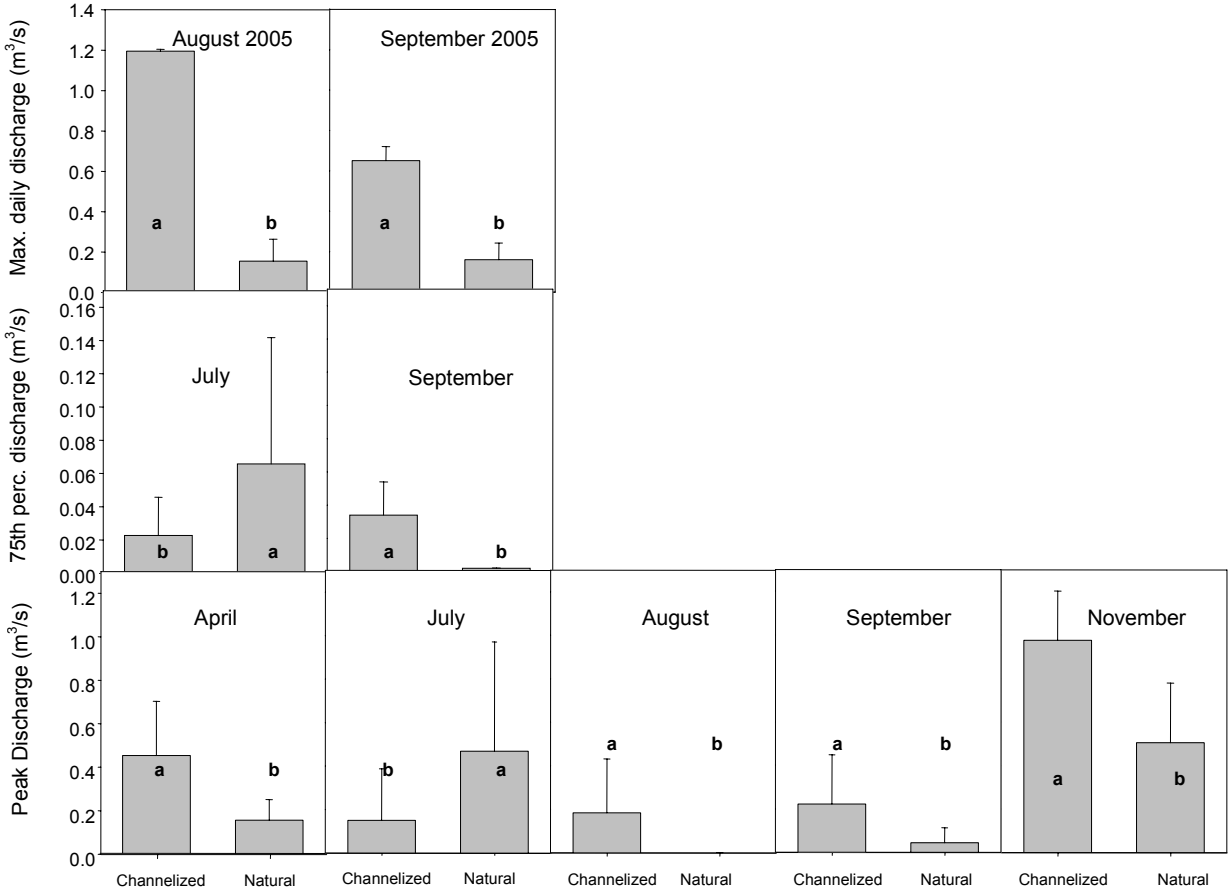

Fig. 6 Mean and standard deviation of high flow response variables in channelized and natural headwater streams in the Upper Big Walnut Creek basin. Differences in this response variable only occurred during these time periods.

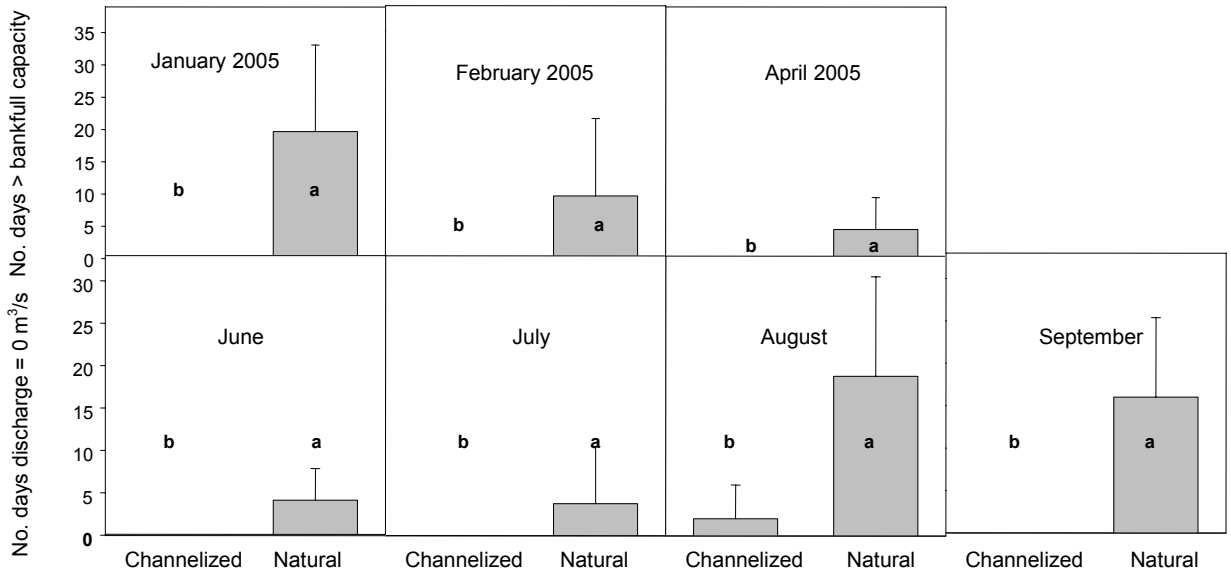

Fig. 7 Mean and standard deviation of frequency response variables in channelized and natural headwater streams in the Upper Big Walnut Creek basin.

types in number of days with zero discharge per month occurred in the late spring and summer months of June, July, August, and September (Fig. 7). The maximum number of days with zero discharge (24.5 days) was measured in August 2005. Similarly, the average annual number of days that bankfull capacity was exceeded was significantly greater in the natural streams (80 days) compared to the natural streams (0 days). Significant ($P < 0.05$) differences between stream types in monthly bankfull exceedence days were noted in the winter and early spring months of January, February and April 2005 (Fig. 7).

Rate-of-change variables

Mean time to peak was greater ($P < 0.05$) in natural streams compared to channelized streams only during March (Fig. 8), by approximately one day. Similarly, mean time-to-peak index was greater ($P < 0.05$) in natural streams compared to channelized streams in August and October 2005, but not for the other months of 2005 or 2006 (Fig. 8). Mean time-to-recession index indicated that recession time was greater ($P < 0.05$) in channelized streams compared to natural streams in August and November. No significant differences were noted between stream types for actual time to recession. Flashiness as measured by the Richards-Baker index (Baker *et al*., 2004) was greater ($P < 0.05$) in natural streams compared to channelized streams only in August and September. No flashiness differences were measured in other months.

DISCUSSION

The paradigm that is often accepted for headwater hydrology (Shields & Cooper, 1994) with respect to magnitude, frequency, and rate of change parameters is that natural sinuous channels when compared to channelized streams are characterized by: (a) discharge magnitudes (average, low and high) that are generally less; (b) more frequent flooding (out-of-bank flows) and more periods of zero discharge; and (c) hydrographs that illustrate a slower response to rainfall and longer recession limbs. The response variables used in this study were selected to compare and contrast two instrumented channelized and natural agricultural headwater streams to the accepted paradigm for hydrology of headwater streams.

Magnitude

Magnitude of flows for headwater streams in UBWC both support and contrast the accepted paradigm and were dependent on level of discharge magnitude being evaluated. Low flows, represented by minimum daily discharge and 10th percentile discharge, were greater in the channelized streams compared to the natural streams, and this is consistent with other findings (Fig. 5). However, these differences were only observed in the late spring and early summer months of June and July, suggesting a seasonal pattern (Smakhtin, 2001). A similar seasonal pattern was noted for low flows in natural streams in North Carolina, USA (Rheinhardt *et al*., 1999). This finding also implies that the entrenchment of channelized streams may result in a more pronounced hydrological connection to the groundwater than the natural streams (Williams & Hynes, 1977). A similar suggestion was made for channelized streams in Wisconsin (Vadas *et al*., 2007). Additionally, the measured differences in low flows might also be a result of greater evapotranspiration within the natural streams due to differences in riparian vegetation between stream types (Smakhtin, 2001). Greater ($P < 0.05$) amounts of canopy cover and woody vegetation were measured in the natural streams compared to the channelized streams. Investigation of June and July rainfall did not provide additional insights for the measured differences in low flows between stream types. Furthermore, with the exception of June 2005, measured rainfall within the natural streams was significantly ($P < 0.05$) greater than the channelized streams, yet low flow indices were greater ($P < 0.05$) in the channelized streams. Differences in low flows suggest that channelization affects baseflow hydrology through interaction with groundwater. Investigation of the slope and relief of the streams further supports this theory. Slopes and relief in the natural streams are greater compared to the channelized streams. The smaller slopes and less relief in the

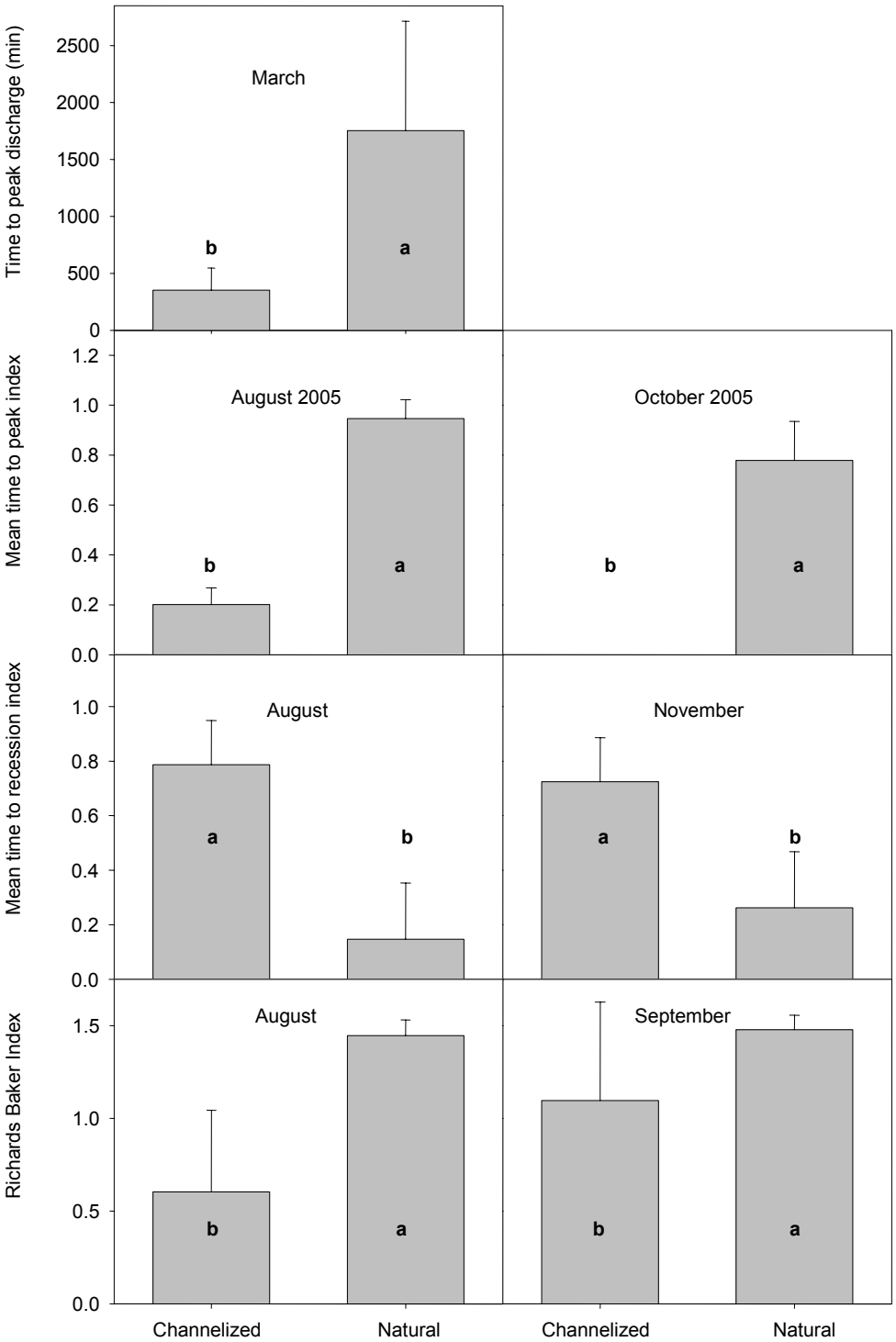

Fig. 8 Mean and standard deviation of rate of change response variables in channelized and natural headwater streams in the Upper Big Walnut Creek basin in July, August, and September. Differences in this response variable only occurred during these time periods.

channelized streams would permit interaction with groundwater (Williams & Hynes, 1977) when that water table was high. Similar findings were suggested by Astrom *et al*. (2001) for streams in Finland.

Average flows indicated by mean and median daily discharge did not provide consistent trends with respect to the accepted paradigm or findings with other studies. Mean daily discharge

was greater in the natural streams in July but the opposite occurred in August and September (Fig. 4). The unexpected July results may be due to differences in precipitation between stream types. Greater precipitation ($P < 0.05$) was measured in the natural streams in July (93.5 mm in 2005; 253 mm in 2006) compared to channelized streams (79.5 mm in 2005; 101.5 mm in 2006). The precipitation difference in July was the result of a summertime convective thunderstorm that developed and remained over the natural watersheds. Despite the differences in precipitation, the increased mean daily discharge for channelized streams compared to natural streams during August and September followed the paradigm and was consistent with discharge patterns in Ireland streams following channelization (Essery & Wilcock, 1990).

A similar inconsistent pattern was also noted with high flow indices of maximum daily discharge and 75th percentile discharge. Significant increases in maximum daily discharge from the channelized streams only occurred in August and September 2005. No significant differences in precipitation were measured during that period. The results of the 75th percentile discharge were consistent with mean daily discharge results from this study. Specifically, 75th percentile discharge in July was greater from the natural streams compared to the channelized streams. Again, this result was attributed to the significant difference in measured rainfall between the channelized and natural streams.

Peak discharge was expected to be greater in the channelized streams (Dybvig & Hart, 1977; Dunn & Mackay, 1996). Results from this study support the paradigm for the months of April, August, September and November. In July, peak discharge was greater in the natural streams, again a result of significantly greater precipitation in the natural streams. Differences in mean monthly event peak discharges ranged from 90% to more than 3500% greater in the channelized streams compared to the natural streams, although most increases were less than 400%. The largest differences were measured in August when the flows in the natural streams were already suppressed. The results here are considerably greater than the 18% increase in peak flow following channelization reported by Dybvig & Hart (1977), but were more consistent with the 90-190% increases documented by Brookes (1988).

Frequency

Frequency assessment of extreme flow measures such as zero-discharge days and bankfull-exceedence days supported the paradigm and were consistent with other studies (Simpson *et al*., 1982; Rheinhardt *et al*., 1999). As expected, the number of days of zero discharge was greatest in the natural streams during the late spring and summer. These hydrology differences occurred despite greater precipitation in the natural streams compared to the channelized streams. This result mirrored a similar finding by Rheinhardt *et al*. (1999), in which they noted natural streams in North Carolina, USA, frequently dried completely during the summer months. Minimal days of zero discharge in channelized streams suggest that channelized streams may have a more pronounced hydrological connection to the groundwater. As was the case with low flow magnitudes, this suggests that an efficient hydrological connectivity with the groundwater may exist (Astrom *et al*., 2001; Vadas *et al*., 2007), due to low slopes and minimal relief. The results from this study were also consistent with findings reviewed and reported by Simpson *et al*. (1982), who recorded frequent periods of zero flow in natural streams compared to continuous flow in channelized streams.

The results from this study also confirm the expectation that flooding will occur more frequently in natural streams. Due to over-enlarged construction and deep incision, exceedence of bankfull flow in channelized streams is rare (Royer *et al*., 2004). The bankfull capacity of natural streams in the UBWC is much less than the channelized streams (Table 2). The results of the number of days that bankfull capacity was exceeded support this facet of the paradigm. Bankfull exceedence was primarily observed in winter (January and February) and early spring (April) but only during 2005. During each of these months, precipitation on the natural watersheds was greater than the rainfall on channelized watersheds, but was only significant ($P < 0.05$) for January. No out-of-bank flows were observed in the channelized streams. These results suggest that the natural streams within the UBWC watershed have a greater connectivity with the flood

plain and this increased connectivity may contribute to potential differences in biogeochemical processing and community structure between stream types. The bankfull capacity results from this study were consistent with studies in Mississippi (Shields & Cooper, 1994), North Carolina (Rheinhardt *et al*., 1999) and Ohio (Powell *et al*., 2007), but contradicted the suggestion that channelization may increase the frequency of out-of-bank flows (Swales, 1982).

Rate-of-change variables

Rate-of-change variables generally support the expectation that natural streams respond more slowly to rainfall. Increasing rate of change variables such as mean monthly time to peak discharge and time-to-peak-discharge index exhibit patterns which support this concept (channelized streams < natural streams. For widespread rainfall events where direct comparisons could be made, time to peak discharge from the natural streams lagged that of the channelized streams by approximately 300 min. The measured difference within the UBWC is substantially greater than the 10 to 20 min suggested by Moussa *et al*. (2002), but similar to the 240-min increase in time to peak discharge noted by Spaling (1995).

Investigation of the time of recession and time-of-recession index on the headwater streams of UBWC watershed contradict the suggestion that natural streams will have a greater time of recession when compared to channelized streams. Mean monthly event time to recession was approximately 400 min less in the natural streams compared to the channelized streams. Significant differences were noted in August and November. Precipitation was greater in the natural streams in 2005 and no differences were noted between stream types in 2006. However, the recession limbs of the hydrographs for natural streams were significantly less than the channelized streams, despite the differences in rainfall. The longer recession limbs for channelized streams were attributed to the greater extent of subsurface tile drainage in these watersheds compared to those watersheds of the natural streams. The presence of tile drainage has been noted to extend the recession limbs (Black, 1996).

Differences in time to peak discharge and time of recession along with the greater number of bank full exceedence days and greater number of zero discharge days would imply a greater flashiness in the natural streams. However, differences in the Richards-Baker index (Baker *et al*., 2004) between stream types occurred only in late summer (August and September), when the greatest number of days of zero discharge were observed in the natural streams. Both stream types are considered flashy streams (Royer *et al*., 2004; Schaller *et al*., 2004); however, the results from this study suggest the natural headwater streams are flashier than channelized headwater streams.

To illustrate these findings, an investigation of a single event that occurred in November 2005 was conducted (Fig. 9). Peak discharge was approximately 50% greater in the channelized stream (0.62 m^3/s) compared to the natural stream (0.41 m^3/s), and time to peak discharge occurred 300 min quicker in the channelized system (channelized t_{peak} = 350 min *vs* natural t_{peak} = 650 min). For each of these parameters, the trends between channelized and natural streams were consistent with published findings. However, as previously noted, time of recession was significantly greater in the channelized stream (8750 min) compared to the natural stream (5280 min). The greater time of recession in the channelized streams was attributed to extensive subsurface tile drainage in the channelized watersheds. Dimensionless indices for time to peak and time to recession followed the same trends.

Stream hydrology management

Landowner/operator management of channelized headwater streams in the midwestern USA generally focuses on removal of excess water from agricultural fields without consideration of the effects of these practices on other components of these small streams. The results from this study indicate that this management approach has altered the hydrology of these headwater streams. Conservation practices that cause reductions of flow in the summer and in the winter within the channelized streams may alter the hydrology such that it more closely mimics natural streams. Specifically, reduction of low flows in summer may reduce downstream transport of nutrients and

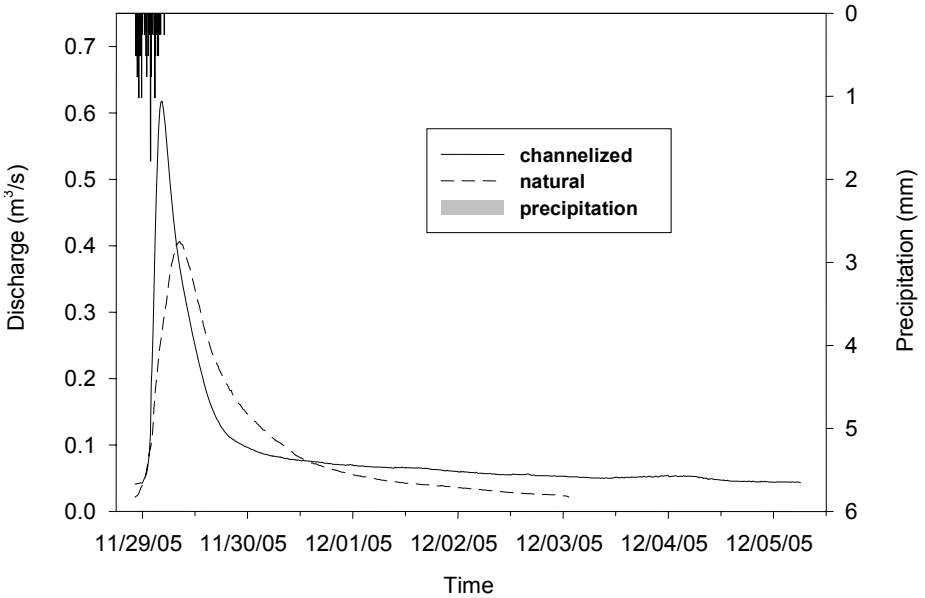

Fig. 9 Channelized and natural hydrographs resulting from an 18.0 mm precipitation event that occurred on 28 November 2005 (11/28/2005). The duration of the hydrograph was determined as the time difference between rainfall initiation and the first point when the discharge rate on the receding limb was within 5% of the discharge rate measured at the beginning of the precipitation event.

chemicals and benefit the biota through mimicking of the flow regime of natural streams. Reduction of high flows in the winter may reduce the impacts of winter flooding on the stream biota.

One potential practice that shows promise in altering the hydrology of channelized streams is drainage water management (Zucker & Brown, 1998), because it involves closing the drains during summer and winter months when hydrological differences between stream types are most apparent. Drainage water management, while effective at reducing nutrient transport from subsurface drainage, may also affect nutrient attenuation in the stream by reducing the flows.

Those practices that alter the hydrology of headwater streams, especially the depth and velocity of flow may adversely affect the ability of the streams to assimilate nutrients (Burns, 1998). Peterson *et al.* (2001) reported that more than 50% of inorganic nitrogen inputs were assimilated in headwater streams, a value confirmed by Kroger *et al.* (2007) in Mississippi agricultural drainage ditches. Streams with low flow volumes and discharge rates generally have greater capacity for pollutant attenuation (Vallett *et al.*, 1996). In vegetated headwater streams, where flow velocity and thus discharge rate is reduced, substantial amounts of nitrate attenuation have been documented (Cooper & Cooke, 1984).

Headwater streams serve as a unique habitat for an array of biological organisms, because of the physical diversity that is created by the juncture of aquatic and terrestrial ecosystems within these lotic ecosystems (Sabo *et al.*, 2005). The unique combination of damp soils, humid air, low temperatures, diffuse light and organic matter create optimal conditions for certain aquatic and terrestrial species to flourish. The biological communities of headwater streams are shaped by their habitat (Southwood, 1988). For example, insect richness and abundance present in intermittent headwater streams surpass those found in similar perennial streams (Feminella, 1996; Dieterich & Anderson, 2000). However, the specialized species of both plants and animals face greater probabilities of localized extinction due to periodic disconnection from flowing water (Fagan, 2002). In channelized streams, agricultural management practices such as water-table management, that promote wetter conditions during certain portions of the year, may influence the aquatic ecology of headwater streams.

Comprehensive research is needed that includes interactions between hydrology, water quality and ecological assessments on headwater streams. Future studies need to evaluate whether imple-

mentation of drainage water management or other practices within channelized streams can alter the hydrology so that it more closely resembles that of natural streams. Furthermore, these assessments should consider the hydrological impacts on the biogeochemical processes that occur in headwater streams.

SUMMARY AND CONCLUSIONS

Hydrological data were collected from two channelized and two natural headwater streams in UBWC watershed from 1 January 2005 to 31 December 2006. The study was designed to compare the hydrology of channelized and natural headwater streams and determine consistency with the accepted paradigm for headwater streams, namely that natural sinuous channels when compared to channelized streams are characterized by: (a) smaller discharge magnitudes (average, low and high), (b) more frequent flooding (out-of-bank flows) and more periods of zero discharge, and (c) discharge hydrographs that respond slower to rainfall and have longer recession limbs. Sixteen response variables selected to provide information on the magnitude, frequency and hydrological rate of change were calculated. The data from this two-year study suggest that:

- magnitude of discharges is generally greater in channelized streams compared to the natural streams;
- natural streams have more frequent periods of zero discharge compared to channelized streams;
- natural streams have more frequent periods when bankfull capacity discharge is exceeded than channelized streams;
- time to peak discharge was much quicker in the channelized streams compared to the natural streams;
- time to recession was greater in the channelized streams compared to the natural streams; and
- natural streams exhibited an overall greater flashiness compared to the channelized streams.

The measured differences in hydrology were not realized throughout the year but were observed only during certain periods of the year, primarily the summer (low flow periods) and winter (wetter periods). The differences were attributed to stream type, subsurface drainage, potential connectivity to groundwater, and evapotranspiration as affected by riparian vegetation. With the exception of recession time, all other contradictions to the accepted paradigm reported in the present study could be explained by precipitation differences between channelized and natural streams.

Based on the results from this study, it can be concluded that channelized streams possess a different hydrology compared to natural streams; however, these differences occur only during certain periods of the year. It can also be concluded that the headwater streams of the UBWC watershed generally follow the accepted hydrology paradigm for headwater streams. The only contradiction to the paradigm was recession times of storm hydrographs of channelized streams. The longer recession times were attributed to an extensive network of subsurface tile drainage. Additional studies across a broad range of climates with various topographic features would further strengthen the paradigm.

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