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Range of variability of channel complexity in urban, restored and forested reference streams

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SUMMARY

1. Channel complexity is an important ecological property of stream systems and is often targeted for restoration in channelised urban streams. However, channel complexity is rarely defined explicitly, and little research on channel complexity has been conducted in streams in urban catchments that have not been directly channelised by human activities. Therefore, it remains unclear whether restoration of non-channelised urban streams has improved complexity.
2. We explicitly define channel complexity and use a multimetric approach to provide a comprehensive assessment of complexity in multiple restored, urban and forested streams on the Maryland Coastal Plain and two streams of differing land use in Colorado. We also expand on the Maryland and Colorado results with a literature survey of channel complexity from diverse geographical regions.
3. Many streams draining urban catchments in Maryland had relatively high values of some complexity metrics compared to forested reference streams in Maryland and compared to the values for pristine streams calculated from the literature. This suggests that streams in urban catchments that are not directly manipulated by human activities (e.g. channelisation or piping) may be able to maintain channel structures beneficial for aquatic organisms even when impervious surfaces are the dominant form of land use in the catchment.
4. Restored streams in Maryland had equal or lower values of many complexity metrics compared to streams draining urban catchments in Maryland. This suggests that restoration of streams draining urban catchments did not improve the overall channel complexity.
5. Our results highlight the need to explicitly define and measure the attributes of channel complexity that are targeted during restoration, to determine whether the streams in urban catchments are truly degraded with respect to channel complexity.
6. Combined with recent synthesis work suggesting that biodiversity may not be improved by increasing the channel complexity, these results indicate that targeting catchment processes may prove a more useful approach to restoration than attempting to move channel complexity in streams draining urban catchments towards conditions in forested reference streams.

Keywords: channel complexity, channel morphology, geomorphic survey, restoration, urbanisation

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Introduction

While stream and river restoration has been dramatically influenced by hydrogeomorphic theory (Palmer & Bernhardt, 2006), ecological theory has also played a role, particularly in terms of the interactions of physical processes with ecological processes and biotic communities. One prominent example comes from theory on the importance of physical heterogeneity in structuring and sustaining ecological systems (Levin & Paine, 1974; Winemiller, Flecker & Hoeinghaus, 2010). In streams, spatial heterogeneity in geomorphology is widely known to interact with flow dynamics to create diverse habitat patches (Palmer, Ambrose & Poff, 1997; Lake, 2000) that, in turn, may influence species diversity and ecological resilience in the face of disturbances such as floods (Townsend, 1989; Hildrew & Giller, 1994). Heterogeneity has received much attention in stream management because it seems more tractable to influence physical structure than the many other factors believed to support productive and diverse ecosystems (Palmer *et al.*, 1997; Palmer, Menninger & Bernhardt, 2010). In fact, central to many stream restoration efforts is the assumption that rehabilitation of physical habitat heterogeneity will lead to the restoration of biological communities (Palmer *et al.*, 1997; Spänhoff & Arle, 2007; Violin *et al.*, 2011).

Various concepts have been used to explore physical heterogeneity in streams, including ones that focus on measurements intended to characterise channel complexity based on reach-scale geomorphic attributes. It is widely assumed that channel complexity plays a critical role in maintaining stream ecosystem structure and function, and studies have shown that channel simplification can lead to reduced diversity and abundance of fish and macroinvertebrates (Jungwirth, Moog & Muhar, 1993; Laasonen, Muotka & Kivijarvi, 1998; Muotka & Syrjänen, 2007), reduced hydraulic retention (Gooseff, Hall & Tank, 2007) and reduced retention of organic matter and nutrients (Muotka & Laasonen, 2002; Grimm *et al.*, 2005; Sheldon & Thoms, 2006; Bukaveckas, 2007). One of the most commonly cited impacts of urban development is the loss of channel complexity owing to more frequent erosive floods that can cause channel incision and bank erosion (Walsh *et al.*, 2005). Additionally, streams are often piped, straightened, channelised or otherwise intentionally simplified for various purposes during catchment urbanisation (Arnold, Boison & Patton, 1982; Ramírez *et al.*, 2009).

Given the evidence that physical complexity is ecologically important, increasing channel complexity has often been the goal of stream restoration (Brookes, Knight & Shields, 1996; Bernhardt *et al.*, 2005; Katz *et al.*, 2007). Many restoration projects on channelised streams have involved increasing substratum, depth, and flow variability (e.g. Jungwirth *et al.*, 1993; Muotka & Laasonen, 2002; Pretty *et al.*, 2003; Bukaveckas, 2007). Only a few studies have evaluated the effects of restoration on channel complexity in streams that have not been deliberately channelised, such as those in urban catchments assumed to be geomorphically simplified by altered flow regimes. While these studies have used various methods for estimating channel complexity, it is clear that restoration does not always increase physical complexity (Larson, Booth & Morley, 2001; Tompkins & Kondolf, 2007; Tullos *et al.*, 2009; Violin *et al.*, 2011).

Even beyond the restoration literature, channel complexity has rarely been defined explicitly and has been measured in different ways depending on the objectives of each study. Some authors have implicitly defined channel complexity as essentially equivalent to hydraulic retention (Grimm *et al.*, 2005; Bernot *et al.*, 2006). Gooseff *et al.* (2007) found that hydraulic retention was correlated with channel complexity, measured using a multimetric index based on slope, longitudinal roughness and sinuosity. Sheldon & Thoms (2006) devised the measures of complexity based on cross-section profile variability and related these measures to the storage of organic matter. Others have used channel complexity to refer to the quality of in-channel habitat, defining streams with large amounts of instream wood, multiple habitat types (pools, riffles, runs, etc.) and large pool volumes as being more complex than channels with flat-bed profiles lacking instream wood (Roper & Scarnecchia, 1995; Schmetterling & Pierce, 1999; Kaufmann *et al.*, 2008; Tullos *et al.*, 2009). The latter definition has also been referred to as habitat heterogeneity, habitat complexity and habitat diversity (Gorman & Karr, 1978; Schlosser, 1982; Shields, Knight & Cooper, 1998; Milner *et al.*, 2008; Violin *et al.*, 2011). These terms are often used loosely and interchangeably to describe either spatial or temporal variability in channel physical features or structures.

We argue that there is a need to be more explicit about how channel complexity is measured and why different aspects of complexity may be more or less emphasised depending on the ecological attribute of interest. This is particularly important in a restoration context because project designs may target different physical aspects of complexity, depending on the goal of the project. Our objectives were to (i) generate a comprehensive measure of channel complexity using a multivariate statistical approach, (ii) use this measure to determine whether different components of channel complexity vary across a

catchment urbanisation gradient, (iii) determine whether these complexity components respond similarly to restoration interventions and (iv) assess the range in channel complexity over a broader geographical area than our study sites. Previous research has generally found indicators of complexity to be lower in non-channelised streams in urban catchments compared to streams in natural reference condition (Pizzuto, Hession & McBride, 2000; Reid, Gregory & Brierley, 2008; Cookson & Schorr, 2009; Violin *et al.*, 2011), and many restoration projects focus on enhancing the channel complexity (Brookes *et al.*, 1996; Bernhardt *et al.*, 2005; Katz *et al.*, 2007). Thus, our null hypothesis was that streams in more urbanised catchments would exhibit the lowest levels of complexity and that, following restoration, each component of complexity would increase relative to non-restored control streams in urban catchments.

Methods

Study sites

We gathered geomorphic data on multiple streams in forested and urban catchments and also on restored streams in urban catchments, all located in the Coastal Plain physiographic province of Maryland (U.S.A). To provide a broader geographic context for the range of variability in complexity observed in Maryland streams, we compared Maryland streams with streams surveyed with the same methodology in the plains and Front Range Mountains of northern Colorado. We also expanded the geographic context by collecting channel complexity values available in the literature for streams across diverse regions.

We surveyed 26 first- or second-order streams in Anne Arundel County Maryland (N 39°03′00″, W 76°37′00″), including nine restored streams (Fig. 1). Although Anne Arundel County is contained entirely within the Coastal Plain physiographic province, it is further subdivided into the Glen Burnie rolling upland district in the northern part of the county and the similar but somewhat more dissected Crownsville Upland District in the central and southern parts of the county (Reger & Cleaves, 2008; Fig. 1). In addition, sediments in the central region of the county are of Tertiary origin and are primarily composed of glauconitic fine to medium sand and silts (Mack, 1962; Glaser, 1968). Sediments in the northern regions of the county are of Cretaceous origin and are also composed primarily of sand, silts and clays, but contain more gravel than southern formations (Mack, 1962; Glaser, 1968).

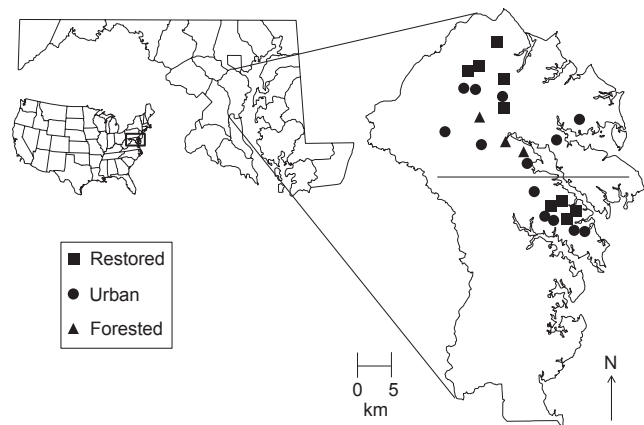All restoration projects were stability restoration projects, involving a combination of channel manipulation

Fig. 1 Map of Anne Arundel County, Maryland, showing the location of study sites. The line across the map separates northern from southern streams.

and bank stabilisation activities, all performed with heavy machinery (Fig. 2). At each restored site, banks were graded and backfilled to achieve designed cross-section profiles, and boulders and large logs were added along several banks at each site to help deflect high flow away from the banks and stabilise cross-section morphology. In addition, the channel at each site was reconstructed to achieve a designed slope profile, which was stabilised by different combinations of rock vanes, rock weirs, rip-rap and log weirs at the different sites.

For each of the study streams, catchment area (0.06–3.8 km^2) and land use were determined using GISHydro2000, an ArcView GIS-based software package developed to aid in hydrological analyses in Maryland

Fig. 2 Photograph showing a representative restored stream, located in northern Anne Arundel County, Maryland. Large boulders have been placed on the channel banks to prevent bank erosion and have been placed in the channel to prevent channel incision.

(Moglen, 2007). The application uses 30-m resolution digital elevation models (DEMs) to delineate catchments and has land-use data current to 2002. The percentage of riparian area occupied by impervious surface along each study reach was measured using Google Earth (Google Inc., Mountain View, CA, U.S.A). Each stream was traced manually on satellite images, and all impervious surfaces within 30 m of the stream were delineated and tabulated.

Land use in the catchments was predominantly a mixture of forest and urban development. Agricultural land use was variable, but did not exceed 34% in any single catchment. Restored streams were all located in catchments with more than 30% impervious surface cover. The other 16 streams were located in catchments spanning a range of development, from 5 to 75% impervious surface cover (Table 1). We divided non-restored streams into forested reference streams and urban streams by classifying all streams with at least 15% impervious surface cover in their catchments as urban. Previous work has shown that most streams in catchments with more than 15% impervious cover show signs of biological impairment (Klein, 1979; Wang *et al.*, 2000; Ourso & Frenzel, 2003). However, urban streams in this study were not independently assessed as to their level of impairment (e.g. by measuring biotic indices, water quality, or channel stability indices), and therefore, urban stream refers to any stream in a catchment with more than 15% impervious surface cover. The forested streams in this study have some development in their catchments and may have been impacted by agriculture in the last century. As such, they are best classified as least disturbed (Stoddard *et al.*, 2006).

Quantifying channel complexity

We sought a measure of channel complexity that accounted for channel attributes that are commonly assumed important to ecological patterns and processes. For example, heterogeneous bed sediments and variation in depth created by irregular bedforms can enhance surface water flux into the hyporheic zone (Cardenas, Wilson & Zlotnik, 2004; Mutz, Kalbus & Meinecke, 2007; Hester & Doyle, 2008). In addition, the presence of both deep, slow-flowing water (i.e. pools) and shallow rapidly flowing water (i.e. riffles) as well as a wide distribution of bed sediment sizes increases habitat heterogeneity in streams, which is assumed to increase the diversity of stream biotic communities (Palmer *et al.*, 2010). To capture these important ecological attributes of stream channels, we attempted to design a measure of channel complexity that assessed overall variability in channel morphology.

We took an approach similar to that of Bartley & Rutherfurd (2005) and used multiple metrics to assess variability in the following four aspects of channel morphology: (i) cross-section profile, (ii) longitudinal profile, (iii) planform profile and (iv) bed sediment distribution (Table 2). It was important to measure all four aspects to assess the overall channel complexity, because each aspect can vary independently in response to disturbance (Bartley & Rutherfurd, 2005). For example, knowledge of the longitudinal profile variability (i.e. knowing how channel depth varies downstream) provides no information on the heterogeneity of the bed sediments.

The metrics were generated from channel surveys that included cross-section, long profile, planform and grain-size measurements (see below and Baker, Bledsoe & Mueller Price (2012) for details on the survey protocol). Cross-section profiles were simplified by measuring only wetted width, maximum depth and maximum velocity to increase the number of cross-sections sampled at each stream. Variation in maximum cross-section velocity was used as a measure of cross-sectional variability, because changes in cross-section shape drive changes in velocity through the principle of flow conservation. Variability in planform profile was described by the metric sinuosity.

All but two of the metrics we used have been previously described elsewhere (see Table 2). We developed two new metrics of variation in wetted width for this study by applying calculations to wetted width profiles (wetted width measured at successive points downstream, see Fig. 3) that were originally applied to longitudinal profiles. The first was the fractal dimension of the wetted width profile. Fractal dimension measures the crookedness of a line and is calculated using the program Vfractal (Nams, 1996; http://www.nsac.ns.ca/envsci/staff/vnams/Fractal.htm). The fractal dimension can take a value between one and two, with one indicating a straight line and two indicating a line with sufficient crookedness to completely fill a plane (Nams, 1996). Bartley & Rutherfurd (2005) used fractal dimension as a metric of the variability in longitudinal and cross-section profiles. The second new metric of width variation was average width-profile concavity (AWC), calculated as:

$$AWC = \left(\frac{1}{n}\right)\left(\sum_{i=1}^{n}\left|\frac{d^2w_i}{dx_i^2}\right|\right)$$

where n = number of cross-sections, w = wetted width and x = distance downstream from the top of the reach (Fig. 3). This equation substitutes cross-section wetted

Table 1 Land-use characteristics for Maryland study streams

Stream (Lat/Long Coordinates)	Type (Year restored)	Order	Catchment area (km²)	% Urban in catchment	% Impervious in catchment	% Forest in catchment	% Agriculture in catchment	% Impervious in buffer	% Forest in buffer
Plum Creek (N 39°03′31″, W 76°35′17″)	Forested	1	2.4	35	11	62	2	0	100
Severn Run Trib. 1 (N 39°04′34″, W 76°37′07″)	Forested	2	2.1	31	10	55	14	0	100
Severn Run Trib. 2 (N 39°06′21″, W 76°39′03″)	Forested	1	0.5	14	4	79	0	1	95
S. Fork Jabez Branch (N 39°03′60″, W 76°39′06″)	Urban	2	2.4	34	18	28	34	0	100
Broad Creek (N 39°00′05″, W 76°33′36″)	Urban	1	0.4	31	17	51	3	0	100
Cockey Creek (N 39°07′06″, W 76°30′48″)	Urban	1	0.6	71	48	26	3	0	100
Cypress Creek (N 39°04′33″, W 76°32′12″)	Urban	2	2.1	88	47	4	0	1	95
Harbor Center East (N 38°58′33″, W 76°32′31″)	Urban	1	0.3	91	76	1	0	11	87
Harbor Center West (N 38°58′29″, W 76°33′02″)	Urban	2	0.8	79	69	2	0	0	100
Herald Harbor (N 39°02′56″, W 76°34′39″)	Urban	1	0.06	54	26	34	0	2	95
Marley Creek Tributary (N 39°08′02″, W 76°37′03″)	Urban	1	0.7	73	34	20	2	11	63
Picture Spring Branch (N 39°05′33″, W 76°41′47″)	Urban	1	1.0	42	28	58	0	2	92
Sawmill Creek Trib. at Queenstown Rd. East (N 39°09′06″, W 76°39′39″)	Urban	2	3.8	50	18	29	16	0	100
Sawmill Creek Trib. at Queenstown Rd. West (N 39°09′07″, W 76°39′42″)	Urban	1	0.9	50	24	38	4	0	99
Spa Creek Tributary at Hilltop Lane East (N 38°57′47″, W 76°30′29″)	Urban	1	0.2	95	61	0	0	7	77
Spa Creek Tributary at Hilltop Lane West (N 38°57′49″, W 76°30′31″)	Urban	1	0.1	89	63	6	5	0	96
Cowhide Branch (N 38°59′30″, W 76°32′14″)	Restored (1994)	1	0.4	85	67	15	0	0	100
Elvaton Towne Centre (N 39°07′17″, W 76°37′19″)	Restored (2004)	2	1.4	82	32	13	3	10	67
Harundale Town Center (N 39°09′12″, W 76°36′23″)	Restored (2005)	1	1.1	81	42	5	0	0	100
Muddy Bridge Branch (N 39°10′32″, W 76°38′41″)	Restored (1997)	2	2.8	81	70	8	4	0	89
Spa Creek (N 38°58′23″, W 76°31′03″)	Restored (2001)	1	0.9	87	60	7	1	4	77
Sawmill Creek Trib. 9 (N 39°10′54″, W 76°38′09″)	Restored (1994)	2	1.7	81	34	11	1	0	100
Sawmill Creek Trib. 10 (N 39°10′58″, W 76°37′24″)	Restored (1998)	1	0.8	86	34	11	0	0	95
Weems Ck. Trib. Bristol Dr. (N 38°59′11″, W 76°31′10″)	Restored (1997)	1	0.5	79	38	10	0	1	95
Weems Ck. Trib. Moreland (N 38°59′06″, W 76°31′37″)	Restored (1999)	1	0.2	85	69	10	0	0	99

Table 2 Complexity metrics used in this study

Metric	Dimension	Equation	Description
Cross-section profile variation			
Coefficient of variation of width	–	$CVW = \left(\dfrac{s_w}{\overline{w}}\right)$	Standard deviation of widths scaled by mean width
Width residual[*]	–	$WR = \dfrac{\sum\limits_{i=1}^{p}\left(\lvert w_i - \overline{w}\rvert I_p\right)}{\overline{w}}$	Sum of proportionally weighted deviations in width scaled by mean width (Baker *et al.*, 2012)
Average width concavity[*]	$\dfrac{L}{L^2}$	$AWC = \sum\limits_{i=1}^{n}\left(\left\lvert\dfrac{d^2 w_i}{dx_i^2}\right\rvert I_p\right)$	Proportionally weighted concavities at successive points along the width profile – modified from Anderson *et al.* (2005)
Fractal mean of width profile (D_{wwp})	–	Determined by simulation using the program Vfractal, with a window range of 0.25, random seed start of 1.0 and 30 divisions (Nams, 1996; http://www.nsac.ns.ca/envsci/staff/vnams/Fractal.htm)	Crookedness of width profile (see text). Width profile was detrended prior to analysis
Coefficient of variation of maximum cross-section velocity	–	$CVV = \left(\dfrac{s_v}{\overline{v}}\right)$	Standard deviation of maximum cross-section velocity scaled by mean maximum cross-section velocity
Longitudinal profile variation			
Coefficient of variation of maximum cross-section depths	–	$CVD = \left(\dfrac{s_z}{\overline{z}}\right)$	Standard deviation of maximum cross-section depths scaled by mean maximum cross-section depth
Longitudinal roughness[*]	L	$LR = \sum\limits_{i=1}^{n}\left[\left(z_{obs,i} - z_{pred,i}\right)I_p\right]$	Proportionally weighted deviations in thalweg elevation from a straight line between the thalweg elevations at the top and bottom of the reach (Gooseff *et al.*, 2007; Baker *et al.*, 2012)
Average water surface concavity[*]	$\dfrac{L}{L^2}$	$AWSC = \sum\limits_{i=1}^{n}\left(\left\lvert\dfrac{d^2 z_{w,i}}{dx_i^2}\right\rvert I_p\right)$	Proportionally weighted concavities at successive points along the water-surface profile (modified from Anderson *et al.*, 2005)
Average thalweg concavity[*]	$\dfrac{L}{L^2}$	$AThC = \sum\limits_{i=1}^{n}\left(\left\lvert\dfrac{d^2 z_i}{dx_i^2}\right\rvert I_p\right)$	Proportionally weighted concavities at successive points along the thalweg elevation profile (Anderson *et al.*, 2005; Baker *et al.*, 2012)
Fractal mean of longitudinal profile (D_{lp})	–	Determined by simulation using the program Vfractal, with a window range of 0.25, random seed start of 1.0 and 30 divisions (Nams, 1996; http://www.nsac.ns.ca/envsci/staff/vnams/Fractal.htm)	Crookedness of thalweg elevation profile – used by Bartley & Rutherfurd (2005). Longitudinal profile was detrended prior to analysis
Standard deviation	L	$SD = \sqrt{\dfrac{1}{N}\sum\limits_{i=1}^{n}\left(z_i - z_{min}\right)^2}$	Standard deviation of thalweg elevations relative to the highest point in the thalweg profile (Bartley & Rutherfurd, 2005). Longitudinal profile was detrended prior to analysis
Bed sediment distribution			
Heterogeneity	–	$Het = \dfrac{d_{84}}{d_{50}}$	84th largest particle relative to median particle size – larger values indicate a greater range of substrate sizes
Sorting	–	$Sort = \dfrac{\phi 84 - \phi 16}{2}$	Measures the standard deviation of the bed sediment size distribution (Briggs, 1977; Bartley & Rutherfurd, 2005)
Fredle index	L	$f_i = \dfrac{\sqrt{d_{16} d_{84}}}{\sqrt{\dfrac{d_{75}}{d_{25}}}}$	Measures the porosity of bed sediments (Lotspeich & Everest, 1981)
Gradation coefficient	–	$s_{grad} = \dfrac{\left(\dfrac{d_{84}}{d_{50}} + \dfrac{d_{50}}{d_{16}}\right)}{2}$	Measures the spread of the bed sediment distribution (Bunte & Abt, 2001)

Table 2 (Continued)

Metric	Dimension	Equation	Description
Sediment coefficient of variation	L^{-1}	$CV_s = \dfrac{\sqrt{\dfrac{d_{84}}{d_{16}}}}{d_{50}}$	Geometric standard deviation of bed sediment distribution relative to median particle size (Baker, 2009)
Channel planform variability			
Sinuosity	–	$s = \dfrac{L}{L_s}$	Channel length relative to straight-line distance between top and bottom of reach

[*]Proportional weighting was calculated as half the distance between successive measurement points upstream and downstream of measurement point i relative to total reach length using, $I_p = \dfrac{(x_{i+1} - x_{i-1})/2}{L}$, where x = distance and L = reach length (Baker *et al.*, 2012).

width for water surface elevation in the equation for average water surface concavity developed by Anderson *et al.* (2005) and applied by Gooseff *et al.* (2007) as a measure of channel complexity. The metric reflects the overall variation of the wetted channel width along the stream reach (i.e. the degree to which the stream channel changes from narrow to wide, and vice versa, between the cross-sections throughout the study reach).

Field surveys of channel complexity

The survey methodology is described by Baker *et al.* (2012), but is summarised here. Study reaches were established at each stream by measuring a length 15 times the estimated bankfull width. We divided the reach
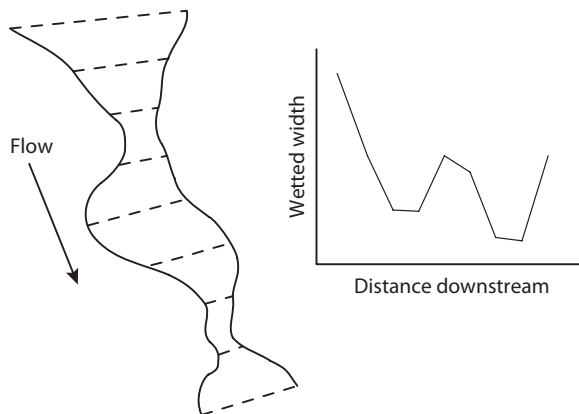
Fig. 3 Planform view of hypothetical reach showing cross-section measurement points (dotted lines) and resulting wetted width profile. The wetted width profile was used to calculate CV width, width residual, fractal mean of wetted width and average width-profile concavity (AWC). Concavity at a measurement point increases as the difference in wetted width between the measurement point and each adjacent measurement point increases and the difference in wetted width between the adjacent measurement points decreases; that is, the line connecting three sequential measurement points becomes more peaked in the middle. Thus, AWC is higher for wetted width profiles that have more of a zigzag or saw-tooth pattern.

into at least 20 equally spaced sections by running at least 21 transects perpendicular to the stream. Along each transect, we measured wetted width, maximum stream depth and maximum flow velocity during baseflow conditions. The cross-section measurements were used to calculate the coefficient of variation (CV) of width, CV maximum depth, CV maximum velocity, width residual, AWC and fractal mean of the wetted width profile (see Table 2). Grain-size distributions within the wetted width of each reach were quantified by measuring between 600 and 1200 particles throughout the reach. Grain-size distributions were used to calculate sorting, the gradation coefficient, the Fredle index, the sediment coefficient of variation and sediment heterogeneity (see Table 2). We also surveyed the longitudinal profile of each reach. Measurement points were located at breaks in slope, and the channel bed elevation, water surface elevation and water depth were recorded at each point. Longitudinal profile surveys were used to calculate longitudinal roughness, average water surface concavity, average thalweg concavity, standard deviation of depths and fractal mean of the longitudinal profile (see Table 2). Sinuosity was calculated by dividing the reach length by the straight-line distance between the upstream and downstream points of the reach, both measured using aerial photographs.

Comparisons with other study sites

Data from Colorado study sites were provided by Baker *et al.* (2012) and came from six reaches on two streams. Sheep Creek (N 40°55′48″, W 105°38′16″) was located at an elevation of 2530 m and had minimal development in the catchment, although it was influenced by a small dam upstream and one reach was actively grazed by livestock (Reach C). Spring Creek was located in an urbanised catchment in the town of Fort Collins (N 40°30′50″, W 105°4′7″) at an elevation of 1500 m. One reach was located

in a municipal park, one reach was deliberately straightened, and one reach had extensively rip-rapped banks and grade control structures.

We also surveyed the literature to find papers that reported values of CV velocity, CV depth and CV width or that reported enough information to calculate these metrics. Papers were acquired by first examining studies that had evaluated the effects of stream restoration on habitat heterogeneity (reviewed in Palmer *et al.*, 2010). We also collected papers by searching Web of Science[SM] (Thomson Reuters, New York City, NY, U.S.A) for the keywords: fish, habitat, transect and stream. These keywords were chosen because we needed papers that measured width, depth and velocity along multiple transects and so that we could limit the papers examined to those in which transects were established specifically for the purpose of assessing fish habitat in relatively small streams and rivers. We also looked through the citations of papers found on Web of Science[SM] for additional relevant papers. We only included papers that measured at least five transects in a stream reach and reported either direct CV measures or means with standard deviations or standard errors with sample sizes.

Statistical analysis

To generate a comprehensive measure of channel complexity (Objective 1), we used principle component analysis (PCA) combined with a correlation table (Table 3) of the longitudinal profile, cross-section profile and bed sediment distribution metrics to reduce the number of metrics used in subsequent analyses. Both Maryland and Colorado data were included in this analysis. Where we had multiple metrics for one aspect of complexity (cross-section profile, longitudinal profile and sediment distribution), we kept the metric that had the most explanatory power on the first two components (indicated by the magnitude of the vector in a PCA biplot) and eliminated metrics that were significantly correlated to that metric. We ran a second PCA with the reduced set of metrics to simplify the biplot and to visualise graphically how streams from the different regions grouped together. All additional analyses used this reduced set of metrics.

To determine whether urban development decreased the complexity of Maryland streams (Objective 2), we used canonical correlation analysis (CCA) to examine the relationship between land-use variables (% forested, % impervious and % agriculture) and the reduced set of complexity variables. Wilks's lambda (λ) was used to test the significance of relationships.

To assess the effects of restoration on channel complexity in Maryland streams, we compared channel complexity metrics in restored streams with metrics in urban streams (Objective 3). We did not statistically test whether restored streams were different from forested streams owing to insufficient statistical power ($n = 3$ forested streams). We used region (north or south Anne Arundel County) as a blocking variable in our analyses, because geological differences between the regions (see Study Sites) suggested that channel morphology might differ between streams in these regions, and we indeed found that streams in the north and south had significantly different average geomorphic properties (MANOVA, $F_{(4, \ 15)} = 3.7054$, $P = 0.027$; Fig. 4). We

Table 3 Correlation table of complexity metrics with both Maryland and Colorado streams included

	CVW	WR	AWC	D_{wwp}	CVV	CVD	LR	AWSC	AThC	D_{lp}	SD	Het	Sort	f_i	s_{grad}	CV_s
CVW	1	**0.96**	0.17	**0.50**	0.02											
WR		1	0.20	**0.48**	0.05											
AWC			1	**0.71**	−0.28											
D_{wwp}				1	0.07											
CVV					1											
CVD						1	0.14	**0.38**	**0.47**	**0.63**	0.14					
LR							1	0.13	0.22	−0.09	**0.68**					
AWSC								1	**0.85**	0.42	0.003					
AThC									1	0.42	0.08					
D_{lp}										1	−0.07					
SD											1					
Het												1	**0.71**	−0.26	**0.67**	**0.59**
Sort													1	−0.28	**0.92**	**0.79**
f_i														1	−0.31	−0.48
s_{grad}															1	**0.86**
CV_s																1

Only correlations between metrics measuring the same aspect of channel morphologic variability are shown. Numbers in bold are significant at $\alpha = 0.05$. See Table 2 for metric names.
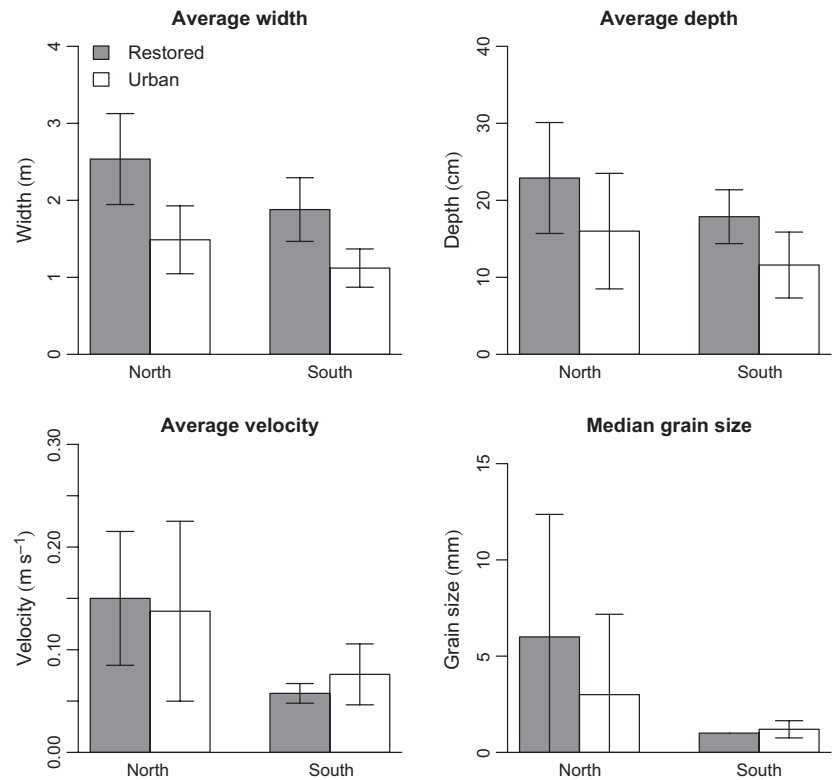
Fig. 4 Average values of width, maximum depth, maximum velocity and median grain size at northern restored ($n = 5$), northern urban ($n = 8$), southern restored ($n = 4$) and southern urban streams ($n = 5$) in Anne Arundel County, Maryland. Error bars are standard deviations.

compared all metrics in the reduced set using a fixed-effects MANOVA. We also tested for a difference in each aspect of complexity (cross-section profile, longitudinal profile, sediment distribution and planform profile) between restored and urban streams using either ANOVA or MANOVA depending on whether each aspect was represented by one or multiple metrics. The Fredle index, the gradation coefficient, sediment standard deviation, sediment heterogeneity and average water surface concavity were $\log_{10}$-transformed prior to analyses. All other variables met assumptions of homogeneity of variance and normality tested on residual variances calculated within groups. All statistical tests were run using R version 2.11.0 (R Foundation for Statistical Computing, Vienna, Austria).

To gain an understanding of the variability in channel complexity across streams of varying land use and between geographical regions (Objective 4), we compared values from the literature survey with the Maryland and Colorado data with plots of CV velocity versus CV depth and CV width versus CV depth.
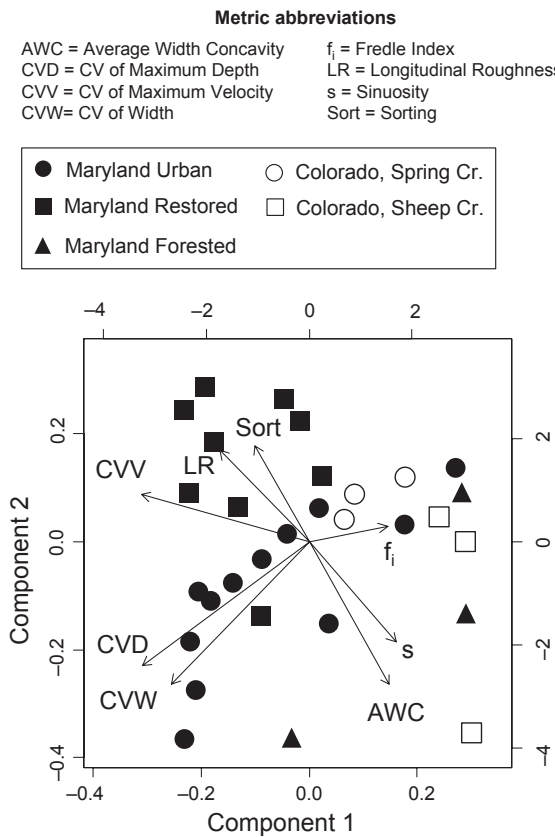
Results

Objective 1: quantifying channel complexity

The first two components of the PCA using all complexity metrics explained 46% of the variance between streams

(see Fig. S1). All of the sediment distribution metrics, except the Fredle index, clustered together on the biplot of the first two components, indicating high correlation among these metrics (see also Table 3). The Fredle index was significantly correlated only with the sediment coefficient of variation. Therefore, we chose the Fredle index and sediment sorting as the sediment metrics for further analyses. CV maximum velocity, CV width and AWC were chosen as the width metrics for further analyses, because they were not significantly correlated with each other. Width residual was excluded, because it was significantly correlated with CV width, and fractal mean of the width profile was excluded because it was significantly correlated with both AWC and CV width. Four of the six longitudinal profile metrics (CV depth, fractal mean, average thalweg concavity and average water surface concavity) grouped together on the biplot and were significantly correlated. Longitudinal roughness and standard deviation of the longitudinal profile were significantly correlated with each other, and neither was significantly correlated with any other longitudinal profile metric. Therefore, we chose CV depth and longitudinal roughness as the longitudinal profile metrics for further analyses, because they had the most explanatory power along components 2 and 3, respectively.

The first two components of the PCA using the reduced set of metrics explained 48% of the variance

Metric abbreviations

AWC = Average Width Concavity	f_i = Fredle Index
CVD = CV of Maximum Depth	LR = Longitudinal Roughness
CVV = CV of Maximum Velocity	s = Sinuosity
CVW= CV of Width	Sort = Sorting

● Maryland Urban ○ Colorado, Spring Cr.

■ Maryland Restored □ Colorado, Sheep Cr.

▲ Maryland Forested

Fig. 5 Biplot of components 1 and 2 from the principle component analysis (PCA) with the reduced set of complexity metrics. Arrows and black letters denote complexity metric vectors. Symbols represent different types of streams as specified in the legend.

between streams. No overall gradient of complexity was apparent in the biplot as different metrics of complexity pointed in opposite directions (Fig. 5). All Colorado streams had positive scores on component 1, and the three Spring Creek reaches grouped together closely. The three Sheep Creek reaches were separated along component 2. Two Maryland forested streams and two Maryland urban streams grouped closely with the Spring Creek reaches and two reaches of Sheep Creek. Seven of the nine Maryland restored streams grouped together in the top-left quadrant of the biplot. In contrast, all but one of the streams in the lower left quadrant were urban streams.

Objective 2: channel complexity along an urbanisation gradient

The first canonical function from the CCA of the relationship between land-use variables and complexity metrics had a relatively high correlation coefficient, but explained only 12% of the shared variance in the complexity metrics and was not significant (Table 4;

Table 4 Results of the canonical correlation analysis (CCA) between land-use variables and complexity metrics using only Maryland streams

Canonical function	Df 1	Df 2	Wilks's λ	P-value	R
CF 1	24	38.3	0.16	0.176	0.81
CF 2	14	28.0	0.47	0.556	0.70
CF 3	6	15.0	0.92	0.970	0.27

Variable	Coefficient
% Forest	0.0139
% Impervious	0.0075
% Agriculture	0.0082
CVW	−0.73
AWC	4.65
CVV	−0.41
CVD	0.19
LR	0.13
Sort	0.04
f_i	0.06
s	0.55

Loadings on only the first canonical function are presented. See Table 2 for metric abbreviations.

Wilks's $\lambda_{(24,38.3)} = 0.17$, $P = 0.203$). We had predicted that complexity metrics would decline with increasing impervious cover, since it has been assumed that urban development reduces channel complexity. However, the weak relationship in the CCA showed that this was not the case. This did not appear to be an artefact of insufficient statistical power, because many complexity metrics tended to increase with increasing impervious cover, as indicated by the sign of the complexity metric loadings on the first canonical function (Table 4).

Objective 3: channel complexity in restored, urban and forested streams

The block by treatment interaction effect in the overall MANOVA of complexity data was not statistically significant ($F_{(8,10)} = 1.4322$, $P = 0.29$), indicating that the complexity metrics in both northern and southern streams were responding similarly to restoration, and we could interpret the main effects of block (geological region) and treatment (restoration or urban) separately. The block effect was significant ($F_{(8,10)} = 8.0049$, $P = 0.002$) and indicated that blocking in the analysis was useful. Restored streams were significantly different from urban streams overall ($F_{(8,10)} = 8.5205$, $P = 0.001$). As with the overall results, the block by treatment interaction was not significant and the block effect was significant in separate analyses of longitudinal profile, cross-section profile and bed sediment distribution variability. Restored streams
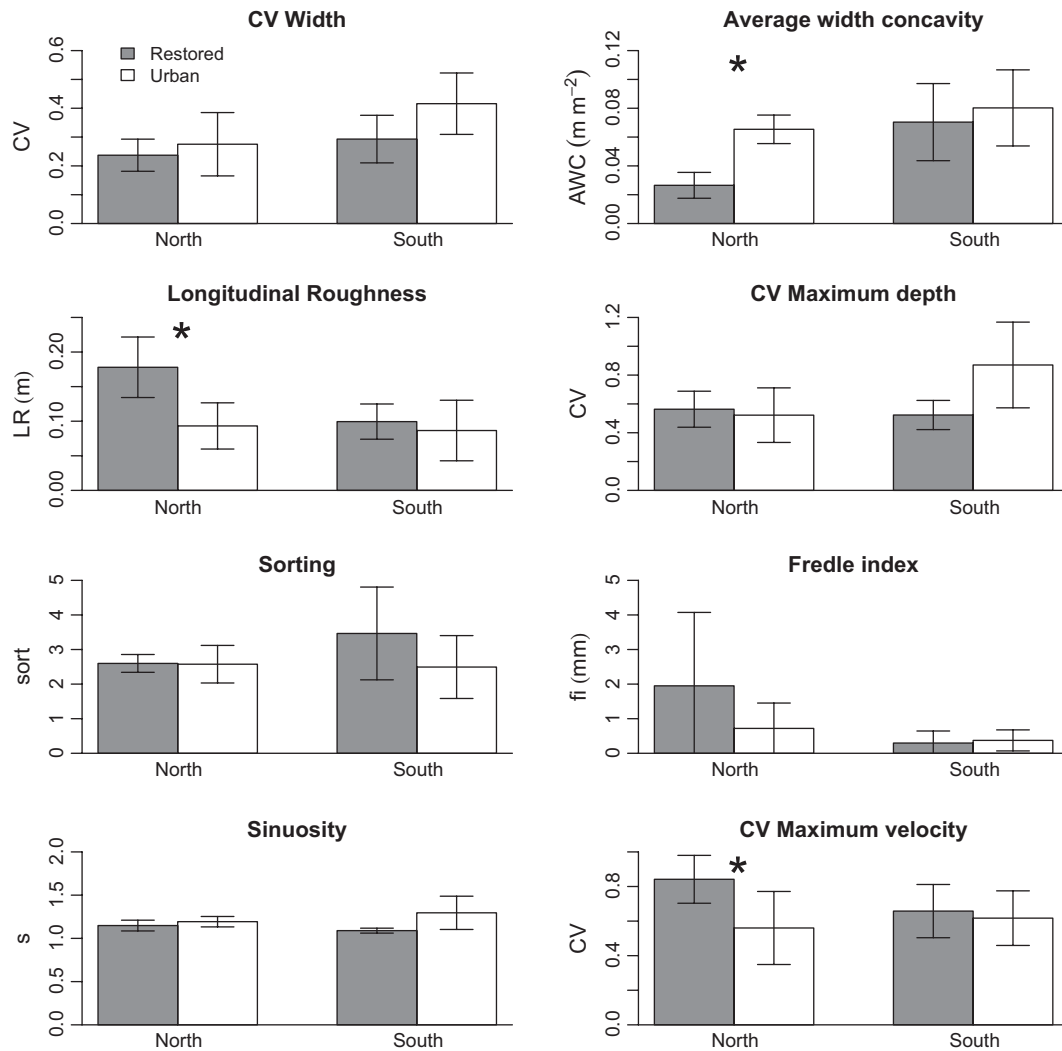
Fig. 6 Comparison of individual complexity metrics for northern restored ($n = 5$), northern urban ($n = 8$, except longitudinal roughness, $n = 7$), southern restored ($n = 4$) and southern urban streams ($n = 5$) in Anne Arundel County, Maryland. * above bars indicates a significant difference between restored and urban streams within that region (north or south) at $\alpha = 0.05$. Error bars are standard deviations.

had significantly different cross-section variability compared with urban streams ($F_{(3,16)} = 6.53$, $P = 0.004$), with restored streams having lower measures of CV width and AWC and higher measures of CV maximum velocity (Fig. 6). Restored streams were significantly different from urban streams in terms of longitudinal profile variation ($F_{(2,16)} = 8.6190$, $P = 0.003$) and marginally different in terms of sediment distribution ($F_{(2,17)} = 3.3231$, $P = 0.06$), but the direction varied between metrics and between northern and southern streams. The block effect was not significant for sinuosity, but this did not significantly change the interpretation of the main effect of restoration. Restored streams had significantly lower sinuosity than urban streams ($F_{(1,18)} = 6.0995$, $P = 0.024$).

Values of complexity metrics for the three forested streams generally fell within the range of values seen at

the restored and urban streams. However, values at the forested streams were more often at the lower end of the range, with one forested stream having the lowest values of CV velocity and Fredle index of any Maryland stream. Whether overall complexity in forested streams was significantly different from urban or restored streams was not tested because of low sample size of forested streams ($n = 3$).

Objective 4: geographic range in channel complexity

Our literature survey resulted in data on CV velocity and CV depth for 112 individual reaches and data on CV width and CV depth for 98 reaches (Figs. 7 and 8). Catchment area of selected streams ranged from 7.3 to 84 000 km^2 and reach length from 10 to 2000 m. Most
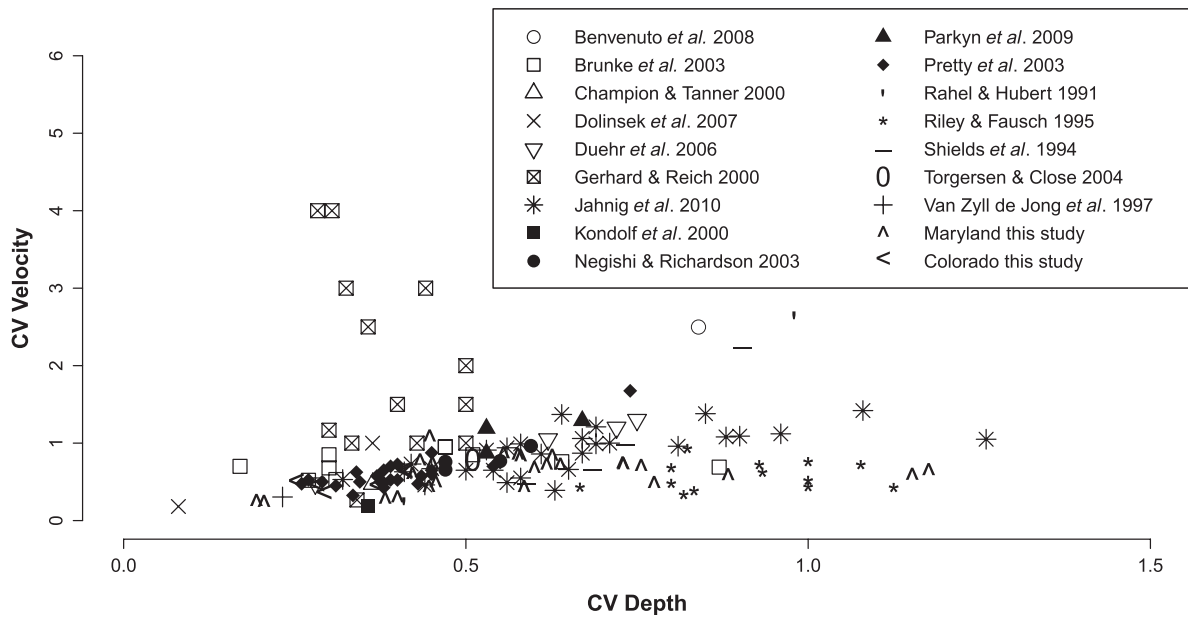
Fig. 7 Biplot of CV velocity versus CV depth showing the range in values for these variables determined from the literature survey relative to the range observed in the current study. CV velocity includes measures of CV maximum velocity and CV average velocity. CV depth includes measures of CV maximum depth, CV bankfull depth and CV average depth. Different types of streams in the current study are not differentiated on the plot. Details about the reach characteristics for each paper in the literature survey are provided in Table S1.
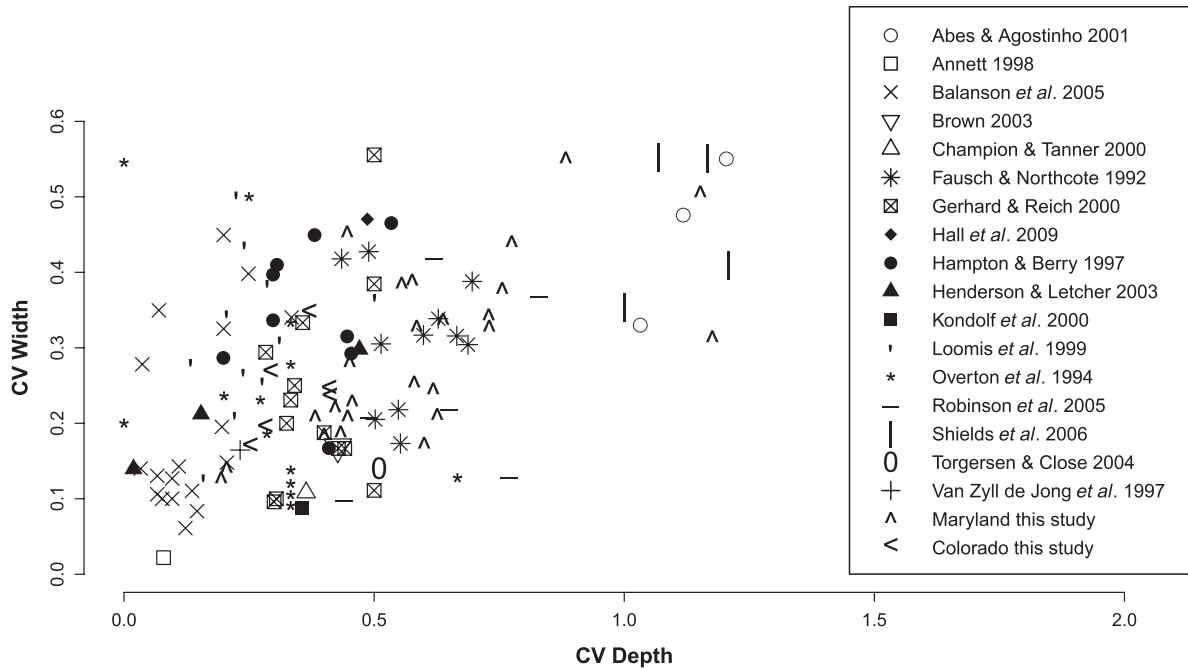
Fig. 8 Biplot of CV width versus CV depth showing the range in values for these variables determined from the literature survey relative to the range observed in the current study. CV width includes measures of CV bankfull width and CV wetted width. CV depth includes measures of CV maximum depth, CV bankfull depth and CV average depth. Different types of streams in the current study are not differentiated on the plot. Details about the reach characteristics for each paper in the literature survey are provided in Table S1.

studies were located in temperate zones, but ranged from prairie and coastal streams to mountain streams. Land use was also variable across streams, ranging from nearly pristine to agricultural and urban dominated. Numerous studies also reported data for restored streams.

Streams from the literature mostly fell within the range of values for CV depth and CV width seen in the Maryland study streams (Fig. 8). One concrete channel in Florida, U.S.A, and numerous streams in urban catchments in Ohio, U.S.A, had lower values of both CV depth and CV width than the lowest values seen in the Maryland study streams (Annett, 1998; Balanson *et al.*, 2005). Very few streams had higher values of CV width and CV depth than the highest values seen in the Maryland study streams. In contrast, there were numerous reaches, primarily those restored with large-wood additions in Germany, which had higher values of CV velocity than the highest values seen in Maryland study sites (Gerhard & Reich, 2000; Fig. 7).

About half of the Maryland urban streams ranked in the top 30% of streams for both CV depth and CV width, although none ranked in the top 30% for CV velocity. One Maryland forested stream and one Maryland restored stream ranked in the top 30% for CV width, and the same forested stream and three different Maryland restored streams ranked in the top 30% for CV depth. Colorado streams ranked in the lower 50% for CV velocity and CV depth and generally ranked in the middle 50% for CV width, with the reach containing riprap and grade control structures on Spring Creek ranking in the top 30%.

Discussion

Using multiple metrics of channel complexity and by applying PCA, we assessed how four aspects of channel complexity differed among streams of varying land use across geographical regions. Assessment of different aspects of channel complexity was used previously to investigate the changes in channel geomorphic diversity caused by increased sediment loading (Bartley & Rutherfurd, 2005). Our application of the approach led to unexpected results regarding urban land use and the effects of restoration on channel complexity. The metrics we measured did not combine to a single gradient of complexity. Streams with high values of one metric often had low values of other metrics. Thus, our approach demonstrated the limitation in using any single variable as an indicator of overall channel complexity. In addition, because different measurements of the same attribute sometimes yielded conflicting results, the approach highlighted the importance of explicitly defining channel complexity and the methodology used to measure it.

Urbanisation and channel complexity

It has often been assumed that urban development of forested watersheds leads to simplification of stream channels and loss of channel complexity, either through channelisation and straightening or through urban-induced hydrological changes (Walsh *et al.*, 2005). Therefore, we hypothesised that streams in urban catchments would have lower channel complexity than forested reference streams, but our surveys of non-channelised streams across a gradient of catchment urbanisation (collectively referred to as urban streams, regardless of the state of degradation) did not support this. First, the PCA results showed that there was no single gradient of complexity, and it was not possible to define streams in urban catchments as having lower or higher complexity than forested streams. Second, we did not find a significant relationship between land use and complexity metrics in Maryland streams (Table 4), which we would have expected if streams in more urbanised catchments had lower complexity. Multiple metrics, including CV width, CV maximum velocity and sorting, tended to increase with impervious surface cover (Table 4). Third, many urban streams in Maryland ranked in the top third of sites surveyed in the literature for two complexity metrics (CV width and CV depth), which included many near-pristine streams.

Research over the past 40 years has shown that the mean value of many aspects of channel morphology changes predictably in response to urbanisation. Channels generally become wider and more deeply incised in response to urban development (Wolman, 1967; Hammer, 1972; Booth, 1990; Hardison *et al.*, 2009). In contrast, our findings suggest that variability in some aspects of channel morphology (e.g. CV depth, CV width) does not respond predictably to increased urban development in the catchment and that overall variability in channel morphology (i.e. channel complexity) is not consistently lower in streams draining urban catchments compared to forested reference streams. Some aspects of channel morphology did vary consistently between urban and forested streams, as Maryland urban and forested streams grouped separately on the PCA biplot. However, there were multiple complexity metrics that were not different in urban and forested streams, suggesting that channel morphology can adjust to urbanisation in highly variable ways; that is, urbanisation does not always reduce variability of all aspects of complexity.

Our results contrast to the previous research reporting lower channel complexity in urban streams compared to

reference streams (Davis *et al.*, 2003; Grimm *et al.*, 2005; Walsh *et al.*, 2005; Gooseff *et al.*, 2007). However, much of this work has focused on streams that were concrete-lined or deliberately straightened, and studies have typically been limited to five urban streams or less. We surveyed a relatively large number of streams in urban catchments (*n* = 12 in Maryland alone) that were not directly channelised or straightened by human activities and found that the complexity was relatively high in these streams relative to forested reference streams. Our results for the urban streams do not appear anomalously high nor results from the forested streams anomalously low, as all streams fell within the range of variability for several complexity metrics seen across diverse geographical regions from the literature survey. Instead, these results indicate that urban land use in a catchment does not necessarily lead to channel simplification when channels are not directly manipulated, and this conclusion should be relevant beyond our focal study region, given the fact that our study streams are within the range of variability in channel complexity seen across streams from diverse regions.

Rather than assuming channels in urban catchments are geomorphically simplified, we found that it is important to measure multiple aspects of channel complexity. One of the Colorado stream reaches we surveyed has been purposefully straightened, and this reach had relatively low values for many complexity metrics, including the lowest values of sinuosity, sorting and three longitudinal profile metrics (standard deviation, fractal mean and average thalweg concavity). However, this reach had relatively high values for some metrics, highlighting the fact that even channelised streams can have high complexity in certain attributes. We also found that metrics of the same aspect of complexity were often uncorrelated (for example CV width and AWC). AWC measures sequential variation in the width profile, whereas CV width measures average deviation from the mean width. Similarly, longitudinal roughness measures sequential variation in the longitudinal profile, whereas CV depth measures average deviation from the mean depth. The unique information provided by each metric was important in separating streams, as seen in the PCA biplot. Maryland urban streams were separated from each other along a gradient of CV width and CV depth but were separated from Maryland restored streams by a gradient of longitudinal roughness and AWC. By measuring multiple aspects of complexity, we gained a better understanding of how channel morphological variability responds to urbanisation when the channels are not constrained.

Factors influencing channel complexity within and across geographical regions

There has been a great deal of recent discussion on the difficulties of identifying appropriate reference sites or the appropriate reference condition (Stoddard *et al.*, 2006; Bernhardt & Palmer, 2007; Herlihy *et al.*, 2008; Baattrup-Pedersen *et al.*, 2009; Hawkins, Olson & Hill, 2010). Today, almost all ecosystems are impacted by humans to some extent and urbanisation is a rapidly growing land-use change (Paul & Meyer, 2001). The forested streams in our study have some urban development in their catchments and were probably affected by agriculture in the past. Thus, while we classified these streams as our reference sites, they are in fact the least-disturbed sites, and it is possible that current and past land use has caused a reduction in channel complexity from historical levels (e.g. 300 years ago). While we cannot dismiss this possibility (much of the Mid-Atlantic region was impacted by agriculture in the last two centuries), comparison with non-urbanised streams from other regions suggests that the levels of complexity we found in the Maryland reference streams are not unusually low (i.e. they were within the range of channel complexity seen across diverse geographical regions). Further, the lack of a clear gradient in channel complexity along an urbanisation gradient supports our conclusion that urban development does not necessarily lead to overall reductions in channel complexity. Previous research has also provided some evidence that complexity is not always reduced by urbanisation. Hammer (1972) observed that small urban streams in Pennsylvania had particularly variable cross-sectional areas, while Kang & Marston (2006) found that urbanisation only affected sinuosity patterns through direct manipulation such as rip-rap installations and channelisation.

The lack of clear and consistent relationships between complexity and urbanisation probably reflects the large number of factors that can vary across catchments even if they have comparable levels of urban development. For example, the urban streams we surveyed had a well-forested buffer, even when impervious cover in the catchment exceeded 60%. Riparian vegetation exerts a strong influence on channel morphology independent of the level of catchment urbanisation (Hession *et al.*, 2003), and a forested buffer along an urban stream could maintain or even enhance channel complexity via increased inputs of wood. Increasing impervious surface cover in catchments has been linked to flashier, more powerful floods and increased bank erosion (Dunne & Leopold, 1978; Arnold *et al.*, 1982; Booth, 1990), which

could increase lateral movement of the channel across the landscape and transport trees, fallen logs and other debris (e.g. discarded lumber and concrete, shopping carts, tires) into the channel more rapidly. Instream wood and urban debris in channels can increase the channel complexity by creating variations in scour and fill patterns (Robison & Beschta, 1990; Abbe & Montgomery, 1996; Buffington *et al.*, 2002). However, this process requires that stabilisation structures, which are common in urban streams, do not prevent bank erosion (Segura & Booth, 2010). The urban streams we surveyed in Maryland were not deliberately stabilised, and the process of increased inputs of wood and urban debris may explain the trend towards increased complexity, but this remains to be tested.

Previous work has shown that channel morphology responds differently to urbanisation in different geoclimatic settings (Utz & Hilderbrand, 2011), and it is possible that the relatively high complexity of the Maryland streams in this study (all located on the Coastal Plain) reflects a unique response of Coastal Plain streams to urbanisation. In comparison with Piedmont streams (the neighbouring physiographic province in Maryland), Coastal Plain streams suffer less geomorphic degradation with increasing urbanisation (Utz & Hilderbrand, 2011). This differential response has been attributed to the finer sediments and lower topographic relief of Coastal Plain streams, which may buffer changes in sediment supply and hydrological patterns associated with urban development (Utz & Hilderbrand, 2011). Thus, it is possible that channel complexity is also less severely impacted by urbanisation in Coastal Plain streams relative to streams from other regions, but this remains to be tested.

Restoration and channel complexity

We hypothesised that complexity in restored streams would be higher compared to non-restored streams in urban catchments. Analysis of the Maryland sites showed that restored streams differed significantly from urban streams in terms of overall complexity, but this difference was non-directional; there was no consistent overall complexity gradient. Restored streams did have somewhat higher CV velocity compared to urban streams, and northern restored streams had higher longitudinal roughness compared to northern urban streams. Both CV velocity and longitudinal roughness have been used previously in attempts to explain the patterns of transient storage and macroinvertebrate diversity (Brooks *et al.*, 2002; Negishi & Richardson, 2003; Gooseff *et al.*, 2007;

Baker *et al.*, 2012), suggesting that restoration may have had some benefit for hydraulic retention and habitat quality. However, restored streams had similar or lower values of many complexity metrics compared to urban streams, including sediment sorting and sinuosity, which have also been used in attempts to explain the patterns of transient storage and biodiversity (DeMarch, 1976; Robertson & Milner, 2006; Gooseff *et al.*, 2007).

Without pre-restoration data, it is impossible to conclude with certainty that restoration did not improve overall channel complexity of some stream reaches compared to their more degraded state. It is also possible that restoration increased channel complexity during high flows, as we did not measure channel complexity during storm events. Previous work has shown that large boulders and logs such as those added during restoration can increase hydraulic retention during storms, but the effect has been less pronounced during storm events than at baseflow (Webster *et al.*, 1987; Muotka & Laasonen, 2002; Dewson, James & Death, 2007). Nonetheless, the high variability in complexity we observed across urban streams makes it unlikely that the geomorphic restoration approach used on our study sites consistently increased the overall channel complexity across a variety of flow levels.

Biological implications

Restoration has often attempted to increase the physical heterogeneity of perceived degraded streams, because theory predicts that species diversity should increase when physical heterogeneity increases. However, recent synthesis suggests that even when indicators of habitat heterogeneity are improved by restoration, macroinvertebrate diversity often does not increase in response (Palmer *et al.*, 2010; Louhi *et al.*, 2011; but see Miller, Budy & Schmidt, 2010). The lack of response of macroinvertebrate diversity is probably due to processes operating at the catchment scale that alter flow regimes, degrade water quality and prevent dispersal (Miller *et al.*, 2010; Palmer *et al.*, 2010; Sundermann, Stoll & Haase, 2011). We emphasise the importance of measuring multiple aspects of physical complexity in stream channels to ensure that overall heterogeneity has improved with restoration. The results of our comprehensive measure of channel complexity and previous studies in urban catchments (Tullos *et al.*, 2009; Violin *et al.*, 2011) suggest that restoration may not always result in increased channel complexity, in part because physical heterogeneity may not be a limiting factor for biodiversity in non-channelised urban streams. Therefore, invertebrate recovery may not have the oppor-

tunity to be influenced by channel complexity if other catchment-scale factors are limiting.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Biplot of components 1 and 2 from the PCA using all 17 complexity metrics showing complexity metric vectors. Loadings of LR and SD were very low on components 1 and 2; therefore, labels for these metrics and all sites are omitted for clarity.

Table S1. List of papers used in Figs 7 & 8, along with number, type, and location of study reaches in each paper.

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