Elsevier Editorial System(tm) for Geomorphology Manuscript Draft

Manuscript Number: GEOMOR-4376R2

Title: Tracking geomorphic signatures of watershed suburbanization with multitemporal LiDAR

Article Type: Research Paper

Keywords: LiDAR time series; urbanization; land cover change; digital elevation models; anthropogenic geomorphology; watershed

Corresponding Author: Mr. Daniel Kyle Jones, M.S.

Corresponding Author's Institution: U.S. Geological Survey

First Author: Daniel Kyle Jones, M.S.

Order of Authors: Daniel Kyle Jones, M.S.; Matthew E Baker, Ph.D; Andrew J Miller, Ph.D; S. Taylor Jarnagin, Ph.D; Dianna M Hogan, Ph.D

Abstract: Urban development practices redistribute surface materials through filling, grading, and terracing, causing drastic changes to the geomorphic organization of the landscape. Many studies document the hydrologic, biologic, or geomorphic consequences of urbanization using space-for-time comparisons of disparate urban and rural landscapes. However, no previous studies have documented geomorphic changes from development using multiple dates of high-resolution topographic data at the watershed scale. This study utilized a time series of five sequential Light Detection and Ranging (LiDAR) derived digital elevation models (DEMs) to track watershed geomorphic changes within two watersheds throughout development (2002-2008) and across multiple spatial scales (0.01-1 km2). Development-induced changes were compared against an undeveloped forested watershed during the same time period. Changes in elevations, slopes, hypsometry, and surface flow pathways were tracked throughout the development process to assess watershed geomorphic alterations. Results suggest that development produced an increase in sharp topographic breaks between relatively flat surfaces and steep slopes, replacing smoothly varying hillslopes and leading to greater variation in slopes. Examinations of flowpath distributions highlight systematic modifications that favor rapid convergence in unchanneled upland areas. Evidence of channel additions in the form of engineered surface conduits is apparent in comparisons of pre- and post-development stream maps. These results suggest that topographic modification, in addition to impervious surfaces, contributes to altered hydrologic dynamics observed in urban systems. This work highlights important considerations for the use of repeat LiDAR flights in analyzing watershed change through time. Novel methods introduced here may allow improved understanding and targeted mitigation of the processes driving geomorphic changes during development and help guide future research directions for development-based watershed studies.

GEOMORPHOLOGY JOURNAL EDITORIAL REVIEW

All editorial changes and suggestions were accepted and can be seen in the "LiDAR timeseries paper Final 032714 track changes.docx" document.

- Sequential LiDAR DEMs used to track geomorphic changes during urbanization process
- Developing watersheds compared against undeveloped forested reference watershed
- Smoothly varying hillslopes replaced by sharp topographic breaks
- Evidence of channel burial coupled with additions of engineered runoff conduits
- Increased watershed connectivity independent of impervious surface cover and pipes

1	Tracking geomorphic signatures of watershed suburbanization with multitemporal LiDAR
2	
3	Daniel K. Jones ^{a,b*} , Matthew E. Baker ^{b,1} , Andrew J. Miller ^{b,2} , S. Taylor Jarnagin ^{c,3} , Dianna M.
4	Hogan ^{a,4}
5	
6 7 8	^a U.S. Geological Survey, Eastern Geographic Science Center, 12201 Sunrise Valley Drive, Reston, VA 20192, USA
9 10 11	^b Department of Geography and Environmental Systems, University of Maryland, Baltimore County, Sondheim Hall, 1000 Hilltop Circle, Baltimore, MD 21250, USA
12 13 14 15	^c U.S. Environmental Protection Agency (USEPA) Landscape Ecology Branch, Environmental Sciences Division, USEPA/ORD National Exposure Research Laboratory, Mail Drop E243-05 109 T.W. Alexander Drive, Research Triangle Park, NC 27711, USA
16 17 18 19 20	*Corresponding author. Present address: U.S. Geological Survey, Eastern Geographic Science Center, 12201 Sunrise Valley Drive, Reston, VA 20192, USA; Tel.: <u>+1</u> (703) 648-5120; Fax: <u>+1</u> (703) 648-4603; E-mail: dkjones@usgs.gov.
21 22 23 24	 ¹E-mail: mbaker@umbc.edu. ²E-mail: miller@umbc.edu. ³E-mail: jarnagin.taylor@epa.gov. ⁴E-mail: dhogan@usgs.gov.

26 Abstract

28	Urban development practices redistribute surface materials through filling, grading, and
29	terracing, causing drastic changes to the geomorphic organization of the landscape. Many studies
30	document the hydrologic, biologic, or geomorphic consequences of urbanization using space-for-
31	time comparisons of disparate urban and rural landscapes. However, no previous studies have
32	documented geomorphic changes from development using multiple dates of high-resolution
33	topographic data at the watershed scale. This study utilized a time series of five sequential Light
34	Detection and Ranging (LiDAR) derived digital elevation models (DEMs) to track watershed
35	geomorphic changes within two watersheds throughout development (2002-2008) and across
36	multiple spatial scales (0.01-1 km ²). Development-induced changes were compared against an
37	undeveloped forested watershed during the same time period. Changes in elevations, slopes,
38	hypsometry, and surface flow pathways were tracked throughout the development process to
39	assess watershed geomorphic alterations. Results suggest that development produced an increase
40	in sharp topographic breaks between relatively flat surfaces and steep slopes, replacing smoothly
41	varying hillslopes and leading to greater variation in slopes. Examinations of flowpath
42	distributions highlight systematic modifications that favor rapid convergence in unchanneled
43	upland areas. Evidence of channel additions in the form of engineered surface conduits is
44	apparent in comparisons of pre- and post-development stream maps. These results suggest that
45	topographic modification, in addition to impervious surfaces, contributes to altered hydrologic
46	dynamics observed in urban systems. This work highlights important considerations for the use
47	of repeat LiDAR flights in analyzing watershed change through time. Novel methods introduced
48	here may allow improved understanding and targeted mitigation of the processes driving

49 geomorphic changes during development and help guide future research directions for development-based watershed studies. 50 51 52 *Keywords*: LiDAR time series; urbanization; land cover change; digital elevation models; anthropogenic geomorphology; watershed 53 54 1. Introduction 55 56 At least one-third of the Earth's continental surface has undergone some form of anthropogenic 57 geomorphological activity (Rózsa, 2010). Of these activities, construction and urban 58 development stand out as ongoing and expanding causes of geomorphic change characterized by 59 rapid, complex, and multiscalar processes. Throughout urban development, extensive landscape 60 grading, leveling, and terracing can change the fundamental organization of topography within a 61 watershed (Tenenbaum et al., 2006; Csima, 2010). The current ability to track, quantify, and 62 63 predict development-induced geomorphic changes is hindered by insufficient data and reliance on methodologies developed for traditional geomorphic studies in natural settings (Djokic and 64 Maidment, 1991; Haff, 2003; Gironás et al., 2010; Rózsa, 2010; Szabo, 2010). High-resolution 65 topographic data, such as Light Detection and Ranging (LiDAR), is required to resolve surface 66 flowpaths and visualize roads and other fine-scale features in urban landscapes (Djokic and 67 Maidment, 1991; Tenenbaum et al., 2006; Hunter et al., 2008; Gironás et al., 2010). Sequential 68 topographic data sets are needed to track and quantify the multiscalar (Bochis and Pitt, 2005; 69 Tenenbaum et al., 2006; Bochis, 2007) and temporally variable (MDE, 2000; Dietz and Clausen, 70 2008) topographic changes throughout development. No studies have utilized a high-resolution 71

72 digital elevation model (DEM) time series to track geomorphic changes throughout the

73 development process.

74

75	The topographic footprint of development is visually striking on the ground and from the air,
76	highlighting large-scale landscaping carried out during initial development phases (Csima,
77	2010). Final smoothing and regrading occurs at finer scales that are less immediately apparent in
78	topographic data, but are nonetheless important for understanding surficial drainage and altered
79	geomorphic characteristics (MDE, 2000; Tenenbaum et al., 2006). How best to quantify such
80	topographic changes is unclear in terms of selecting geomorphic variables and spatial scales that
81	most effectively capture observed changes (Haff, 2003; Rózsa, 2010). Topographic variables
82	such as slope, curvature, and their distribution relative to watershed area play important roles in
83	sediment transport and erosion dynamics (Moore et al., 1991; Montgomery and Foufoula-
84	Georgiou, 1993; James et al., 2007), channel formation (Band, 1993; Montgomery and Foufoula-
85	Georgiou, 1993), and surface water – groundwater exchanges (Beven and Kirkby, 1979; Moore
86	et al., 1991; Tenenbaum et al., 2006). However, topographic controls on hydrologic and
87	geomorphic processes may be altered in urban landscapes because of infrastructure (e.g., roads,
88	pipes) (Djokic and Maidment, 1991; Tenenbaum et al., 2006; Gironás et al., 2009; Rózsa, 2010;
89	Choi, 2012).
90	

Five sequential LiDAR-derived DEMs spanning the development of two small, historically
agricultural watersheds were obtained to track geomorphic changes throughout development.
The goal of this study is to understand how and where geomorphic changes manifest within these
watersheds and to understand their implications for watershed geomorphic and hydrologic

95	processes prior to accounting for influences of stormwater infrastructure. The DEM coverage of
96	a third, forested reference watershed was used to track temporal variation not attributable to
97	development. This work will introduce a number of novel methods for tracking temporal
98	geomorphic changes using sequential LiDAR DEMs and will highlight unique geomorphic
99	signatures of the development process. Results of this study will help guide ongoing research
100	efforts that focus on the coupled influence of topography and infrastructure on watershed
101	function.
102	
103	2. Site description
104	
105	For this study, three watersheds in Montgomery County, Maryland, within the Piedmont
106	Physiographic Province were examined. All three watersheds are within the Mt. Airy Uplands
107	District, characterized by siltstones and quartzite with underlying crystalline bedrock consisting
108	of a phyllite/slate unit, with average annual precipitation of 106.4 cm (Reger and Cleaves, 2008;
109	Hogan et al., $\frac{20132014}{2014}$). Soper Branch (forested control) drains an area of ~ 3.4 km ² with an
110	overall mean gradient of 13%. Land cover is predominantly classified as deciduous forest (~
111	85%) and small percentages of low-density housing and agriculture (6 and 9%, respectively)
112	(Hogan et al., 20132014; Dr. J.V. Loperfido, USGS, oral communication, July 2013). Tributaries
113	104 and 109 (T104 and T109, urbanizing) drain areas of ~ 1.2 and 0.9 km^2 with mean gradients
114	of 11 and 8%, respectively. Tributaries 104 and 109 are historically agricultural watersheds that
115	underwent extensive suburban development from 2003 to the present. Tributary 104 land use
116	shifted from 41% agriculture, 0.3% barren, 42% forest, and 17% urban in 2002 to 2%
117	agriculture, 15% barren, 19% forest, and 64% urban in 2008. Across the same time period, T109

changed from 64% agriculture, 1% barren, 25% forest, and 10% urban to 45% agriculture, 13%
barren, 25% forest, and 17% urban (Hogan et al., 20132014). Both T104 and T109 were used in
analyses of development-induced geomorphic changes. However, development in T109 was not
complete at the time of the last LiDAR flight, so the final T109 DEM represents a different stage
of development than T104.

123

Tributaries 104 and 109 fall within the Clarksburg Special Protection Area (CSPA, established in 124 125 1994) and are subject to development guidelines and restrictions (Maryland DEP, 2013). Broadly speaking, the Special Protection Area designation identifies areas with high quality natural 126 resources and requires ongoing and future development projects to implement best available 127 water quality and quantity protection measures. Water quality and quantity measures often 128 exceed minimum local and state regulations and include extensive Best Management Practices 129 130 (BMPs) implementation during (sediment and erosion controls; S&EC) and after development (stormwater management; SWM) (Hogan et al., 20132014). Each watershed has extensive storm 131 sewer (SS) infrastructure in addition to noted BMP and SWM structures. While SS infrastructure 132 likely plays a key role in dictating watershed hydrology, the purpose of this study is to document 133 geomorphic changes and their hydrologic implications independent of SS influence. Ongoing 134 135 research will incorporate SS infrastructure to distinguish its effects from geomorphic impacts and better account for watershed hydrologic dynamics. 136

137

138 **3. Data description and methods**

140	Five sequential LiDAR-derived 1-m bare-earth point clouds were collected at semiannual
141	intervals from 2002 to 2008 to track development-induced topographic changes in T104 and
142	T109 and background topographic changes in Soper Branch. Detailed LiDAR vendor,
143	instrumentation, and accuracy information are provided by Jarnagin (2010). Building removal
144	and bare-earth point cloud filtering was performed by each LiDAR vendor utilizing proprietary
145	software, summarized in Table 1. Differences in bare-earth filtering algorithms used by different
146	vendors may have caused interpolated topography within filtered building footprints to vary
147	between dates. Therefore, topographic patterns within building footprints may reflect filtering
148	artifacts and should be interpreted with a degree of uncertainty.
149	
150	Insert Table 1 near here.
151	
152	LiDAR was collected as part of a larger monitoring effort to track watershed changes throughout
153	development and to document development effects on local resources through time (Jarnagin,
154	2008). Detailed comparisons between LiDAR spot elevations and field-surveyed elevations
155	
	across a range of slope, elevation, and land use classes are reported by Gardina (2008) and
156	across a range of slope, elevation, and land use classes are reported by Gardina (2008) and Jarnagin (2010). One-meter resolution DEMs were interpolated from bare-earth point clouds
156 157	across a range of slope, elevation, and land use classes are reported by Gardina (2008) and Jarnagin (2010). One-meter resolution DEMs were interpolated from bare-earth point clouds using the natural neighbor interpolation algorithm (Sibson, 1981). The DEMs were then
156 157 158	across a range of slope, elevation, and land use classes are reported by Gardina (2008) and Jarnagin (2010). One-meter resolution DEMs were interpolated from bare-earth point clouds using the natural neighbor interpolation algorithm (Sibson, 1981). The DEMs were then coarsened to 2-m horizontal resolution to smooth and reduce noise in the interpolated
156 157 158 159	across a range of slope, elevation, and land use classes are reported by Gardina (2008) and Jarnagin (2010). One-meter resolution DEMs were interpolated from bare-earth point clouds using the natural neighbor interpolation algorithm (Sibson, 1981). The DEMs were then coarsened to 2-m horizontal resolution to smooth and reduce noise in the interpolated topography. All subsequent spatial analyses were performed using the interpolated 2-m DEMs
156 157 158 159 160	across a range of slope, elevation, and land use classes are reported by Gardina (2008) and Jarnagin (2010). One-meter resolution DEMs were interpolated from bare-earth point clouds using the natural neighbor interpolation algorithm (Sibson, 1981). The DEMs were then coarsened to 2-m horizontal resolution to smooth and reduce noise in the interpolated topography. All subsequent spatial analyses were performed using the interpolated 2-m DEMs in ArcMap 9.3 ¹ (EsriESRI, Redlands, CA).

 $^{^{1}}$ Any use of trade, firm, or product names is for identification purposes only and does not imply endorsement by the U.S. Government.

162 *3.1. Elevation change*

163

164 Differencing sequential DEMs has been used to estimate sediment budgets, to identify nutrient 165 and sediment sources and sinks (Thoma et al., 2005), and to track gully evolution through time 166 (Perroy et al., 2010). Raw difference calculations, however, do not incorporate any estimate of the error inherent across different DEMs or LiDAR vendors (e.g., they imply that all observed 167 elevation differences are real). Further, LiDAR precision has been shown to vary across land 168 cover classes—with forest cover exhibiting the lowest precision (Gardina, 2008; Jarnagin, 2010). 169 Therefore, comparisons of absolute elevation change estimates across differing land cover 170 classes may be misleading. 171

172

To correct for the inherent variability in elevation estimates through time, DEM differences were
expressed as standard deviations (SD) through time calculated for each pixel in each watershed
as

$$SD = \sqrt{\frac{1}{N} \sum_{i=year}^{N} (x_i - \mu)^2}$$
(1)

176

where *N* is the number of DEM years (5), x_i is the elevation for a given pixel *x* in year *i*, and μ is the mean elevation of pixel *x* across the five DEM years. The distribution of elevation SDs in Soper Branch was then used to quantify background elevation variability in T104 and T109. The SD distribution in Soper Branch was filtered to exclude all known areas with recent anthropogenic activities or structures to assure the distribution of SDs were indicative of the background signal. Any remaining non-zero SD in Soper Branch was assumed to be attributable

183	to either natural causes or uncertainty in the LiDAR data. Because of the decreased elevation
184	precision observed within forested pixels (e.g., Gardina, 2008; Jarnagin, 2010), the use of Soper
185	Branch to quantify background LiDAR variability was a conservative baseline for detecting
186	change in nonforest areas. To detect elevation changes associated with the development process
187	resulting SD maps were classified based on the distribution of SDs in Soper Branch, with an
188	additional class added to distinguish SD values outside of the range observed in Soper Branch.
189	Classes represent SD values less than or equal to the mean, within three standard deviations of
190	the mean, and SD values greater than three standard deviations from the mean. Any elevation
191	change above the maximum SD observed in Soper Branch is assumed to be attributable to the
192	development process.
193	

3.2. Slope change

196	The distribution of local slopes from before and after development in T104 were quantified and
197	classified to ranges relevant to landscape development decisions described by Csima (2010;
198	Table 2). Each slope class in the pre-development landscape provides an indication of the
199	relative development costs and earth-moving practices used across the watershed. A
200	representative cross section was extracted for pre- (2002) and post- (2008) development years to
201	highlight changes in the juxtaposition of high and low sloping areas and to differentiate spatial
202	patterns associated with modified and unmodified areas. More broadly, changes in local terrain
203	created by reallocating and relocating slopes were mapped using areal standard deviations of
204	slope within a 10 x 10 pixel square neighborhood of every focal pixel x_i . Comparison of maps

205 resulting from pre- and post-development DEMs further highlighted changes in the variability of local landscapes associated with development practices. 206 207 208 Insert Table 2 near here. 209 210 3.3. Hypsometric curves 211 212 Hypsometric curves represent the proportion of a watershed's area (a/A) that is above a given elevation (h/H), providing a generalized approximation of hillslope shape within the watershed. 213 214 Traditionally, hypsometric curves have been used in discussions of landscape evolution across broad spatial extents (e.g., Strahler, 1957). Other studies have found hypsometric curve shape 215 indicative of dominant erosional mechanisms (Harlin, 1980; Luo, 2000), hydrologic response 216 (Luo and Harlin, 2003), and infiltration dynamics (Vivoni et al., 2008). Hypsometric curves were 217 generated for each DEM year based on first-order catchment and full watershed scales to 218 219 compare and contrast hillslope topographic alterations at increasingly broader spatial extents. Consistent boundaries were used for each year to assure that any hypsometric variability through 220 221 time was attributable to topographic changes and not to boundary shifts caused by topographic 222 modification along drainage divides. Hypsometric curves for each year were compared to assess 223 hillslope level changes through time. A map of net fill and excavation (DEM₂₀₀₈ - DEM₂₀₀₂) was also developed to help interpret hypsometric trends. 224 225 226 3.4. Drainage network change

228	Topographically based drainage network delineation methods are widely used across a range of
229	land covers and climates. The most common approaches rely on threshold relationships of
230	derivative watershed properties (e.g., drainage area, slope area relationship) to define
231	upslope channel extents (e.g., O'Callaghan and Mark, 1984; Montgomery and Foufoula-
232	Georgiou, 1993). Other techniques utilize local topography to extract convergent drainage
233	features and stream heads directly (e.g., plan/profile curvature), but have seen much less use due
234	tobecause of higher topographic data resolution required for feature detection (Tribe, 1992;
235	Band, 1993; Tarboton and Ames, 2001; Lindsay, 2006). A number of threshold-type approaches
236	have been shown to provide reasonable approximations of field-surveyed channel networks
237	(extent and complexity) (Heine et al., 2004; James et al., 2007; James and Hunt, 2010).
238	However, threshold-based methods are insufficient for determining the location and occurrence
239	of artificial urban conduits (e.g., swales, gutters) whose location is based on design
240	specifications, not physical processes (Gironás et al., 2010; Jankowfsky et al., 2012).
241	
242	Topographic openness (a measure of tangential curvature; see Yokoyama et al., 2002) was
243	employed to identify surface networks in the pre-development terrain of T104 and then applied
244	to the post-development terrain to compare surface network changes. Topographic openness is
245	an angular relation of horizontal distance to vertical relief, calculated from above
246	(positive/zenith) and below (negative/nadir) a topographic surface (DEM). For an angle less
247	than \leq 90°, openness is equivalent to the internal angle of an inverted cone, its apex at the focal
248	DEM pixel, constrained by neighboring elevations within a specified radial distance.
249	Topographic openness is more robust in identifying surface convexities and concavities than
250	commonly used profile and plan curvature (Yokoyama et al., 2002) and has been successfully

251	applied to LiDAR to identify convergent topography (Molloy and Stepinski, 2007; Sofia et al.,
252	2011). Topographic openness was calculated using an Arc Macro Language (AML) script
253	(written by M.E. Baker, <u>UMBC-2005</u> , personal communication, 2005) that reproduces the
254	methods detailed in Yokoyama et al. (2002). The AML extracts DEM values for all relevant cells
255	in a neighborhood set for each focal pixel x_i (defined by stepwise increments of one pixel width
256	in each of eight azimuth directions until a specified search radius is reached; here we used 100
257	m) in a landscape. For each increment, the horizontal distance from and elevation above the
258	focal pixel is calculated, and an arctan function converts opposite:adjacent ratios to angular
259	degrees. The AML tracks a running maximum and minimum angle across each radial increment
260	and all smaller increments for all eight directions, converts the resulting maxima and minima to
261	zenith and nadir angles, and computes the mean of each across all eight directions. Thus the
262	final openness values represent the averaged openness measure for all eight azimuths across the
263	specified search radius.
264	
265	Difference DEMs and ortho-imagery were used to identify detention basins and other potential
266	barriers to surface flow. Pre- and post-development DEMs were filled to overcome internal
267	drainages (i.e., "_pits")_) and then subtracted from unfilled DEMs to assess filling extents. Paths
268	were carved from detention basin low points to the next downslope pixel of equal or lesser
269	elevation outside of the filled zone. Where possible, carved pathways followed detention basin
270	outlets identified from areal and ground surveys. No attempt was made to account for flowpaths
271	within internal drainage basins or subsurface drainage infrastructure. Straight-line pathways were
272	enforced for all unknown detention basin outlets. Flow directions were calculated for each year

273 from the pit-resolved DEMs by enforcing drainage from each DEM pixel to the adjacent or

274	diagonal pixel with the greatest drop in relief (see O'Callaghan and Mark, 1984). D8 flow
275	directions were calculated for each year using the pit resolved DEMs (e.g., O'Callaghan and
276	Mark, 1984), Resulting flow direction surfaces were used to generate drainage networks and
277	other derivative surfaces from which drainage networks and other derivative surfaces were
278	generated .
279	
280	To create a stream map, ortho-imagery and hillshaded DEMs were overlain with openness grids
281	to determine the critical openness for identifying surface depressions in the pre-development
282	T104 DEM. A negative openness (nadir) angle of 91.5 ^o degrees was determined to sufficiently
283	capture all visible surface depressions. All pixels at or above 91.5 ^o degrees were identified, and
284	then connected using a D8-based accumulation operation to enforce downslope continuity from
285	each depression (Tarboton and Baker, 2008). The pre-development stream map (as defined by
286	downslope accumulation of depression pixels) was then tested for agreement with the constant
287	drop law, which states that the mean elevation drop across channels within a given Strahler order
288	should not be significantly different from the mean drop in the next higher order (Tarboton et al.,
289	1991). Incremental accumulation thresholds of depression pixels were used to prune the pre-
290	development stream map until it satisfied the constant drop law. The pre-development
291	accumulation threshold was then applied to the post-development depression accumulation map
292	to define the post-development stream map. Pre- and post-development stream maps were
293	overlain and compared to assess network changes. Field visits were also conducted to classify
294	channels as either natural (defined banks, sorted bed-load, evidence of ongoing or recent flow) or
295	artificial (e.g., swales, outflow pipes, rip rap).

297 4. I	Results
-----------------	---------

299	Hillshades of each DEM year highlight the spatial pattern of surface modifications incrementally
300	throughout development (Figure Fig. 1). Initial large-scale resurfacing throughout the watershed
301	is clear in 2004 and 2006 hillshades, with urban or suburban infrastructure distinguishable in the
302	terrain. Fine-scale grading and smoothing that is much less visually apparent in the LiDAR
303	characterize late-stage development in 2006 and 2008. Valley burial is evident in the western
304	portion of the watershed (see red arrow in Figure Fig. 1), replaced by a smooth upland housing
305	cluster and roadway. Mainstem valley form remained relatively constant throughout the time
306	series, with little to no visual evidence of lateral channel movement.
307	
308	Insert Figure 1 near here.
309	
310	4.1. Elevation standard deviations
311	
312	Pixelate elevation standard deviations (SD) calculated across the five DEM years were
313	approximately normally distributed in Soper Branch with a mean of 0.063 m and a standard
314	deviation of 0.034 m, ranging from 0.002-to 0.870 m. Areas with temporal SDs greater than or
315	equal to three standard deviations of the watershed mean (≥ 0.163 m) were focused within
316	riparian zones at or near stream banks and near the basin outlet within a relatively flat and wide
317	floodplain area (Figure Fig. 2). Jarnagin (2010) reported similar LiDAR errors within densely
318	vegetated riparian zones in comparisons between ground-truth and LiDAR spot elevations
319	(absolute mean difference of 0.216 m with a standard deviation of 0.723 m and a maximum

320	difference of 1.180 m). Moderately high SDs (0.063-0.163 m) are also apparent on northeast-
321	(NE) facing hillslopes. The temporal variation observed on NE-NE-facing slopes was greater
322	than systematic errors reported for ground survey and LiDAR-derived elevations, which
323	exhibited a mean absolute difference of ~ 0.05 m (Gardina, 2008).
324	
325	Elevation changes in T104 and T109 classified to the distribution of temporal SDs in Soper
326	Branch highlight large areas exhibiting substantial elevation changes greater than the variability
327	observed in forested controls. White areas in T104 and T109 signify temporal elevation SD
328	values that are above the maximum observed in Soper Branch (> 0.870 m), encompassing
329	approximately ~ 24.4% and 9.9% of total watershed area, respectively. Distinct patches of high
330	elevation variability are primarily located in development parcels evident in the post-
331	development hillshades (2008 panel in Figure-Fig. 1). High temporal variability (0.163-0.870 m)
332	is also apparent along the mainstem channel of $T104_{\overline{2}}$ but is less evident in T109. Relatively low
333	temporal SD values in the southern undeveloped portion of T109 and within riparian zones in
334	T104 reflect magnitudes of temporal variability similar to those observed in Soper Branch. Such
335	heterogeneous distribution of elevation change is consistent with the observation that earth-
336	moving practices were not spatially uniform across developing parcels.
337	
338	Insert Figure 2 here.

- 339
- 4.2. Slopes 340

342	The footprint of development is clearly distinguishable from unmodified hillslopes in a visual	
343	comparison of pre- and post-development slope maps (Figure Fig. 3). Development created	
344	abrupt slope changes in the landscape, replacing relatively smooth topographic profiles (i.e., gray	
345	boxes in inset). Moderate to high slope classes (>12%) were present along roads, housing	
346	parcels, and stormwater management features, despite the use of bare-earth LiDAR with	
347	buildings removed by filtering. Valley infill is apparent in the slope transect between points p_{a}	Form
348	and b at ~ 180 m with no evidence of the original valley structure in the post-development	Form
349	topography. High-frequency variation between low slope and high slope features is evident in the	
350	slope transect between 420 and 580 m across a developed subdivision.	
351		
352	Insert Figure 3 here.	
353		
354	Areal slope standard deviations calculated using a 10 x 10 pixel moving window show a marked	
355	increase in the spatial variability of local slope values in post-development topography (Figure	
356	Fig. 4). The overall distribution of variation in local slopes exhibited a positive shift from the	
357	pre- (mean areal slope standard deviation of 2.35 ± 2.26 -%) to post-development terrain (mean	
358	areal slope standard deviation of 4.69 \pm 3.54-%). Highly variable slope zones in 2002 were	
359	limited to riparian corridors and pre-existing development plots in the northern section of T104.	
360	By contrast, post-development slopes exhibit greater local variation (i.e., both-steeper and flatter	
361	terrain in close proximity) associated with the grading of subdivisions and road embankments.	
362		
363	Insert Figure 4 here.	

Formatted: Font: Italic

Formatted: Font: Italic

363

365 *4.3. Hypsometry*

367	Despite substantial topographic changes across the watershed visible in hillshades and slope
368	maps representing different stages of development, hypsometric changes due to the to
369	development only manifest when observed across small extents with relatively uniform, high
370	magnitude surface changes (Figure-Fig. 5). Distinctly terraced hypsometric curves appear in the
371	end-development phase topography, mirroring abrupt slope changes along roadways and
372	surrounding housing parcels (see insets A and C in Figure Fig. 5). Valley infill in subwatershed
373	A (see red arrow in Figure Fig. 1) created a sharp elevation gradient to the remaining riparian
374	lowlands, reflected in the 2007 and 2008 hypsometric curves. Terracing and leveling of upslope
375	transportation corridors also contribute to the terraced hypsometric form. Hypsometric trends of
376	the larger subwatershed B ₇ and at the full watershed scale (D) did not exhibit detectable temporal
377	changes.
378	
379	Insert Figure 5 here.
380	
381	4.4. Drainage network changes
382	
383	Substantial redistribution of overland flowpaths is evident in comparisons of pre- and post-
384	development flow direction grids (Figure Fig. 6). As with slope comparisons, the most drastic
385	changes in flow directions are focused along roadways and within housing parcels. Small patches
386	of uniform flow directions mirroring housing and road footprints have replaced large, contiguous
387	patches of homogenous flow directions (i.e., parallel flow lines) on upland hillslopes. Fine-scale

388	variation in flow directions within relatively minor elevation change zones (see elevation change
389	inset in Figure Fig. 6) are coupled with more dramatic modifications within drainage features
390	and near infrastructure. As a result of these alterations to the flow field, flow accumulation
391	distributions exhibited a negative shift, with accumulation quartiles decreasing from 4, 11, and
392	29 pixels in 2002 to 1, 4, and 12 pixels in 2008. Distributional shifts reflect drainage dissection
393	and the fragmented flow field apparent in Figure Fig. 6 with small, locally convergent pathways
394	replacing large, contiguous, parallel flowpaths.
395	
396	Insert figure 6 here.
397	
398	A depression pixel (openness \geq 91.5°) accumulation threshold of three pixels was found to
399	satisfy the constant drop criterion in the pre-development terrain of T104. The three-pixel
400	threshold was then applied to the post-development terrain to evaluate surface network changes.
401	Comparisons of pre- and post-development drainage network structure in T104 indicate a net
402	gain in stream length of 4.25 km (~ 52% increase) throughout the watershed ($\frac{\text{Figure-Fig.}}{\text{Fig.}}$).
403	Additions were common along transportation infrastructure as swales or gutters typical in this
404	watershed. Upslope extensions of existing channels also occurred extending beyond pre-existing
405	piped infrastructure at the apparent head of pre-development drainage lines (inset A in Figure
406	Fig. 7 <u>A</u>). Valley infill (see subwatershed A in Figure see Fig. 6 <u>A</u>) caused the loss of a tributary,
407	but was replaced by an artificial conduit that paralleled a nearby road (inset B in Figure Fig. 7B).
408	Similar conduits are apparent on the eastern side of the watershed as well (inset C in Figure Fig.
409	7 \underline{C}). No substantial changes were apparent in the mainstem channel as suggested by the near 1:1
410	overlap in pre- and post-development networks.

412 Insert Figure 7 here.

413

414 **5. Discussion**

415

The growing footprint of development in T104 is clearly visible in the DEM hillshade time 416 series, with distinct early₂ and late-stage development phases operating at unique spatial scales 417 (Figure Fig. 1). Large-scale cutting and filling to support major infrastructure characterizes early 418 419 development, evident in the 2004 and 2006 hillshades. In contrast, fine-scale leveling and 420 grading of housing parcels characterize late-stage development (MDE, 2000). Fine-scale earth movingearth-moving practices are less immediately apparent in hillshades, but are detectable in 421 derivative data sets, as this study has shown. Results show that geomorphic changes associated 422 with urban development are significant and non-uniform, and could have implications for 423 management and conservation efforts. 424

425

Initial analysis of background elevation changes in Soper Branch revealed non-zero standard 426 427 deviations focused on northeast_ (NE) facing hillslopes, and within riparian and floodplain areas (Figure Fig. 2). Increased variation on NE hillslopes may reflect flight paths taken during LiDAR 428 collection, or possible aspect differences in vegetation and soils. Slightly lower systematic errors 429 430 reported in Gardina (2008) were attributed in part to methods used to derive bare-earth point clouds, and, in part, to LiDAR system error. It is likely that tThe NE artifact likely is a 431 combination of vegetation and LiDAR system errors. Riparian and floodplain variability in 432 Soper Branch can be attributed to LiDAR errors reported by Jarnagin (2010). In comparisons 433

between LiDAR elevations and field-field-surveyed spot elevations, Jarnagin observed greater
LiDAR error in densely vegetated riparian zones and on steep slopes common around incised
channels. Distinguishing temporal variability attributable to artifacts in the LiDAR time series
was necessary before reaching any quantitative conclusions about topographic changes resulting
from development.

439

Elevation standard deviations classified to distinguish background and development-induced 440 changes clearly show that earth moving in T104 and T109 was nonetheless substantially greater 441 than background geomorphic changes observed in Soper Branch. Magnitudes similar to temporal 442 443 standard deviations found in Soper Branch were observed in T104 across pre-existing housing parcels and riparian zones left untouched to comply with riparian protection policies. Somewhat 444 higher variability observed along the mainstem channel in T104 may indicate subtle channel 445 446 shifts and bank erosion throughout the time period despite attempts to insulate the channel from the hydrologic and geomorphic effects of development. It is a Also, possible that some of the 447 448 observed elevation changes may possibly reflect artifacts produced by removing buildings from the raw LiDAR point clouds. Because of the proprietary nature of the LiDAR processing, it was 449 not possible to evaluatinge the bare_-earth detection algorithms used by the data providers was 450 not possible for this study. 451

452

453 Surface changes throughout development in T104 and T109 altered slopes to support

454 infrastructure, enforce drainage, and promote infiltration. Comparison of pre- and post-

455 development slope maps in T104 shows a marked increase in high slope classes with

456 development as well as reallocation across space (Figure Fig. 3). High slope classes focused

457	along transportation corridors and surrounding detention basins are likely to promote surface
458	drainage. Slopes leading toward streams in the pre-development map appear to steepen with
459	development as well, likely reflecting upland filling and terracing. Stream burial is a frequently
460	cited phenomenon in urban watersheds (Leopold et al., 2005; Elmore and Kaushal, 2008; Roy et
461	al., 2009; Doyle and Bernhardt, 2011) and is apparent on the western side of T104 (~_180 m in
462	transect inset of Figure Fig. 3). However, it is unclear without infrastructure design documents it
463	is difficult to determine whether the stream is piped under its original flowpath, or if it has been
464	redirected to flow alongside the nearby main-road running north to south.
465	
466	Regular shifts between high and low slopes within subdivisions likely reflect housing parcels
467	(low slopes) separated by graded lawns and swales (higher slopes) to promote drainage (Figure

Fig. 4). Low slopes within building footprints reflect the building removal algorithm applied to
LiDAR point clouds to extract bare-earth points used in this study to create DEMs. The spatial
distribution of high and low slopes in part controls the spatial distribution of runoff generation
and infiltration zones (Beven and Kirkby, 1979; Tenenbaum et al., 2006). Shifts in the spatial
pattern and magnitude of slopes may contribute to altered watershed processes including runoff
generation, nutrient and sediment transport, and surface water-groundwater water – groundwater
exchanges.

475

Hypsometric trends within small subwatersheds of T104 appear to mirror aforementioned
steepening of valley walls with development (Figure Fig. 5). Upland filling and grading further
exacerbates the disparity in elevations between the now now-developed uplands and the riparian
lowlands. Redistribution of flowpaths at and around valley infills likely altered surface and

480 subsurface water exchanges, thus changing the functional connectivity of upland and lowland areas. Dynamics are further complicated by stormwater management infrastructure, such as 481 detention ponds and infiltration trenches, typically located between upland (development plots) 482 483 and lowland (riparian zone) areas to capture and treat overland runoff before it enters local streams (Montgomery County Planning Department, 1994). Thus, riparian areas may no longer 484 485 be functionally connected to upland areas during rain events unless stormwater management outfalls are triggered. Further research is required to investigate the nature of the altered surface-486 groundwater surface - groundwater connections. Lack of temporal trends in the larger 487 subwatershed topography or throughout the entire watershed result from spatial averaging, and 488 489 may indicate a detection limit for tracking parcel or block-level topographic change with 490 hypsometry.

491

492 Development caused a substantial reconfiguration of overland flowpaths from large contiguous areas of uniform directions to small, spatially fragmented patches (Figure-Fig. 6). The non-493 494 random distribution of smaller patches mirrors housing footprints, transportation corridors, and 495 stormwater management infrastructure, and reflects landscape-engineering practices that promote efficient collection and drainage of overland runoff (Figure Fig. 7). Adjacent pixels with 496 uniform directions indicate parallel flowpaths, which will not converge until a pixel with a 497 differing direction is encountered downslope (O'Callaghan and Mark, 1984). By introducing 498 499 heterogeneity into the flow direction surface, development has created both more dissected 500 subbasins and increased opportunities for small flowpaths to converge. Increased convergence in upland areas causes overland flow to reach moderately low accumulations more often and very 501 high accumulations more rarely than in the pre-development terrain. Decreased median and first 502

503 first-quartile values between 2002 and 2008 reflect the dominance of low accumulation pathways 504 with development. Such alterations are likely the cumulative result of many site-specific efforts to increase local water conveyance, but their cumulative effect should also have implications for 505 506 patterns of soil moisture, variable source area, erosion, infiltration, and recharge (Beven and 507 Kirkby, 1979; Moore et al., 1991; Tenenbaum et al., 2006). To our knowledge, a geomorphic driver of increased upland convergence in developed terrain has yet to be described in the 508 literature. Typically, pipes and impervious surfaces are thought to be the causal agents of altered 509 runoff, nutrient, and sediment dynamics in urban watersheds (e.g., Paul and Meyer, 2001; Dietz 510 and Clausen, 2008; Roy et al., 2008). However, our results indicate that the geomorphic 511 modifications that occur with development are substantial and could also contribute to altered 512 513 watershed functions.

514

515 Comparisons of pre- and post-development drainage networks reveal channel additions through 516 engineered surface conduits (e.g., swales, culverts), and losses due tocaused by valley infill or 517 subsurface routing (Figure Fig. 7). Despite noted variability in elevations along stream banks, only minor shifts were apparent in the mainstem of T104. Results of this study also raise 518 questions about what constitutes a channel in an urban landscape. Traditional channel 519 definitions, characterized by defined banks and sorted bedloads (Montgomery and Dietrich, 520 1989; Heine et al., 2004) exclude engineered surface conduits that become active during 521 522 precipitation events (Doyle and Bernhardt, 2011). Excluding these artificial conduits and subsurface stormwater pipes may under-represent the surficial connectivity of urban watersheds. 523 524 Without infrastructure design documents, the true drainage connectivity of the watershed is unclear. Ongoing work will explore methods for incorporating subsurface drainage features into 525

526 T104 network representations (e.g., Gironás et al., 2009; Choi, 2012; Jankowfsky et al., 2012) and determine how best to incorporate BMP infrastructure into predicted network 527 representations. Nevertheless, this study indicates an overall increase in surface connectivity 528 529 with development independent of changes in impervious surface cover or subsurface stormwater 530 infrastructure. Increased connectivity would result in faster and larger storm peaks if left unchecked by stormwater management infrastructure. Therefore, considering geomorphic 531 532 changes in addition to impervious surface cover impacts is important for remediation efforts in 533 urban areas.

534

535 6. Conclusions

536

537 This study has shown the utility of sequential LiDAR-derived DEMs for tracking and 538 quantifying the geomorphic changes associated with development. Using a forested watershed as a reference, background topographic variability was quantified and differentiated from 539 540 development-induced topographic change. Utilizing first- and second-order topographic 541 derivatives, this study demonstrated that development generates increasingly disjointed hillslopes characterized by abrupt slope changes separating flat upland areas. Temporal variation in 542 543 elevations, slopes, and hypsometric curves likely contributes to altered watershed functions, but 544 further research is required to understand their importance relative to stormwater infrastructure. 545 Substantial modification of overland flowpaths resulted in subtle changes to delineated network structure, highlighting additions and losses to the pre-development network. This study's ability 546 547 to detect natural and manmade ephemeral surface conduits provides a more complete accounting of watershed hydrologic connectivity. Better accounting of upslope ephemeral channel 548

549	extensions may help in designating areas for protection in future development projects. The
550	geomorphic signal of increased landscape convergence and drainage density indicates more rapid
551	runoff generation and conveyance independent of impervious surface cover or storm sewers. A
552	better understanding of how and where geomorphic changes occur throughout development may
553	enable a better understanding of pollutant mobilization and retention processes. Ongoing work
554	seeks to incorporate known subsurface pipe and BMP structures into surface network
555	representations to understand watershed hydrologic response dynamics.
556	
557	Results presented here raise important considerations for temporal topographic studies. Standard
558	topographic methods developed for use in larger, mostly non-urban watersheds (e.g., DEM
559	differencing, hypsometry) have limited applicability for tracking urbanization unless summarized
560	across a relatively small extent. Additional research is needed to gain a better understanding and
561	to develop novel methods for tracking and quantifying urban topographic modifications.
562	
563	7. Acknowledgements
564	
565	LiDAR funding provided in part by the U.S. Environmental Protection Agency under contract
566	number EP-D-05-088 to Lockheed Martin. The U.S. Environmental Protection Agency through
567	its Office of Research and Development collaborated in the research described here. This
568	manuscript has been subjected to Agency review and approved for publication. This work would
569	not have been possible without the Clarksburg Integrated Study Partnership, which includes the
570	U.S. Environmental Protection Agency Landscape Ecology Branch (USEPA LEB), Montgomery
571	County Department of Environmental Protection (DEP), the U.S. Geological Survey Eastern

572	Geographic Science Center (USGS EGSC), the University of Maryland (UMD), and the	
573	University of Maryland, Baltimore County (UMBC). We would like to thank Adam Bentham	
574	and one anonymous referee for providing constructive feedback on our paper during the review	
575	process.	
576		
577	8. References	
578		
579	Band, L.E., 1993. Extraction of <u>c</u> Channel <u>n</u> Networks and <u>t</u> Topographic <u>p</u> Parameters from	Formatted: Line spacing: Double
580	<u>d</u> Ðigital <u>e</u> Elevation <u>d</u> Ðata. In: <u>K.J.</u> Beven <u>, K.J., and M.J.</u> Kirkby <u>, M.J. (EditorsEds.</u>),	
581	Channel Network Hydrology. Wiley, New York, NY, pp. 13-42.	
582	Beven, K.J., and Kirkby, M.J., 1979. A physically based, variable contributing area model of	
583	basin hydrology. Hydrological Sciences Bulletin , 24(1), 43-69.	
584	Bochis, E.C., 2007. Magnitude of impervious surfaces in urban areas. M.S. Thesis, University of	
585	<u>Alabama, Tuscaloosa, 165 pp.</u>	
586	Bochis, E.C., and Pitt, R., 2005. Site development characteristics for stormwater modeling, In:	Formatted: Line spacing: Double
587	78th Annual Water Environment Federation Technical Exposition and Conference,	
588	Washington, D.C., October 29-November 2. Washington, D.C., pp. 37.	
589	Bochis, E.C., 2007. Magnitude of impervious surfaces in urban areas, University of Alabama,	
590	Tuscaloosa, 165 pp.	
591	Choi, Y., 2012. A new algorithm to calculate weighted flow-accumulation from a DEM by	
592	considering surface and underground stormwater infrastructure. Environmental	
593	Modelling & Software , 30(0):-). 81-91.	

594	Csima, P., 2010. Urban development and anthropogenic geomorphology. In: J. Szabó, J., L.	
595	Dávid, L.and., D. Lóczy, D. (Editors.), Anthropogenic Geomorphology: A Guide to Man-	
596	Made Landforms. Springer, <u>New York, NY</u> , pp. 179-187.	
597	Dietz, M.E., John C. Clausen, J.C., 2008. Stormwater runoff and export changes with	Formatted: Line spacing: Double
598	development in a traditional and low impact subdivision. Journal of Environmental	
599	Management, $8_{\underline{1}}$; 7.	
600	Djokic, D., and Maidment, D.R., 1991. Terrain analysis for urban stormwater modelling.	
601	Hydrological Processes , 5(1):), 115-124.	
602	Doyle, M.W., and Bernhardt, E.S., 2011. What is a stream? Environmental Science &	
603	Technology , 45(2):). 354-359.	
604	Elmore, A.J., and Kaushal, S.S., 2008. Disappearing headwaters: patterns of stream burial due to	
605	urbanization. Frontiers in Ecology and the Environment, $6(6)$. 308-312.	
606	Gardina, V.J., 2008. Analysis of LIDAR data for fluvial geomorphic change detection at a small	
607	Maryland stream. Master of Science of M.S. Thesis, Civil Engineering, University of	
608	Maryland, College Park, College Park, 156 pp.	
609	Gironás, J., Niemann, J.D., Roesner, L.A., Rodriguez, F., and Andrieu, H., 2009. A morpho-	
610	climatic instantaneous unit hydrograph model for urban catchments based on the	
611	kinematic wave approximation. Journal of Hydrology , 377÷ <u>,</u> 317-334.	
612	Gironás, J., Niemann, J.D., Roesner, L.A., Rodriguez, F., and Andrieu, H., 2010. Evaluation of	
613	methods for representing urban terrain in stormwater modeling. Journal of Hydrologic	
614	Engineering <u>15(1).</u> : <u>141-14</u> .	
	I	

615	Haff, P.K., 2003. Neogeomorphology, predictionPrediction, and the Anthropic
616	landscapeLandscape. American Geophysical Union, Washington, DC, ETATS-UNIS, 12
617	pp.
618	Harlin, J.M., 1980. The effect of precipitation variability on drainage basin morphometry.
619	American Journal of Science , 280(8):-), 812-825.
620	Heine, R.A., Lant, C.L., and Sengupta, R.R., 2004. Development and comparison of approaches
621	for automated mapping of stream channel networks. Annals of the Association of
622	American Geographers , 94(3):-), 477-490.
623	Hogan, D.M., Jarnagin, S.T., Loperfido, J.V., and Van Ness, K., 20132014. Mitigating the
624	Effects effects of Landscape landscape Development development on Streams streams in
625	Urbanizing urbanizing Watershedswatersheds. Journal of the American Water Resources
626	Association <u>50(1), 163-178</u> .
627	Hunter, N.M., Bates, P.D., Neelz, S., Pender, G., Villanueva, I., Wright, N.G., Liang, D.,
628	Falconer, R.A., Lin, B., Waller, S., Crossley, A.J., and Mason, D.C., 2008.
629	Benchmarking 2D hydraulic models for urban flooding. Proceedings of the ICE - Water
630	Management , 161(1): 13-30.
631	James, L.A., Hunt, K.J., 2010. The LiDAR-side of headwater streams mapping channel networks
632	with high-resolution topographic data. Southeastern Geographer 50(4), 523-539.
633	James, L.A., Watson, D.G., and Hansen, W.F., 2007. Using LiDAR data to map gullies and
634	headwater streams under forest canopy: South Carolina, USA. Catena, 71:-, 132-144.
635	James, L.A. and Hunt, K.J., 2010. The LiDAR-side of headwater streams mapping channel
636	networks with high resolution topographic data. Southeastern Geographer, 50(4): 523-
637	539.

638	Jankowfsky, S., Branger, F., Braud, I., Gironás, J., and Rodriguez, F., 2012. Comparison of
639	catchment and network delineation approaches in complex suburban environments:
640	application to the Chaudanne catchment, France. Hydrological Processes-, doi:
641	10.1002/hyp.9506.
642	Jarnagin, S.T., 2008. Collaborative research: streamflow, urban riparian zones, BMPs, and
643	impervious surfaces. U.S. Environmental Protection Agency, Washington, D.C.,
644	EPA/600/F-08/001.
645	Jarnagin, S.T., 2010. Using repeated LIDAR to characterize topographic changes in riparian
646	areas and stream channel morphology in areas undergoing urban development: An
647	accuracy assessment guide for local watershed managers. U.S. Environmental Protection
648	Agency, Washington, D.C., EPA/600/R-10/120, p. 167.
649	Leopold, L.B., Huppman, R., and Miller, A.J., 2005. Geomorphic effects of urbanization in
650	forty-one years of observation. Proceedings of the American Philosophical Society,
651	149(3):). 349-371.
652	Lindsay, J.B., 2006. Sensitivity of channel mapping techniques to uncertainty in digital elevation
653	data. International Journal of Geographical Information Science, 20(6). 669-692.
654	Luo, W., 2000. Quantifying groundwater-sapping landforms with a hypsometric technique.
655	Journal of Geophysical Research: Planets , 105(E1):), 1685-1694.
656	Luo, W., and Harlin, J.M., 2003. A theoretical travel time based on watershed hypsometry.
657	Journal of the American Water Resources Association, 39(4);). 785-792.
658	Maryland Department of the Environment (MDE), 2000. Maryland stormwater Stormwater
659	design-Design manualManual. Center for Watershed Protection and the Maryland
660	Department of the Environment, Baltimore, MD.

661	(DEP), Maryland Department of Environmental Protection (DEP), 2013. Special Protection
662	Areas,
663	http://www6.montgomerycountymd.gov/dectmpl.asp?url=/content/dep/water/whatarespas
664	.asp.
665	Molloy, I., and Stepinski, T.F., 2007. Automatic mapping of valley networks on Mars.
666	Computers & Geosciences , 33(6):), 728-738.
667	Montgomery County Planning Department, 1994. Clarksburg Master Plan and Hyattstown
668	Special Study Area. Montgomery County Planning Department, Silver Spring, MD.
669	Montgomery, D.R., and Dietrich, W.E., 1989. Source areas, drainage density, and channel
670	initiation. Water Resources Research , 25(8):), 1907-1918.
671	Montgomery, D.R., and Foufoula-Georgiou, E., 1993. Channel network source representation
672	using Digital Elevation Models. Water Resources Research , 29(12). 3925-3934.
673	Moore, I.D., Grayson, R.B., and Ladson, A.R., 1991. Digital terrain modelling: A review of
674	hydrological, geomorphological, and biological applications. Hydrological Processes,
675	5(1):_), _3-30.
676	O'Callaghan, J.F. <u>, and Mark, D.M., 1984. The extraction of drainage networks from digital</u>
677	elevation data. Computer Vision, Graphics, and Image Processing , 28(3):), 323-344 .
678	Paul, M.J., and Meyer, J.L., 2001. Streams in the urban landscape. Annual Review of Ecology
679	and Systematics , 32(1):-), 333-365.
680	Perroy, R.L., Bookhagen, B., Asner, G.P. <u>, and Chadwick, O.A., 2010. Comparison of gully</u>
681	erosion estimates using airborne and ground-based LiDAR on Santa Cruz Island,
682	California. Geomorphology, 118-, 288-300.

683	Reger, J.P., and Cleaves, E.T., 2008. Draft physiographic map of Maryland and explanatory text
684	for the physiographic map of Maryland. Maryland Geological Survey Open File Report
685	08-03-01.
686	Roy, A.H., Wenger, S.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D., Thurston,
687	H.W., and Brown, R.R., 2008. Impediments and Solutions solutions to
688	Sustainablesustainable, Watershedwatershed-Scale scale Urban-urban Stormwater
689	stormwater Managementmanagement: Lessons lessons from Australia and the United
690	States. Environmental Management , 42 : 344-359.
691	Roy, A.H., Dybas, A.L., Fritz, K.M., and Lubbers, H.R., 2009. Urbanization affects the extent
692	and hydrologic permanence of headwater streams in a midwestern US metropolitan area.
693	Journal of the North American Benthological Society , 28(4):-), 911-928.
694	Rózsa, P., 2010. Nature and extent of human geomorphological impact: a review. In: Szabó, J.,
695	Dávid, L., Lóczy, D. (Eds.), Anthropogenic Geomorphology: A Guide to Man-Made
696	Landforms. Springer, New York, NY, pp.In: J. Szabó, L. Dávid and D. Lóczy (Editors),
697	Anthropogenic Geomorphology: A Guide to Man Made Landforms. Springer, pp. 273-
698	290.
699	Sibson, R., 1981. A Brief brief Description description of Natural Neighbour neighbour
700	Interpolation interpolation. In: V. Barnett, V. (EditorEd.), Interpreting Multivariate Data.
701	John Wiley & Sons, New York, NY, pp. 21-36.
702	Sofia, G., Tarolli, P., Cazorzi, F., and Dalla Fontana, G., 2011. An objective approach for feature
703	extraction: distribution analysis and statistical descriptors for scale choice and channel
704	network identification Hydrology and Earth System Sciences- 15(5+) 1387-1402

705	Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Transactions of the
706	American Geophysical Union , 38 : , 913-920.
707	Szabo, J., 2010. Anthropogenic geomorphology: Subject and system. In: Szabó, J., Dávid, L.,
708	Lóczy, D. (Eds.), Anthropogenic Geomorphology: A Guide to Man-Made Landforms.
709	Springer, New York, NY, pp. In: J. Szabó, L. Dávid and D. Lóczy (Editors),
710	Anthropogenic Geomorphology: A Guide to Man Made Landforms. Springer, pp. 3-10.
711	Tarboton, D.G., Ames, D.P., 2001. Advances in the Mapping of Flow Networks from Digital
712	Elevation Data, The World Water and Environmental Resources Congress. ASCE,
713	<u>Orlando, Florida, May 20-24, pp. 166-175.</u>
714	Tarboton, D.G., Baker, M.E., 2008. Towards an algebra for terrain-based flow analysis. In:
715	Mount, N., Harvey, G., Aplin, P., Priestnall, G. (Eds.), Representing, Modeling and
716	Visualizing the Natural Environment: Innovations in GIS 13. CRC Press, New York, NY,
717	<u>pp. 167-194.</u>
718	Tarboton, D.G., Bras, R.L., and-Rodriguez-Iturbe, I., 1991. On the extraction of channel
719	networks from digital elevation data. Hydrological Processes, 5(1):-). 81-100.
720	Tarboton, D.G. and Ames, D.P., 2001. Advances in the Mapping of Flow Networks from Digital
721	Elevation Data, The World Water and Environmental Resources Congress. ASCE,
722	Orlando, Florida, USA, pp. 166-175.
723	Tarboton, D.G., and Baker, M.E., 2008. Towards an Algebra for Terrain-Based Flow Analysis.
724	In: G.L.H. N. J. Mount, P. Aplin, and G. Priestnall (Editor), Representing, Modeling and
725	Visualizing the Natural Environment: Innovations in GIS 13. CRC Press, pp. 167-194.
726	Tenenbaum, D.E., Band, L.E., Kenworthy, S.T., and Tague, C.L., 2006. Analysis of soil
727	moisture patterns in forested and suburban catchments in Baltimore, Maryland, using

728	high-resolution photogrammetric and LIDAR digital elevation datasets. Hydrological
729	Processes , 20 : , 219-240.
730	Thoma, D.P., Gupta, S.C., Bauer, M.E., and Kirchoff, C.E., 2005. Airborne laser scanning for
731	riverbank erosion assessment. Remote Sensing of Environment , 95(4):-), 493-501.
732	Tribe, A., 1992. Automated recognition of valley lines and drainage networks from grid digital
733	elevation models: a review and a new method. Journal of Hydrology , 139 ; 2 63-293.
734	Vivoni, E.R., Di Benedetto, F., Grimaldi, S., and Eltahir, E.A.B., 2008. Hypsometric control on
735	surface and subsurface runoff. Water Resources Research , 44(12). W12502.
736	Yokoyama, R., Shirasawa, M., and Pike, R.J., 2002. Visualizing topography by openness: A new
737	application of image processing to digital elevation models. Photogrammetric
738	Engineering & Remote Sensing; $68(3)$; 257-265.
739	
740	9- <u>List of</u> Figures and Tables
741	
742	
	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs)
743	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs) spanning the development process in T104 show the topographic footprint of development
743 744	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs) spanning the development process in T104 show the topographic footprint of development increasing through time. Boxes highlight topographic differences between early- and late-stage
743 744 745	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs) spanning the development process in T104 show the topographic footprint of development increasing through time. Boxes highlight topographic differences between early- and late-stage development practices. The red arrow denotes a valley that was buried during development.
743 744 745 746	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs) spanning the development process in T104 show the topographic footprint of development increasing through time. Boxes highlight topographic differences between early- and late-stage development practices. The red arrow denotes a valley that was buried during development.
743 744 745 746 747	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs) spanning the development process in T104 show the topographic footprint of development increasing through time. Boxes highlight topographic differences between early- and late-stage development practices. The red arrow denotes a valley that was buried during development. Fig. 2. Elevation change through time quantified as temporal standard deviations (SD) calculated
743 744 745 746 747 748	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs)spanning the development process in T104 show the topographic footprint of developmentincreasing through time. Boxes highlight topographic differences between early- and late-stagedevelopment practices. The red arrow denotes a valley that was buried during development.Fig. 2. Elevation change through time quantified as temporal standard deviations (SD) calculatedfor each DEM pixel. Map values are classified to the distribution of elevation variation observed
743 744 745 746 747 748 749	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs)spanning the development process in T104 show the topographic footprint of developmentincreasing through time. Boxes highlight topographic differences between early- and late-stagedevelopment practices. The red arrow denotes a valley that was buried during development.Fig. 2. Elevation change through time quantified as temporal standard deviations (SD) calculatedfor each DEM pixel. Map values are classified to the distribution of elevation variation observedin Soper Branch (forested control). Black and dark gray areas represent values below and within
751	represent temporal variation in elevation greater than three standard deviations above the areal
-----	---
752	mean in Soper Branch; whereas white areas are greater than the maximum, and both indicate
753	areas of substantial development.
754	
755	Fig. 3. Comparisons of pre- (2002) and post- (2008) development slope distributions in T104
756	classified to ranges relevant to development practices (see Table 2 after Csima, 2010). Inset
757	shows a cross-sectional profile of slope along the dashed red line between points a and c.
758	Substantial differences in the variability of local slopes are evident in the profile between
759	developed (shaded zone) and undeveloped (unshaded) parcels. High slopes ring roads, swales,
760	and detention features and manifest as high magnitude variation across the lateral transect.
761	
762	Fig. 4. Areal slope standard deviations calculated using a 10x10 pixel moving window for pre-
763	and post-development T104 slope maps. As in pixelate slope maps, highly variable slope zones
764	are concentrated along road corridors and around detention ponds. Nevertheless, a substantial
765	increase in the local variability of slope is apparent in 2008, with high standard deviation values
766	widely distributed across the watershed.
767	
768	Fig. 5. Hypsometric variability through time exhibits distinctly different patterns across first-
769	order subwatersheds in T104 (A, B, and C). Hypsometry of relatively small subwatersheds that
770	underwent substantial resurfacing (A ~ 0.09 km^2 and C ~ 0.03 km^2) shifted from smooth (black
771	curves) to terraced curve forms (gray curves) reflecting grading of developed parcels. However,
772	extensive resurfacing was not apparent in hypsometric trends of larger subwatersheds (B ~ 0.43
773	km^2) or at the full watershed scale (D ~ 1.18 km ²).

774	
775	Fig. 6. Extensive topographic modification (e.g., C) associated with grading throughout
776	development (2002-2008) causes substantial variation in overland flowpath directions and
777	elevation change (D) in T104. Comparisons between pre- and post-development years show that
778	fine-scale flow direction changes at the hillslope scale are coupled with the designed orientation
779	and gradients of road networks (A and B, with each color representing a unique direction of
780	overland flow). Large patches of a single color indicate parallel flow lines down a hillslope,
781	whereas fragmentation of the 2002 map in 2008 necessarily indicates redirection and
782	convergence of previously unconnected contributing areas.
783	
784	Fig. 7. Comparison of pre- (blue lines) and post- (red dashed lines) development channel
785	network delineations suggest increased network density with development in T104. Added
786	channels include upslope extensions beyond existing culverts (A) and vegetated swales parallel
787	to roadways (C). Comparisons to pre-development topography show a minor tributary that has
788	been buried during development (B).
789	

Table 1 . Building r year provi	emoval and ba ded by S.T. Ja	re-earth point clo rnagin (2013, per	ud processing information sonal communication, 201	n for each LiDAR 3). ⁴ a	•	Formatted: Space After: 0 pt, Line spacing: single Formatted Table
LiDAR Year<u>y</u>ear	Instrument	Vendor	Building Removal removal Softwaresoftware	Bare-earth Filteringfiltering	.	- Formatted: Left
2002	Optech ALTM-2025	Airborne 1	Optech's REALM 2.27	Terrascan (running on Microstation)	4	- Formatted: Left
2004	Optech ALTM-2033	Laser Mapping Specialists Inc.	Applanix POSPROC & Optech's REALM (versions not specified)	Spectra's Terramodel	•	- Formatted: Left
2006	Optech ALTM-3100	Canaan Valley Institute	Optech's REALM (version not specified)	Microstation 8 with Terrascan	4	- Formatted: Left
2007	Optech ALTM-3100	Canaan Valley Institute	Optech's REALM (version not specified)	Microstation 8 with Terrascan	4	- Formatted: Left
2008	Leica ALS- 50	Sanborn	Applanix POSPROC 4.3	Leica ALS post- processing and Terrasolid Terrascan	4	- Formatted: Left

¹Any-^aAny use of trade, firm, or product names is for identification purposes only and does not imply endorsement by the U.S. Government.

Formatted: Space After: 0 pt, Line spacing: single

Formatted Table

Table 2 . Slope classes and associated economic costs and considerations for urban development (adapted from Csima, 2010) .		
Angle of slope	Development potential and the required landscaping	
Up to 5%	Easy and economic development potential. In general, terracing not necessary; landscaping exclusively restricts to drainage. Relief does not pose a limit either to build-up density or building size.	
5-12%	Increased development costs. Landscaping is inevitable; development is only possible with terracing and slope leveling. Somewhat limited development.	
12-25%	Development potential at significant cost and labor expenditure, only with terraces and supporting walls provided. Major topographic transformation; relief fundamentally controls the type of development to be applied.	
25-35%	Limited potential for urban development. Low building density with small-sized buildings.	
Above 35%	Unsuitable for urban development.	















1	Tracking geomorphic signatures of watershed suburbanization with multitemporal LiDAR
2	
3	Daniel K. Jones ^{a,b*} , Matthew E. Baker ^{b,1} , Andrew J. Miller ^{b,2} , S. Taylor Jarnagin ^{c,3} , Dianna M.
4	Hogan ^{a,4}
5	
6 7	^a U.S. Geological Survey, Eastern Geographic Science Center, 12201 Sunrise Valley Drive, Reston, VA 20192, USA
8 9 10	^b Department of Geography and Environmental Systems, University of Maryland, Baltimore County, Sondheim Hall, 1000 Hilltop Circle, Baltimore, MD 21250, USA
11 12 13 14	^c U.S. Environmental Protection Agency (USEPA) Landscape Ecology Branch, Environmental Sciences Division, USEPA/ORD National Exposure Research Laboratory, Mail Drop E243-05 109 T.W. Alexander Drive, Research Triangle Park, NC 27711, USA
15 16 17 18 19	*Corresponding author. Present address: U.S. Geological Survey, Eastern Geographic Science Center, 12201 Sunrise Valley Drive, Reston, VA 20192, USA; Tel.: +1 (703) 648-5120; Fax: +1 (703) 648-4603; E-mail: dkjones@usgs.gov.
20 21 22 23 24 25	 ¹E-mail: mbaker@umbc.edu. ²E-mail: miller@umbc.edu. ³E-mail: jarnagin.taylor@epa.gov. ⁴E-mail: dhogan@usgs.gov.

26 Abstract

27

Urban development practices redistribute surface materials through filling, grading, and 28 29 terracing, causing drastic changes to the geomorphic organization of the landscape. Many studies 30 document the hydrologic, biologic, or geomorphic consequences of urbanization using space-for-31 time comparisons of disparate urban and rural landscapes. However, no previous studies have documented geomorphic changes from development using multiple dates of high-resolution 32 topographic data at the watershed scale. This study utilized a time series of five sequential Light 33 34 Detection and Ranging (LiDAR) derived digital elevation models (DEMs) to track watershed geomorphic changes within two watersheds throughout development (2002-2008) and across 35 multiple spatial scales (0.01-1 km²). Development-induced changes were compared against an 36 undeveloped forested watershed during the same time period. Changes in elevations, slopes, 37 hypsometry, and surface flow pathways were tracked throughout the development process to 38 assess watershed geomorphic alterations. Results suggest that development produced an increase 39 in sharp topographic breaks between relatively flat surfaces and steep slopes, replacing smoothly 40 varying hillslopes and leading to greater variation in slopes. Examinations of flowpath 41 42 distributions highlight systematic modifications that favor rapid convergence in unchanneled upland areas. Evidence of channel additions in the form of engineered surface conduits is 43 apparent in comparisons of pre- and post-development stream maps. These results suggest that 44 45 topographic modification, in addition to impervious surfaces, contributes to altered hydrologic dynamics observed in urban systems. This work highlights important considerations for the use 46 of repeat LiDAR flights in analyzing watershed change through time. Novel methods introduced 47 48 here may allow improved understanding and targeted mitigation of the processes driving

49	geomorphic changes during development and help guide future research directions for
50	development-based watershed studies.
51	
52	Keywords: LiDAR time series; urbanization; land cover change; digital elevation models;
53	anthropogenic geomorphology; watershed
54	
55	1. Introduction
56	
57	At least one-third of the Earth's continental surface has undergone some form of anthropogenic
58	geomorphological activity (Rózsa, 2010). Of these activities, construction and urban
59	development stand out as ongoing and expanding causes of geomorphic change characterized by
60	rapid, complex, and multiscalar processes. Throughout urban development, extensive landscape
61	grading, leveling, and terracing can change the fundamental organization of topography within a
62	watershed (Tenenbaum et al., 2006; Csima, 2010). The current ability to track, quantify, and
63	predict development-induced geomorphic changes is hindered by insufficient data and reliance
64	on methodologies developed for traditional geomorphic studies in natural settings (Djokic and
65	Maidment, 1991; Haff, 2003; Gironás et al., 2010; Rózsa, 2010; Szabo, 2010). High-resolution
66	topographic data, such as Light Detection and Ranging (LiDAR), is required to resolve surface
67	flowpaths and visualize roads and other fine-scale features in urban landscapes (Djokic and

Maidment, 1991; Tenenbaum et al., 2006; Hunter et al., 2008; Gironás et al., 2010). Sequential

69 topographic data sets are needed to track and quantify the multiscalar (Bochis and Pitt, 2005;

Tenenbaum et al., 2006; Bochis, 2007) and temporally variable (MDE, 2000; Dietz and Clausen,

71 2008) topographic changes throughout development. No studies have utilized a high-resolution

digital elevation model (DEM) time series to track geomorphic changes throughout thedevelopment process.

74

The topographic footprint of development is visually striking on the ground and from the air, 75 76 highlighting large-scale landscaping carried out during initial development phases (Csima, 77 2010). Final smoothing and regrading occurs at finer scales that are less immediately apparent in topographic data, but are nonetheless important for understanding surficial drainage and altered 78 geomorphic characteristics (MDE, 2000; Tenenbaum et al., 2006). How best to quantify such 79 80 topographic changes is unclear in terms of selecting geomorphic variables and spatial scales that most effectively capture observed changes (Haff, 2003; Rózsa, 2010). Topographic variables 81 such as slope, curvature, and their distribution relative to watershed area play important roles in 82 sediment transport and erosion dynamics (Moore et al., 1991; Montgomery and Foufoula-83 Georgiou, 1993; James et al., 2007), channel formation (Band, 1993; Montgomery and Foufoula-84 Georgiou, 1993), and surface water – groundwater exchanges (Beven and Kirkby, 1979; Moore 85 et al., 1991; Tenenbaum et al., 2006). However, topographic controls on hydrologic and 86 geomorphic processes may be altered in urban landscapes because of infrastructure (e.g., roads, 87 88 pipes) (Djokic and Maidment, 1991; Tenenbaum et al., 2006; Gironás et al., 2009; Rózsa, 2010; Choi, 2012). 89

90

Five sequential LiDAR-derived DEMs spanning the development of two small, historically
agricultural watersheds were obtained to track geomorphic changes throughout development.
The goal of this study is to understand how and where geomorphic changes manifest within these
watersheds and to understand their implications for watershed geomorphic and hydrologic

processes prior to accounting for influences of stormwater infrastructure. The DEM coverage of
a third, forested reference watershed was used to track temporal variation not attributable to
development. This work will introduce a number of novel methods for tracking temporal
geomorphic changes using sequential LiDAR DEMs and will highlight unique geomorphic
signatures of the development process. Results of this study will help guide ongoing research
efforts that focus on the coupled influence of topography and infrastructure on watershed
function.

102

103 **2. Site description**

104

For this study, three watersheds in Montgomery County, Maryland, within the Piedmont 105 106 Physiographic Province were examined. All three watersheds are within the Mt. Airy Uplands District, characterized by siltstones and quartzite with underlying crystalline bedrock consisting 107 of a phyllite/slate unit, with average annual precipitation of 106.4 cm (Reger and Cleaves, 2008; 108 Hogan et al., 2014). Soper Branch (forested control) drains an area of ~ 3.4 km² with an overall 109 110 mean gradient of 13%. Land cover is predominantly classified as deciduous forest (~ 85%) and 111 small percentages of low-density housing and agriculture (6 and 9%, respectively) (Hogan et al., 2014; Dr. J.V. Loperfido, USGS, oral communication, July 2013). Tributaries 104 and 109 112 (T104 and T109, urbanizing) drain areas of ~ 1.2 and 0.9 km² with mean gradients of 11 and 8%, 113 respectively. Tributaries 104 and 109 are historically agricultural watersheds that underwent 114 extensive suburban development from 2003 to the present. Tributary 104 land use shifted from 115 41% agriculture, 0.3% barren, 42% forest, and 17% urban in 2002 to 2% agriculture, 15% 116 barren, 19% forest, and 64% urban in 2008. Across the same time period, T109 changed from 117

64% agriculture, 1% barren, 25% forest, and 10% urban to 45% agriculture, 13% barren, 25%
forest, and 17% urban (Hogan et al., 2014). Both T104 and T109 were used in analyses of
development-induced geomorphic changes. However, development in T109 was not complete at
the time of the last LiDAR flight, so the final T109 DEM represents a different stage of
development than T104.

123

Tributaries 104 and 109 fall within the Clarksburg Special Protection Area (CSPA, established in 124 1994) and are subject to development guidelines and restrictions (Maryland DEP, 2013). Broadly 125 126 speaking, the Special Protection Area designation identifies areas with high quality natural 127 resources and requires ongoing and future development projects to implement best available water quality and quantity protection measures. Water quality and quantity measures often 128 129 exceed minimum local and state regulations and include extensive Best Management Practices (BMPs) implementation during (sediment and erosion controls; S&EC) and after development 130 (stormwater management; SWM) (Hogan et al., 2014). Each watershed has extensive storm 131 132 sewer (SS) infrastructure in addition to noted BMP and SWM structures. While SS infrastructure likely plays a key role in dictating watershed hydrology, the purpose of this study is to document 133 134 geomorphic changes and their hydrologic implications independent of SS influence. Ongoing research will incorporate SS infrastructure to distinguish its effects from geomorphic impacts and 135 136 better account for watershed hydrologic dynamics.

137

138 **3. Data description and methods**

140 Five sequential LiDAR-derived 1-m bare-earth point clouds were collected at semiannual intervals from 2002 to 2008 to track development-induced topographic changes in T104 and 141 T109 and background topographic changes in Soper Branch. Detailed LiDAR vendor, 142 143 instrumentation, and accuracy information are provided by Jarnagin (2010). Building removal and bare-earth point cloud filtering was performed by each LiDAR vendor utilizing proprietary 144 145 software, summarized in Table 1. Differences in bare-earth filtering algorithms used by different vendors may have caused interpolated topography within filtered building footprints to vary 146 between dates. Therefore, topographic patterns within building footprints may reflect filtering 147 148 artifacts and should be interpreted with a degree of uncertainty. 149

115

150 Insert Table 1 near here.

151

LiDAR was collected as part of a larger monitoring effort to track watershed changes throughout 152 development and to document development effects on local resources through time (Jarnagin, 153 154 2008). Detailed comparisons between LiDAR spot elevations and field-surveyed elevations 155 across a range of slope, elevation, and land use classes are reported by Gardina (2008) and 156 Jarnagin (2010). One-meter resolution DEMs were interpolated from bare-earth point clouds using the natural neighbor interpolation algorithm (Sibson, 1981). The DEMs were then 157 coarsened to 2-m horizontal resolution to smooth and reduce noise in the interpolated 158 topography. All subsequent spatial analyses were performed using the interpolated 2-m DEMs 159 in ArcMap 9.3¹ (ESRI, Redlands, CA). 160

¹ Any use of trade, firm, or product names is for identification purposes only and does not imply endorsement by the U.S. Government.

Differencing sequential DEMs has been used to estimate sediment budgets, to identify nutrient 164 and sediment sources and sinks (Thoma et al., 2005), and to track gully evolution through time 165 (Perroy et al., 2010). Raw difference calculations, however, do not incorporate any estimate of 166 the error inherent across different DEMs or LiDAR vendors (e.g., they imply that all observed 167 elevation differences are real). Further, LiDAR precision has been shown to vary across land 168 cover classes—with forest cover exhibiting the lowest precision (Gardina, 2008; Jarnagin, 2010). 169 170 Therefore, comparisons of absolute elevation change estimates across differing land cover 171 classes may be misleading.

172

To correct for the inherent variability in elevation estimates through time, DEM differences were
expressed as standard deviations (SD) through time calculated for each pixel in each watershed
as

$$SD = \sqrt{\frac{1}{N} \sum_{i=year}^{N} (x_i - \mu)^2}$$
(1)

176

177 where *N* is the number of DEM years (5), x_i is the elevation for a given pixel *x* in year *i*, and μ is 178 the mean elevation of pixel *x* across the five DEM years. The distribution of elevation SDs in 179 Soper Branch was then used to quantify background elevation variability in T104 and T109. The 180 SD distribution in Soper Branch was filtered to exclude all known areas with recent 181 anthropogenic activities or structures to assure the distribution of SDs were indicative of the 182 background signal. Any remaining non-zero SD in Soper Branch was assumed to be attributable 183 to either natural causes or uncertainty in the LiDAR data. Because of the decreased elevation precision observed within forested pixels (e.g., Gardina, 2008; Jarnagin, 2010), the use of Soper 184 Branch to quantify background LiDAR variability was a conservative baseline for detecting 185 change in nonforest areas. To detect elevation changes associated with the development process, 186 187 resulting SD maps were classified based on the distribution of SDs in Soper Branch, with an 188 additional class added to distinguish SD values outside of the range observed in Soper Branch. Classes represent SD values less than or equal to the mean, within three standard deviations of 189 the mean, and SD values greater than three standard deviations from the mean. Any elevation 190 191 change above the maximum SD observed in Soper Branch is assumed to be attributable to the 192 development process.

193

```
194 3.2. Slope change
```

195

The distribution of local slopes from before and after development in T104 were quantified and 196 197 classified to ranges relevant to landscape development decisions described by Csima (2010; Table 2). Each slope class in the pre-development landscape provides an indication of the 198 199 relative development costs and earth-moving practices used across the watershed. A representative cross section was extracted for pre- (2002) and post- (2008) development years to 200 highlight changes in the juxtaposition of high and low sloping areas and to differentiate spatial 201 202 patterns associated with modified and unmodified areas. More broadly, changes in local terrain created by reallocating and relocating slopes were mapped using areal standard deviations of 203 204 slope within a 10 x 10 pixel square neighborhood of every focal pixel x_i . Comparison of maps

resulting from pre- and post-development DEMs further highlighted changes in the variability of
local landscapes associated with development practices.

207

208 Insert Table 2 near here.

209

210 *3.3. Hypsometric curves*

211

Hypsometric curves represent the proportion of a watershed's area (a/A) that is above a given 212 213 elevation (h/H), providing a generalized approximation of hillslope shape within the watershed. Traditionally, hypsometric curves have been used in discussions of landscape evolution across 214 broad spatial extents (e.g., Strahler, 1957). Other studies have found hypsometric curve shape 215 216 indicative of dominant erosional mechanisms (Harlin, 1980; Luo, 2000), hydrologic response (Luo and Harlin, 2003), and infiltration dynamics (Vivoni et al., 2008). Hypsometric curves were 217 generated for each DEM year based on first-order catchment and full watershed scales to 218 219 compare and contrast hillslope topographic alterations at increasingly broader spatial extents. 220 Consistent boundaries were used for each year to assure that any hypsometric variability through 221 time was attributable to topographic changes and not to boundary shifts caused by topographic modification along drainage divides. Hypsometric curves for each year were compared to assess 222 hillslope level changes through time. A map of net fill and excavation (DEM₂₀₀₈ – DEM₂₀₀₂) was 223 224 also developed to help interpret hypsometric trends.

225

226 *3.4. Drainage network change*

228 Topographically based drainage network delineation methods are widely used across a range of land covers and climates. The most common approaches rely on threshold relationships of 229 derivative watershed properties (e.g., drainage area, slope – area relationship) to define upslope 230 231 channel extents (e.g., O'Callaghan and Mark, 1984; Montgomery and Foufoula-Georgiou, 1993). 232 Other techniques utilize local topography to extract convergent drainage features and stream 233 heads directly (e.g., plan/profile curvature) but have seen much less use because of higher topographic data resolution required for feature detection (Tribe, 1992; Band, 1993; Tarboton 234 and Ames, 2001; Lindsay, 2006). A number of threshold-type approaches have been shown to 235 236 provide reasonable approximations of field-surveyed channel networks (extent and complexity) (Heine et al., 2004; James et al., 2007; James and Hunt, 2010). However, threshold-based 237 methods are insufficient for determining the location and occurrence of artificial urban conduits 238 (e.g., swales, gutters) whose location is based on design specifications, not physical processes 239 (Gironás et al., 2010; Jankowfsky et al., 2012). 240

241

Topographic openness (a measure of tangential curvature; see Yokoyama et al., 2002) was 242 employed to identify surface networks in the pre-development terrain of T104 and then applied 243 244 to the post-development terrain to compare surface network changes. Topographic openness is an angular relation of horizontal distance to vertical relief, calculated from above 245 (positive/zenith) and below (negative/nadir) a topographic surface (DEM). For an angle $< 90^{\circ}$, 246 247 openness is equivalent to the internal angle of an inverted cone, its apex at the focal DEM pixel, constrained by neighboring elevations within a specified radial distance. Topographic openness 248 249 is more robust in identifying surface convexities and concavities than commonly used profile and plan curvature (Yokoyama et al., 2002) and has been successfully applied to LiDAR to identify 250

251 convergent topography (Molloy and Stepinski, 2007; Sofia et al., 2011). Topographic openness was calculated using an Arc Macro Language (AML) script (written by M.E. Baker, UMBC, 252 personal communication, 2005) that reproduces the methods detailed in Yokoyama et al. (2002). 253 254 The AML extracts DEM values for all relevant cells in a neighborhood set for each focal pixel x_i 255 (defined by stepwise increments of one pixel width in each of eight azimuth directions until a 256 specified search radius is reached; here we used 100 m) in a landscape. For each increment, the horizontal distance from and elevation above the focal pixel is calculated, and an arctan function 257 converts opposite: adjacent ratios to angular degrees. The AML tracks a running maximum and 258 259 minimum angle across each radial increment and all smaller increments for all eight directions, 260 converts the resulting maxima and minima to zenith and nadir angles, and computes the mean of each across all eight directions. Thus the final openness values represent the averaged openness 261 262 measure for all eight azimuths across the specified search radius.

263

Difference DEMs and orthoimagery were used to identify detention basins and other potential 264 265 barriers to surface flow. Pre- and post-development DEMs were filled to overcome internal drainages (i.e., 'pits') and then subtracted from unfilled DEMs to assess filling extents. Paths 266 267 were carved from detention basin low points to the next downslope pixel of equal or lesser elevation outside of the filled zone. Where possible, carved pathways followed detention basin 268 outlets identified from areal and ground surveys. No attempt was made to account for flowpaths 269 270 within internal drainage basins or subsurface drainage infrastructure. Straight-line pathways were enforced for all unknown detention basin outlets. Flow directions were calculated for each year 271 from the pit-resolved DEMs by enforcing drainage from each DEM pixel to the adjacent or 272

diagonal pixel with the greatest drop in relief (see O'Callaghan and Mark, 1984). Resulting flow
direction surfaces were used to generate drainage networks and other derivative surfaces.

275

276 To create a stream map, orthoimagery and hillshaded DEMs were overlain with openness grids 277 to determine the critical openness for identifying surface depressions in the pre-development T104 DEM. A negative openness (nadir) angle of 91.5° was determined to sufficiently capture 278 all visible surface depressions. All pixels at or above 91.5° were identified, and then connected 279 using a D8-based accumulation operation to enforce downslope continuity from each depression 280 281 (Tarboton and Baker, 2008). The pre-development stream map (as defined by downslope 282 accumulation of depression pixels) was then tested for agreement with the constant drop law, which states that the mean elevation drop across channels within a given Strahler order should 283 284 not be significantly different from the mean drop in the next higher order (Tarboton et al., 1991). Incremental accumulation thresholds of depression pixels were used to prune the pre-285 development stream map until it satisfied the constant drop law. The pre-development 286 287 accumulation threshold was then applied to the post-development depression accumulation map to define the post-development stream map. Pre- and post-development stream maps were 288 289 overlain and compared to assess network changes. Field visits were also conducted to classify channels as either natural (defined banks, sorted bedload, evidence of ongoing or recent flow) or 290 artificial (e.g., swales, outflow pipes, rip rap). 291

292

293 **4. Results**

295	Hillshades of each DEM year highlight the spatial pattern of surface modifications incrementally
296	throughout development (Fig. 1). Initial large-scale resurfacing throughout the watershed is clear
297	in 2004 and 2006 hillshades, with urban or suburban infrastructure distinguishable in the terrain.
298	Fine-scale grading and smoothing that is much less visually apparent in the LiDAR characterize
299	late-stage development in 2006 and 2008. Valley burial is evident in the western portion of the
300	watershed (see red arrow in Fig. 1), replaced by a smooth upland housing cluster and roadway.
301	Mainstem valley form remained relatively constant throughout the time series, with little to no
302	visual evidence of lateral channel movement.
303	
304	Insert Figure 1 near here.
305	
306	4.1. Elevation standard deviations
307	
308	Pixelate elevation standard deviations (SD) calculated across the five DEM years were
309	approximately normally distributed in Soper Branch with a mean of 0.063 m and a standard
310	deviation of 0.034 m, ranging from 0.002 to 0.870 m. Areas with temporal SDs greater than or
311	equal to three standard deviations of the watershed mean (≥ 0.163 m) were focused within
312	riparian zones at or near stream banks and near the basin outlet within a relatively flat and wide
313	floodplain area (Fig. 2). Jarnagin (2010) reported similar LiDAR errors within densely vegetated
314	riparian zones in comparisons between ground-truth and LiDAR spot elevations (absolute mean
315	difference of 0.216 m with a standard deviation of 0.723 m and a maximum difference of 1.180
316	m). Moderately high SDs (0.063-0.163 m) are also apparent on northeast- (NE) facing hillslopes.
317	The temporal variation observed on NE-facing slopes was greater than systematic errors reported

for ground survey and LiDAR-derived elevations, which exhibited a mean absolute difference of
~ 0.05 m (Gardina, 2008).

321	Elevation changes in T104 and T109 classified to the distribution of temporal SDs in Soper
322	Branch highlight large areas exhibiting substantial elevation changes greater than the variability
323	observed in forested controls. White areas in T104 and T109 signify temporal elevation SD
324	values that are above the maximum observed in Soper Branch (> 0.870 m), encompassing ~
325	24.4% and 9.9% of total watershed area, respectively. Distinct patches of high elevation
326	variability are primarily located in development parcels evident in the post-development
327	hillshades (2008 panel in Fig. 1). High temporal variability (0.163-0.870 m) is also apparent
328	along the mainstem channel of T104 but is less evident in T109. Relatively low temporal SD
329	values in the southern undeveloped portion of T109 and within riparian zones in T104 reflect
330	magnitudes of temporal variability similar to those observed in Soper Branch. Such
331	heterogeneous distribution of elevation change is consistent with the observation that earth-
332	moving practices were not spatially uniform across developing parcels.
333	
334	Insert Figure 2 here.
335	
336	4.2. Slopes
337	
338	The footprint of development is clearly distinguishable from unmodified hillslopes in a visual
339	comparison of pre- and post-development slope maps (Fig. 3). Development created abrupt slope
340	changes in the landscape, replacing relatively smooth topographic profiles (i.e., gray boxes in

inset). Moderate to high slope classes (> 12%) were present along roads, housing parcels, and stormwater management features, despite the use of bare-earth LiDAR with buildings removed by filtering. Valley infill is apparent in the slope transect between points *a* and *b* at ~ 180 m with no evidence of the original valley structure in the post-development topography. High-frequency variation between low slope and high slope features is evident in the slope transect between 420 and 580 m across a developed subdivision.

347

348 Insert Figure 3 here.

349

Areal slope standard deviations calculated using a 10 x 10 pixel moving window show a marked 350 increase in the spatial variability of local slope values in post-development topography (Fig. 4). 351 352 The overall distribution of variation in local slopes exhibited a positive shift from the pre- (mean areal slope standard deviation of $2.35 \pm 2.26\%$) to post-development terrain (mean areal slope 353 354 standard deviation of $4.69 \pm 3.54\%$). Highly variable slope zones in 2002 were limited to riparian 355 corridors and preexisting development plots in the northern section of T104. By contrast, post-356 development slopes exhibit greater local variation (i.e., steeper and flatter terrain in close proximity) associated with the grading of subdivisions and road embankments. 357 358 Insert Figure 4 here. 359

360

4.3. Hypsometry

363	Despite substantial topographic changes across the watershed visible in hillshades and slope
364	maps representing different stages of development, hypsometric changes towing to development
365	only manifest when observed across small extents with relatively uniform, high magnitude
366	surface changes (Fig. 5). Distinctly terraced hypsometric curves appear in the end-development
367	phase topography, mirroring abrupt slope changes along roadways and surrounding housing
368	parcels (see insets A and C in Fig. 5). Valley infill in subwatershed A (see red arrow in Fig. 1)
369	created a sharp elevation gradient to the remaining riparian lowlands, reflected in the 2007 and
370	2008 hypsometric curves. Terracing and leveling of upslope transportation corridors also
371	contribute to the terraced hypsometric form. Hypsometric trends of the larger subwatershed B
372	and at the full watershed scale (D) did not exhibit detectable temporal changes.
373	
374	Insert Figure 5 here.
375	
376	4.4. Drainage network changes
377	
378	Substantial redistribution of overland flowpaths is evident in comparisons of pre- and post-
379	development flow direction grids (Fig. 6). As with slope comparisons, the most drastic changes
380	in flow directions are focused along roadways and within housing parcels. Small patches of
381	uniform flow directions mirroring housing and road footprints have replaced large, contiguous
382	patches of homogenous flow directions (i.e., parallel flow lines) on upland hillslopes. Fine-scale

variation in flow directions within relatively minor elevation change zones (see elevation change

inset in Fig. 6) are coupled with more dramatic modifications within drainage features and near

infrastructure. As a result of these alterations to the flow field, flow accumulation distributions

exhibited a negative shift, with accumulation quartiles decreasing from 4, 11, and 29 pixels in
2002 to 1, 4, and 12 pixels in 2008. Distributional shifts reflect drainage dissection and the
fragmented flow field apparent in Fig. 6 with small, locally convergent pathways replacing large,
contiguous, parallel flowpaths.

390

391 *Insert figure 6 here.*

392

A depression pixel (openness $\geq 91.5^{\circ}$) accumulation threshold of three pixels was found to 393 394 satisfy the constant drop criterion in the pre-development terrain of T104. The three-pixel threshold was then applied to the post-development terrain to evaluate surface network changes. 395 Comparisons of pre- and post-development drainage network structure in T104 indicate a net 396 397 gain in stream length of 4.25 km (~ 52% increase) throughout the watershed (Fig. 7). Additions were common along transportation infrastructure as swales or gutters typical in this watershed. 398 Upslope extensions of existing channels also occurred extending beyond preexisting piped 399 400 infrastructure at the apparent head of pre-development drainage lines (Fig. 7A). Valley infill (see Fig. 6A) caused the loss of a tributary but was replaced by an artificial conduit that paralleled a 401 402 nearby road (Fig. 7B). Similar conduits are apparent on the eastern side of the watershed as well (Fig. 7C). No substantial changes were apparent in the mainstem channel as suggested by the 403 near 1:1 overlap in pre- and post-development networks. 404

405

406 Insert Figure 7 here.

407

408 **5. Discussion**

The growing footprint of development in T104 is clearly visible in the DEM hillshade time 410 series, with distinct early- and late-stage development phases operating at unique spatial scales 411 (Fig. 1). Large-scale cutting and filling to support major infrastructure characterizes early 412 development, evident in the 2004 and 2006 hillshades. In contrast, fine-scale leveling and 413 414 grading of housing parcels characterize late-stage development (MDE, 2000). Fine-scale earthmoving practices are less immediately apparent in hillshades but are detectable in derivative data 415 sets, as this study has shown. Results show that geomorphic changes associated with urban 416 417 development are significant and nonuniform and could have implications for management and conservation efforts. 418

419

420 Initial analysis of background elevation changes in Soper Branch revealed nonzero standard deviations focused on northeast- (NE) facing hillslopes and within riparian and floodplain areas 421 (Fig. 2). Increased variation on NE hillslopes may reflect flight paths taken during LiDAR 422 423 collection or possible aspect differences in vegetation and soils. Slightly lower systematic errors reported in Gardina (2008) were attributed in part to methods used to derive bare-earth point 424 425 clouds and, in part, to LiDAR system error. The NE artifact likely is a combination of vegetation and LiDAR system errors. Riparian and floodplain variability in Soper Branch can be attributed 426 to LiDAR errors reported by Jarnagin (2010). In comparisons between LiDAR elevations and 427 428 field-surveyed spot elevations, Jarnagin observed greater LiDAR error in densely vegetated riparian zones and on steep slopes common around incised channels. Distinguishing temporal 429 430 variability attributable to artifacts in the LiDAR time series was necessary before reaching any 431 quantitative conclusions about topographic changes resulting from development.

Elevation standard deviations classified to distinguish background and development-induced 433 changes clearly show that earth moving in T104 and T109 was nonetheless substantially greater 434 than background geomorphic changes observed in Soper Branch. Magnitudes similar to temporal 435 436 standard deviations found in Soper Branch were observed in T104 across preexisting housing 437 parcels and riparian zones left untouched to comply with riparian protection policies. Somewhat higher variability observed along the mainstem channel in T104 may indicate subtle channel 438 shifts and bank erosion throughout the time period despite attempts to insulate the channel from 439 440 the hydrologic and geomorphic effects of development. Also, some of the observed elevation changes may possibly reflect artifacts produced by removing buildings from the raw LiDAR 441 point clouds. Because of the proprietary nature of the LiDAR processing, evaluating the bare-442 earth detection algorithms used by the data providers was not possible for this study. 443

444

Surface changes throughout development in T104 and T109 altered slopes to support 445 infrastructure, enforce drainage, and promote infiltration. Comparison of pre- and post-446 development slope maps in T104 shows a marked increase in high slope classes with 447 448 development as well as reallocation across space (Fig. 3). High slope classes focused along transportation corridors and surrounding detention basins are likely to promote surface drainage. 449 Slopes leading toward streams in the pre-development map appear to steepen with development 450 451 as well, likely reflecting upland filling and terracing. Stream burial is a frequently cited phenomenon in urban watersheds (Leopold et al., 2005; Elmore and Kaushal, 2008; Roy et al., 452 2009; Doyle and Bernhardt, 2011) and is apparent on the western side of T104 (~ 180 m in 453 454 transect inset of Fig. 3). However, without infrastructure design documents it is difficult to

determine whether the stream is piped under its original flowpath or if it has been redirected toflow alongside the nearby road running north to south.

457

Regular shifts between high and low slopes within subdivisions likely reflect housing parcels 458 (low slopes) separated by graded lawns and swales (higher slopes) to promote drainage (Fig. 4). 459 Low slopes within building footprints reflect the building removal algorithm applied to LiDAR 460 point clouds to extract bare-earth points used in this study to create DEMs. The spatial 461 distribution of high and low slopes in part controls the spatial distribution of runoff generation 462 and infiltration zones (Beven and Kirkby, 1979; Tenenbaum et al., 2006). Shifts in the spatial 463 pattern and magnitude of slopes may contribute to altered watershed processes including runoff 464 generation, nutrient and sediment transport, and surface water - groundwater exchanges. 465

466

Hypsometric trends within small subwatersheds of T104 appear to mirror aforementioned 467 steepening of valley walls with development (Fig. 5). Upland filling and grading further 468 469 exacerbates the disparity in elevations between the now-developed uplands and the riparian lowlands. Redistribution of flowpaths at and around valley infills likely altered surface and 470 471 subsurface water exchanges, thus changing the functional connectivity of upland and lowland areas. Dynamics are further complicated by stormwater management infrastructure, such as 472 detention ponds and infiltration trenches, typically located between upland (development plots) 473 474 and lowland (riparian zone) areas to capture and treat overland runoff before it enters local streams (Montgomery County Planning Department, 1994). Thus, riparian areas may no longer 475 be functionally connected to upland areas during rain events unless stormwater management 476 477 outfalls are triggered. Further research is required to investigate the nature of the altered surface

478 – groundwater connections. Lack of temporal trends in the larger subwatershed topography or
479 throughout the entire watershed result from spatial averaging and may indicate a detection limit
480 for tracking parcel or block-level topographic change with hypsometry.

481

Development caused a substantial reconfiguration of overland flowpaths from large contiguous 482 483 areas of uniform directions to small, spatially fragmented patches (Fig. 6). The nonrandom distribution of smaller patches mirrors housing footprints, transportation corridors, and 484 stormwater management infrastructure and reflects landscape-engineering practices that promote 485 486 efficient collection and drainage of overland runoff (Fig. 7). Adjacent pixels with uniform directions indicate parallel flowpaths, which will not converge until a pixel with a differing 487 direction is encountered downslope (O'Callaghan and Mark, 1984). By introducing heterogeneity 488 into the flow direction surface, development has created both more dissected subbasins and 489 increased opportunities for small flowpaths to converge. Increased convergence in upland areas 490 causes overland flow to reach moderately low accumulations more often and very high 491 492 accumulations more rarely than in the pre-development terrain. Decreased median and firstquartile values between 2002 and 2008 reflect the dominance of low accumulation pathways 493 494 with development. Such alterations are likely the cumulative result of many site-specific efforts to increase local water conveyance, but their cumulative effect should also have implications for 495 patterns of soil moisture, variable source area, erosion, infiltration, and recharge (Beven and 496 497 Kirkby, 1979; Moore et al., 1991; Tenenbaum et al., 2006). To our knowledge, a geomorphic driver of increased upland convergence in developed terrain has yet to be described in the 498 499 literature. Typically, pipes and impervious surfaces are thought to be the causal agents of altered 500 runoff, nutrient, and sediment dynamics in urban watersheds (e.g., Paul and Meyer, 2001; Dietz

and Clausen, 2008; Roy et al., 2008). However, our results indicate that the geomorphic
modifications that occur with development are substantial and could also contribute to altered
watershed functions.

504

Comparisons of pre- and post-development drainage networks reveal channel additions through 505 engineered surface conduits (e.g., swales, culverts) and losses caused by valley infill or 506 subsurface routing (Fig. 7). Despite noted variability in elevations along stream banks, only 507 minor shifts were apparent in the mainstem of T104. Results of this study also raise questions 508 509 about what constitutes a channel in an urban landscape. Traditional channel definitions, 510 characterized by defined banks and sorted bedloads (Montgomery and Dietrich, 1989; Heine et al., 2004) exclude engineered surface conduits that become active during precipitation events 511 512 (Doyle and Bernhardt, 2011). Excluding these artificial conduits and subsurface stormwater pipes may underrepresent the surficial connectivity of urban watersheds. Without infrastructure 513 design documents, the true drainage connectivity of the watershed is unclear. Ongoing work will 514 explore methods for incorporating subsurface drainage features into T104 network 515 representations (e.g., Gironás et al., 2009; Choi, 2012; Jankowfsky et al., 2012) and determine 516 517 how best to incorporate BMP infrastructure into predicted network representations. Nevertheless, this study indicates an overall increase in surface connectivity with development independent of 518 changes in impervious surface cover or subsurface stormwater infrastructure. Increased 519 connectivity would result in faster and larger storm peaks if left unchecked by stormwater 520 management infrastructure. Therefore, considering geomorphic changes in addition to 521 522 impervious surface cover impacts is important for remediation efforts in urban areas.

523

524 6. Conclusions

525

This study has shown the utility of sequential LiDAR-derived DEMs for tracking and 526 527 quantifying the geomorphic changes associated with development. Using a forested watershed as 528 a reference, background topographic variability was quantified and differentiated from 529 development-induced topographic change. Utilizing first- and second-order topographic derivatives, this study demonstrated that development generates increasingly disjointed hillslopes 530 characterized by abrupt slope changes separating flat upland areas. Temporal variation in 531 532 elevations, slopes, and hypsometric curves likely contributes to altered watershed functions, but further research is required to understand their importance relative to stormwater infrastructure. 533 Substantial modification of overland flowpaths resulted in subtle changes to delineated network 534 535 structure, highlighting additions and losses to the pre-development network. This study's ability to detect natural and manmade ephemeral surface conduits provides a more complete accounting 536 of watershed hydrologic connectivity. Better accounting of upslope ephemeral channel 537 538 extensions may help in designating areas for protection in future development projects. The geomorphic signal of increased landscape convergence and drainage density indicates more rapid 539 540 runoff generation and conveyance independent of impervious surface cover or storm sewers. A better understanding of how and where geomorphic changes occur throughout development may 541 enable a better understanding of pollutant mobilization and retention processes. Ongoing work 542 543 seeks to incorporate known subsurface pipe and BMP structures into surface network representations to understand watershed hydrologic response dynamics. 544

Results presented here raise important considerations for temporal topographic studies. Standard
topographic methods developed for use in larger, mostly nonurban watersheds (e.g., DEM
differencing, hypsometry) have limited applicability for tracking urbanization unless summarized
across a relatively small extent. Additional research is needed to gain a better understanding and
to develop novel methods for tracking and quantifying urban topographic modifications.

551

552 Acknowledgements

553

554 LiDAR funding provided in part by the U.S. Environmental Protection Agency under contract number EP-D-05-088 to Lockheed Martin. The U.S. Environmental Protection Agency through 555 its Office of Research and Development collaborated in the research described here. This 556 manuscript has been subjected to Agency review and approved for publication. This work would 557 not have been possible without the Clarksburg Integrated Study Partnership, which includes the 558 U.S. Environmental Protection Agency Landscape Ecology Branch (USEPA LEB), Montgomery 559 560 County Department of Environmental Protection (DEP), the U.S. Geological Survey Eastern Geographic Science Center (USGS EGSC), the University of Maryland (UMD), and the 561 562 University of Maryland, Baltimore County (UMBC). We would like to thank Adam Bentham and one anonymous referee for providing constructive feedback on our paper during the review 563 process. 564 565 566 References
568	Band, L.E., 1993. Extraction of channel networks and topographic parameters from digital
569	elevation data. In: Beven, K.J., Kirkby, M.J. (Eds.), Channel Network Hydrology. Wiley,
570	New York, NY, pp. 13-42.
571	Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin
572	hydrology. Hydrological Sciences Bulletin 24(1), 43-69.
573	Bochis, E.C., 2007. Magnitude of impervious surfaces in urban areas. M.S. Thesis, University of
574	Alabama, Tuscaloosa, 165 pp.
575	Bochis, E.C., Pitt, R., 2005. Site development characteristics for stormwater modeling. In: 78th
576	Annual Water Environment Federation Technical Exposition and Conference,
577	Washington, D.C., October 29-November 2. Washington, D.C., p. 37.
578	Choi, Y., 2012. A new algorithm to calculate weighted flow-accumulation from a DEM by
579	considering surface and underground stormwater infrastructure. Environmental
580	Modelling & Software 30(0), 81-91.
581	Csima, P., 2010. Urban development and anthropogenic geomorphology. In: Szabó, J., Dávid,
582	L., Lóczy, D. (Eds.), Anthropogenic Geomorphology: A Guide to Man-Made Landforms.
583	Springer, New York, NY, pp. 179-187.
584	Dietz, M.E., Clausen, J.C., 2008. Stormwater runoff and export changes with development in a
585	traditional and low impact subdivision. Journal of Environmental Management 8, 7.
586	Djokic, D., Maidment, D.R., 1991. Terrain analysis for urban stormwater modelling.
587	Hydrological Processes 5(1), 115-124.
588	Doyle, M.W., Bernhardt, E.S., 2011. What is a stream? Environmental Science & Technology
589	45(2), 354-359.

590	Elmore, A.J., Kaushal, S.S., 2008. Disappearing headwaters: patterns of stream burial due to
591	urbanization. Frontiers in Ecology and the Environment 6(6), 308-312.
592	Gardina, V.J., 2008. Analysis of LIDAR data for fluvial geomorphic change detection at a small
593	Maryland stream. M.S. Thesis, Civil Engineering, University of Maryland, College Park,
594	156 pp.
595	Gironás, J., Niemann, J.D., Roesner, L.A., Rodriguez, F., Andrieu, H., 2009. A morpho-climatic
596	instantaneous unit hydrograph model for urban catchments based on the kinematic wave
597	approximation. Journal of Hydrology 377, 317-334.
598	Gironás, J., Niemann, J.D., Roesner, L.A., Rodriguez, F., Andrieu, H., 2010. Evaluation of
599	methods for representing urban terrain in stormwater modeling. Journal of Hydrologic
600	Engineering 15(1), 1-14.
601	Haff, P.K., 2003. Neogeomorphology, Prediction, and the Anthropic Landscape. American
602	Geophysical Union, Washington, DC, ETATS-UNIS, 12 pp.
603	Harlin, J.M., 1980. The effect of precipitation variability on drainage basin morphometry.
604	American Journal of Science 280(8), 812-825.
605	Heine, R.A., Lant, C.L., Sengupta, R.R., 2004. Development and comparison of approaches for
606	automated mapping of stream channel networks. Annals of the Association of American
607	Geographers 94(3), 477-490.
608	Hogan, D.M., Jarnagin, S.T., Loperfido, J.V., Van Ness, K., 2014. Mitigating the effects of
609	landscape development on streams in urbanizing watersheds. Journal of the American
610	Water Resources Association 50(1), 163-178.
611	Hunter, N.M., Bates, P.D., Neelz, S., Pender, G., Villanueva, I., Wright, N.G., Liang, D.,
612	Falconer, R.A., Lin, B., Waller, S., Crossley, A.J., Mason, D.C., 2008. Benchmarking 2D

613	hydraulic models for urban flooding. Proceedings of the ICE - Water Management
614	161(1), 13-30.

615	James, L.A., Hunt, K.J., 2010. The LiDAR-side of headwater streams mapping channel networks
616	with high-resolution topographic data. Southeastern Geographer 50(4), 523-539.
617	James, L.A., Watson, D.G., Hansen, W.F., 2007. Using LiDAR data to map gullies and
618	headwater streams under forest canopy: South Carolina, USA. Catena 71, 132-144.
619	
620	Jankowfsky, S., Branger, F., Braud, I., Gironás, J., Rodriguez, F., 2012. Comparison of
621	catchment and network delineation approaches in complex suburban environments:
622	application to the Chaudanne catchment, France. Hydrological Processes, doi:
623	10.1002/hyp.9506.
624	Jarnagin, S.T., 2008. Collaborative research: streamflow, urban riparian zones, BMPs, and
625	impervious surfaces. U.S. Environmental Protection Agency, Washington, D.C.,
626	EPA/600/F-08/001.
627	Jarnagin, S.T., 2010. Using repeated LIDAR to characterize topographic changes in riparian
628	areas and stream channel morphology in areas undergoing urban development: An
629	accuracy assessment guide for local watershed managers. U.S. Environmental Protection
630	Agency, Washington, D.C., EPA/600/R-10/120, p. 167.
631	Leopold, L.B., Huppman, R., Miller, A.J., 2005. Geomorphic effects of urbanization in forty-one
632	years of observation. Proceedings of the American Philosophical Society 149(3), 349-
633	371.
634	Lindsay, J.B., 2006. Sensitivity of channel mapping techniques to uncertainty in digital elevation

data. International Journal of Geographical Information Science 20(6), 669-692.

- 636 Luo, W., 2000. Quantifying groundwater-sapping landforms with a hypsometric technique.
- Journal of Geophysical Research: Planets 105(E1), 1685-1694.
- Luo, W., Harlin, J.M., 2003. A theoretical travel time based on watershed hypsometry. Journal of
 the American Water Resources Association 39(4), 785-792.
- 640 Maryland Department of the Environment (MDE), 2000. Maryland Stormwater Design Manual.
- 641 Center for Watershed Protection and the Maryland Department of the Environment,642 Baltimore, MD.
- 643 Maryland Department of Environmental Protection (DEP), 2013. Special Protection Areas,
- http://www6.montgomerycountymd.gov/dectmpl.asp?url=/content/dep/water/whatarespas
 asp.
- Molloy, I., Stepinski, T.F., 2007. Automatic mapping of valley networks on Mars. Computers &
 Geosciences 33(6), 728-738.
- Montgomery County Planning Department, 1994. Clarksburg Master Plan and Hyattstown
 Special Study Area. Montgomery County Planning Department, Silver Spring, MD.
- 650 Montgomery, D.R., Dietrich, W.E., 1989. Source areas, drainage density, and channel initiation.
- 651 Water Resources Research 25(8), 1907-1918.
- Montgomery, D.R., Foufoula-Georgiou, E., 1993. Channel network source representation using
 Digital Elevation Models. Water Resources Research 29(12), 3925-3934.
- Moore, I.D., Grayson, R.B., Ladson, A.R., 1991. Digital terrain modelling: A review of
- hydrological, geomorphological, and biological applications. Hydrological Processes5(1), 3-30.
- O'Callaghan, J.F., Mark, D.M., 1984. The extraction of drainage networks from digital elevation
 data. Computer Vision, Graphics, and Image Processing 28(3), 323-344.

659	Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. Annual Review of Ecology and
660	Systematics 32(1), 333-365.
661	Perroy, R.L., Bookhagen, B., Asner, G.P., Chadwick, O.A., 2010. Comparison of gully erosion
662	estimates using airborne and ground-based LiDAR on Santa Cruz Island, California.
663	Geomorphology 118, 288-300.
664	Reger, J.P., Cleaves, E.T., 2008. Draft physiographic map of Maryland and explanatory text for
665	the physiographic map of Maryland. Maryland Geological Survey Open File Report 08-
666	03-01.
667	Roy, A.H., Wenger, S.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D., Thurston,
668	H.W., Brown, R.R., 2008. Impediments and solutions to sustainable, watershed-scale
669	urban stormwater management: lessons from Australia and the United States.
670	Environmental Management 42, 344-359.
671	Roy, A.H., Dybas, A.L., Fritz, K.M., Lubbers, H.R., 2009. Urbanization affects the extent and
672	hydrologic permanence of headwater streams in a midwestern US metropolitan area.
673	Journal of the North American Benthological Society 28(4), 911-928.
674	Rózsa, P., 2010. Nature and extent of human geomorphological impact: a review. In: Szabó, J.,
675	Dávid, L., Lóczy, D. (Eds.), Anthropogenic Geomorphology: A Guide to Man-Made
676	Landforms. Springer, New York, NY, pp. 273-290.
677	Sibson, R., 1981. A brief description of natural neighbour interpolation. In: Barnett, V. (Ed.),
678	Interpreting Multivariate Data. John Wiley & Sons, New York, NY, pp. 21-36.
679	Sofia, G., Tarolli, P., Cazorzi, F., Dalla Fontana, G., 2011. An objective approach for feature
680	extraction: distribution analysis and statistical descriptors for scale choice and channel
681	network identification. Hydrology and Earth System Sciences 15(5), 1387-1402.

- Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Transactions of the
 American Geophysical Union 38, 913-920.
- 684 Szabo, J., 2010. Anthropogenic geomorphology: Subject and system. In: Szabó, J., Dávid, L.,
- 685 Lóczy, D. (Eds.), Anthropogenic Geomorphology: A Guide to Man-Made Landforms.
 686 Springer, New York, NY, pp. 3-10.
- Tarboton, D.G., Ames, D.P., 2001. Advances in the Mapping of Flow Networks from Digital
 Elevation Data, the World Water and Environmental Resources Congress. ASCE,
 Orlando, Florida, May 20-24, pp. 166-175.
- 690 Tarboton, D.G., Baker, M.E., 2008. Towards an algebra for terrain-based flow analysis. In:
- 691 Mount, N., Harvey, G., Aplin, P., Priestnall, G. (Eds.), Representing, Modeling and
- 692 Visualizing the Natural Environment: Innovations in GIS 13. CRC Press, New York, NY,
 693 pp. 167-194.
- Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1991. On the extraction of channel networks
 from digital elevation data. Hydrological Processes 5(1), 81-100.
- 696 Tenenbaum, D.E., Band, L.E., Kenworthy, S.T., Tague, C.L., 2006. Analysis of soil moisture
- 697 patterns in forested and suburban catchments in Baltimore, Maryland, using high-
- resolution photogrammetric and LIDAR digital elevation datasets. Hydrological
 Processes 20, 219-240.
- Thoma, D.P., Gupta, S.C., Bauer, M.E., Kirchoff, C.E., 2005. Airborne laser scanning for
- riverbank erosion assessment. Remote Sensing of Environment 95(4), 493-501.
- Tribe, A., 1992. Automated recognition of valley lines and drainage networks from grid digital
- ros elevation models: a review and a new method. Journal of Hydrology 139, 263-293.

704	Vivoni, E.R., Di Benedetto, F., Grimaldi, S., Eltahir, E.A.B., 2008. Hypsometric control on
705	surface and subsurface runoff. Water Resources Research 44(12), W12502.
706	Yokoyama, R., Shirasawa, M., Pike, R.J., 2002. Visualizing topography by openness: A new
707	application of image processing to digital elevation models. Photogrammetric
708	Engineering & Remote Sensing 68(3), 257-265.
709	
710	List of Figures
711	
712	Fig. 1. Sequential light detection and ranging (LiDAR) derived digital elevation models (DEMs)
713	spanning the development process in T104 show the topographic footprint of development
714	increasing through time. Boxes highlight topographic differences between early- and late-stage
715	development practices. The red arrow denotes a valley that was buried during development.
716	
717	Fig. 2. Elevation change through time quantified as temporal standard deviations (SD) calculated
718	for each DEM pixel. Map values are classified to the distribution of elevation variation observed
719	in Soper Branch (forested control). Black and dark gray areas represent values below and within
720	three standard deviations of the areal mean in Soper Branch, respectively. Light gray areas
721	represent temporal variation in elevation greater than three standard deviations above the areal
722	mean in Soper Branch; whereas white areas are greater than the maximum, and both indicate
723	areas of substantial development.
724	
725	Fig. 3. Comparisons of pre- (2002) and post- (2008) development slope distributions in T104
726	classified to ranges relevant to development practices (see Table 2 after Csima, 2010). Inset

shows a cross-sectional profile of slope along the dashed red line between points *a* and *c*.
Substantial differences in the variability of local slopes are evident in the profile between
developed (shaded zone) and undeveloped (unshaded) parcels. High slopes ring roads, swales,

and detention features and manifest as high magnitude variation across the lateral transect.

731

Fig. 4. Areal slope standard deviations calculated using a 10x10 pixel moving window for preand post-development T104 slope maps. As in pixelate slope maps, highly variable slope zones are concentrated along road corridors and around detention ponds. Nevertheless, a substantial increase in the local variability of slope is apparent in 2008, with high standard deviation values widely distributed across the watershed.

737

Fig. 5. Hypsometric variability through time exhibits distinctly different patterns across firstorder subwatersheds in T104 (A, B, and C). Hypsometry of relatively small subwatersheds that underwent substantial resurfacing (A ~ 0.09 km^2 and C ~ 0.03 km^2) shifted from smooth (black curves) to terraced curve forms (gray curves) reflecting grading of developed parcels. However, extensive resurfacing was not apparent in hypsometric trends of larger subwatersheds (B ~ 0.43km²) or at the full watershed scale (D ~ 1.18 km^2).

744

Fig. 6. Extensive topographic modification (e.g., C) associated with grading throughout
development (2002-2008) causes substantial variation in overland flowpath directions and
elevation change (D) in T104. Comparisons between pre- and post-development years show that
fine-scale flow direction changes at the hillslope scale are coupled with the designed orientation
and gradients of road networks (A and B, with each color representing a unique direction of

overland flow). Large patches of a single color indicate parallel flow lines down a hillslope,
whereas fragmentation of the 2002 map in 2008 necessarily indicates redirection and
convergence of previously unconnected contributing areas.
Fig. 7. Comparison of pre- (blue lines) and post- (red dashed lines) development channel
network delineations suggest increased network density with development in T104. Added

channels include upslope extensions beyond existing culverts (A) and vegetated swales parallel

to roadways (C). Comparisons to pre-development topography show a minor tributary that has

been buried during development (B).

Table 1

LiDAR year	Instrument	Vendor	Building removal software	Bare-earth filtering
2002	Optech ALTM-2025	Airborne 1	Optech's REALM 2.27	Terrascan (running on Microstation)
2004	Optech ALTM-2033	Laser Mapping Specialists Inc.	Applanix POSPROC & Optech's REALM (versions not specified)	Spectra's Terramodel
2006	Optech ALTM-3100	Canaan Valley Institute	Optech's REALM (version not specified)	Microstation 8 with Terrascan
2007	Optech ALTM-3100	Canaan Valley Institute	Optech's REALM (version not specified)	Microstation 8 with Terrascan
2008	Leica ALS- 50	Sanborn	Applanix POSPROC 4.3	Leica ALS post-processing and Terrasolid Terrascan

Building removal and bare-earth point cloud processing information for each LiDAR year provided by S.T. Jarnagin (personal communication, 2013).^a

^aAny use of trade, firm, or product names is for identification purposes only and does not imply
 endorsement by the U.S. Government.

Table 2

Slope classes and associated economic costs and considerations for urban
development (adapted from Csima, 2010)

Angle of slope	Development potential and the required landscaping
Up to 5%	Easy and economic development potential. In general, terracing not necessary; landscaping exclusively restricts to drainage. Relief does not pose a limit either to buildup density or building size.
5-12%	Increased development costs. Landscaping is inevitable; development is only possible with terracing and slope leveling. Somewhat limited development.
12-25%	Development potential at significant cost and labor expenditure, only with terraces and supporting walls provided. Major topographic transformation; relief fundamentally controls the type of development to be applied.
25-35%	Limited potential for urban development. Low building density with small-sized buildings.
Above 35%	Unsuitable for urban development.

















Table 1

LiDAR year	Instrument	Vendor	Building removal software	Bare-earth filtering
2002	Optech ALTM-2025	Airborne 1	Optech's REALM 2.27	Terrascan (running on Microstation)
2004	Optech ALTM-2033	Laser Mapping Specialists Inc.	Applanix POSPROC & Optech's REALM (versions not specified)	Spectra's Terramodel
2006	Optech ALTM-3100	Canaan Valley Institute	Optech's REALM (version not specified)	Microstation 8 with Terrascan
2007	Optech ALTM-3100	Canaan Valley Institute	Optech's REALM (version not specified)	Microstation 8 with Terrascan
2008	Leica ALS- 50	Sanborn	Applanix POSPROC 4.3	Leica ALS post-processing and Terrasolid Terrascan

^aAny use of trade, firm, or product names is for identification purposes only and does not imply endorsement by the U.S. Government.

1 4010 -	Table	2
----------	-------	---

Slope classes and associated economic costs and considerations for urban
development (adapted from Csima, 2010)

-

Angle of slope	Development potential and the required landscaping
Up to 5%	Easy and economic development potential. In general, terracing not necessary; landscaping exclusively restricts to drainage. Relief does not pose a limit either to buildup density or building size.
5-12%	Increased development costs. Landscaping is inevitable; development is only possible with terracing and slope leveling. Somewhat limited development.
12-25%	Development potential at significant cost and labor expenditure, only with terraces and supporting walls provided. Major topographic transformation; relief fundamentally controls the type of development to be applied.
25-35%	Limited potential for urban development. Low building density with small-sized buildings.
Above 35%	Unsuitable for urban development.













