# Disappearing headwaters: patterns of stream burial due to urbanization

**Andrew J Elmore*** **and Sujay S Kaushal**

**Headwater streams provide important ecosystem services, including clean drinking water, habitat for aquatic life, and rapid processing and uptake of nutrients, which can reduce delivery of nitrogen and phosphorus to downstream coastal waters. Despite their importance to ecosystem functioning, very little research has addressed the extent to which headwater streams are buried beneath the land surface during urbanization. We measured the occurrence of stream burial within a major tributary to the Chesapeake Bay, for streams with catchment areas ranging from 10 ha to $10^4$ ha. We used hydrologic modeling to identify where streams should be and then calibrated a map of impervious surface area, using high-resolution aerial photography to build a stream channel decision-tree classification. We found that 20% of all streams were buried, with streams in low-residential and suburban areas outside Baltimore City exhibiting 19% burial rates. Smaller headwater streams were more extensively buried than larger streams, and this difference increased with increasing impervious surface area. Within Baltimore City, 66% of all streams and 70% of streams in catchments smaller than 260 ha (1 $mi^2$) were buried. In this densely urbanized city, headwater streams are buried to the same extent as is dry land.**

*Front Ecol Environ* 2008; 6(6): 308–312, doi:10.1890/070101

Headwater streams provide aquatic habitat and clean drinking water, and are "hotspots" for ecosystem function relevant to maintenance of water quality in downstream rivers, reservoirs, and estuaries of the US (Peterson *et al.* 2001; Kemp *et al.* 2005; Kaushal *et al.* 2006; Wigington *et al.* 2006; Freeman *et al.* 2007). Small streams contain diverse species of fish, invertebrates, and algae (Wigington *et al.* 2006; Meyer *et al.* 2007), and are critical for retaining and removing nitrogen (Peterson *et al.* 2001). Habitat quality and the potential for nutrient retention in headwater streams can be highly sensitive to changes in watershed land use (Kaushal *et al.* 2006; Wigington *et al.* 2006; Meyer *et al.* 2007), and urbanization causes stream degradation in a variety of ways (Figure 1). The process known as stream burial (where streams are directed into culverts, pipes, concrete-lined ditches, or simply paved over) is probably the most extreme impact of urbanization on streams. Stream burial results in the destruction of natural stream channels and contributes to downstream habitat degradation, aquatic habitat fragmentation, enhanced transport of water and toxic contaminants, and reduction of ecosystem services such as nutrient and sediment retention (Paul and Meyer 2001; Walsh *et al.* 2005). Because they constitute the largest fraction of stream length and are the most economically feasible to bury, the smallest streams are among those most affected by urbanization.

Knowledge of the ecological importance of headwater streams was not reflected in early 20th-century urban development plans. As a result, extensive networks of storm drains used to pipe headwater runoff into larger streams underlie urban areas around the world (Walsh *et al.* 2005). Although this practice is becoming less common, controversy continues regarding *whether* and *how* headwater streams should be protected under law. In the US, the Clean Water Act of 1972 offers some protection for headwater streams (defined as streams with average annual flows of less than 5 $ft^3$ per second), but it is unclear whether the smallest headwater streams and areas of saturated soils with intermittent flow should be protected (Wigington *et al.* 2006), resulting in recent hearings in the US Supreme Court (eg in 2006, *Rapanos v United States*, 04-1034; *Carabell v Army Corps of Engineers*, 04-1384). Another source of federal protection, the Federal Emergency Management Agency (FEMA), only regulates floodplain development, which, for intermittent streams, can be a nebulous concept subject to various interpretations. Stream size based on hydrologic flow is often included in regulatory interpretations for land developers and corporations (Alexander *et al.* 2007; Freeman *et al.* 2007; Meyer *et al.* 2007). However, legislation does not currently include a determination of the smallest stream size (including ephemeral streams) to be protected, or standardized adjustment mechanisms to account for cumulative impacts to entire stream networks (Freeman *et al.* 2007; Meyer *et al.* 2007).

To begin the process of quantifying the cumulative impacts of stream burial on urbanizing catchments, we analyzed the degree and pattern of stream burial across a range of stream sizes (small to medium) for the Baltimore metropolitan region in the mid-Atlantic US. Using this dataset, we tested the hypotheses that the extent of stream burial would (1) increase with increasing urban density and (2) increase with decreasing stream size. Finally, we tested one possible effect of legislation that

---

*Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD* *(andrew@elmore.cc)

Courtesy of K Belt

Courtesy of M Kline, Maryland Biological Stream Survey

*Figure 1. The impact of urbanization on streams can take many forms, but in extreme cases, (a) streams are buried underground in storm drains. Nevertheless, most research has focused on riparian zone condition, highlighting the differences between (b) heavily incised channels with degraded riparian canopy cover and (c) intact forest streams. Note that in (a) the stream is largely disconnected from the riparian zone, yet water may still flow year round, due to groundwater inputs (K Belt pers comm).*

protects streams by studying variations in the pattern of stream burial for catchments smaller and larger than 260 ha (1 $mi^2$). This catchment size (260 ha) is the cut-off for FEMA regulation of floodplain development in the US.

## ■ Methods

### Site description

Previous work in the Chesapeake Bay watershed using remote sensing techniques has shown a 61% increase in developed land from 1990 to 2000 (Jantz *et al.* 2005), with suburban/urban growth expected to increase rapidly in the future (Claggett *et al.* 2004). The Gunpowder–Patapsco watershed (GPWS) selected for this study also includes older development in and around the city of Baltimore. The region is therefore likely to be representative of conditions in modern urbanizing catchments worldwide. Long-term monitoring of watersheds in this region has identified many of the same effects that are seen in urban streams in other countries (Walsh *et al.* 2005). Notably, runoff from impervious surfaces has led to the chemical alteration of streams (Kaushal *et al.* 2005) and stream channel incision (Groffman *et al.* 2002; Figure 1b), both influencing stream processes at multiple scales. Furthermore, this region has been the setting for many studies investigating the impacts of urbanization on aquatic ecosystems (eg Kaushal *et al.* 2005).

### Data analysis

An estimation of stream burial (including ephemeral streams) was completed using a combination of remote sensing techniques and hydrologic modeling based on elevation to delineate hydrologic flow path. Three primary datasets were used: (1) aerial photography (30-cm resolution) provided by the US Geological Survey (USGS), (2) Multi-Resolution Land-cover Consortium (MRLC) impervious surface area (ISA) maps (30-m resolution), and (3) a National Elevation Dataset (NED) digital elevation model (DEM; 10-m resolution). These data were acquired for the entire GPWS (where 30-cm resolution aerial photography was unavailable, 1-m data were substituted). Our method consisted of five steps: (1) hydrologic modeling from the DEM to delineate natural flow lines (streams/rivers; eg Brakebill and Preston 2003), (2) observation of stream condition (intact or buried) at 429 stratified random locations, (3) decision-tree classification of the ISA map using the 429 observations as training data, (4) applying the decision tree to the entire

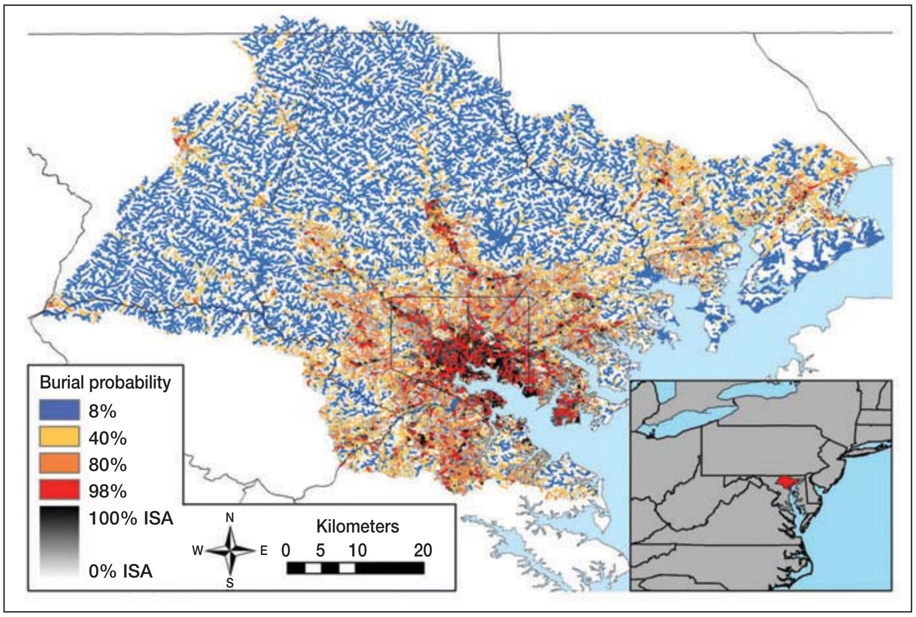

***Figure 2.*** *Stream burial extent for the Gunpowder–Patapsco watershed in eastern Maryland, expressed as a probability of burial based on the distribution of impervious surfaces (shown in shades of gray) in the vicinity of each stream reach.*

3.5 x $10^3$ km$^2$ GPWS, and (5) analyzing the rate of stream burial by catchment area (see WebPanel 1).

We identified all hydrologic flow lines that ran from a catchment area of 10 ha to $10^4$ ha; this captured the range of stream sizes in the watershed and roughly matched the range of stream sizes that are routinely monitored in the Baltimore Ecosystem Study (BES) Long-term Ecological Research project. The lower limit of 10 ha was imposed by our inability to identify streams smaller than this size in aerial photography and does not represent any judgment on our part regarding the condition or importance of streams with a catchment area smaller than 10 ha. We then generated impervious surface area statistics (mean, maximum, minimum, median, sum, standard deviation) for the nine pixels (0.73 ha) surrounding and including each 30-m segment (1 pixel) of the flow line network. Finally, we generated a set of 500 random points along the flow line network for analysis using high-resolution aerial photography. Of the 500 points, clouds obscured 71. We observed each of the remaining 429 stream reaches in the aerial photography and manually classified them into two groups: (1) visible streams in forested land or parkland, and (2) no visible stream (ie the stream reach was probably buried during the course of development).

An algorithm was sought that would rigorously estimate the status of each stream reach (buried or intact) using only the impervious surface area map. For this purpose, an unbiased recursive-partitioning algorithm utilizing a conditional inference framework (Hothorn *et al.* 2006) was used to build a decision-tree classification. The ISA and ISA statistics built from neighboring areas, and stream reach condition (intact or buried) were used as the independent and dependent variables, respectively. Conditional inference partitioning differs from exhaustive search procedures in that each split in the data takes into account the distribution of the dependent data. Therefore, the method does not require bootstrapping from pooled data, results in smaller unbiased trees, and provides the statistical significance of each proposed split (here, constrained to be $P < 0.05$). The decision tree generated consisted of four terminal nodes with 8% (n = 120), 40% (n = 93), 81% (n = 148), and 98% (n = 68) probability of the stream reach being buried in each terminal node.

The decision tree was then applied to the entire GPWS, including Baltimore City. Each dataset was analyzed by catchment size, using linear regression. Two model effects were included: (1) catchment size and (2) a nominal effect indicating whether or not a catchment was larger than 260 ha (1 mi$^2$), the smallest catchment size identified in FEMA floodplain maps.

## Results

Urbanized areas contained disproportionately more buried streams than other areas (Figure 2). In Baltimore City, 66% of streams were buried across catchments spanning 10 to $10^4$ ha in size. In contrast, 19% of streams were buried in the counties outside Baltimore City, and 21% of streams were buried across the entire GPWS. While much of the heavy development corresponds to the main transportation corridors between rural areas and the center of Baltimore City, stream burial is apparent in most regions of the watershed. For example, across the upper watershed, 8% burial probabilities (the lowest classification level) were found in areas with just 4% impervious surface area.

The fraction of buried streams in the GPWS decreased with increasing stream size, from 25% to 14% ($r = 0.89$; $P < 0.0001$; Figure 3). The fraction of buried streams in Baltimore City also decreased with increasing stream size, from 74% to ~20% ($r = 0.79$; $P < 0.0001$), but interaction with the nominal factor separated catchments greater than and less than 260 ha ($P = 0.02$). The fraction of buried streams with catchments smaller than 260 ha did not vary with catchment size, but remained almost constant at ~ 70%. In catchment areas greater than 260 ha, the fraction of buried streams decreased significantly with increasing stream size ($r = 0.75$; $P = 0.01$).

Burial probabilities were interpreted as prediction accuracies (sensu Vayssieres *et al.* 2000). For example, it is 98%

accurate to state that any given flow line segment within the "98% burial probability class" is buried. Averaged for the entire watershed, the decision tree returned an 80% prediction accuracy for buried streams and an 86% prediction accuracy for intact streams. The decision tree returned > 80% accuracy in dense urban environments (stream reaches colored red and dark orange in Figure 2) and 92% accuracy in sparse rural environments (blue in Figure 2). Regions of medium-density development returned the least useful prediction (40%), but these conditions were representative of just 17% of the watershed.

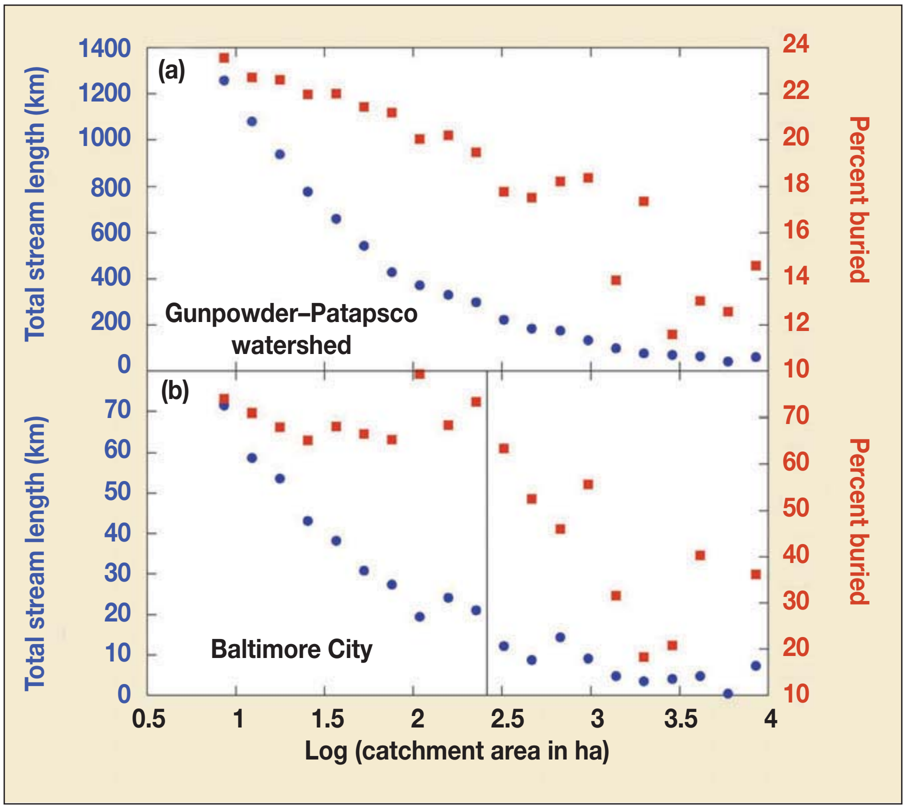

*Figure 3. Fraction of streams buried by catchment size for (a) the Gunpowder–Patapsco watershed and (b) Baltimore City. For Baltimore City, a contrast in slope is significant (P = 0.028) between catchments smaller and larger than 260 ha.*

## Discussion

Headwater streams are buried more extensively than are larger streams at all levels of urban development (low residential, suburban, and urban). Due to the greater area of high-density urban development along the coasts, headwater streams in this watershed are more completely buried on coastal plains than in upland reaches. This may be important from the perspective of coastal water quality, due to the close proximity of these coastal streams to the Chesapeake Bay and, consequently, decreased travel time and reduced potential for in-stream retention and processing of contaminants from urban and atmospheric sources. In heavily urbanized portions of the watershed, results show that larger streams and rivers have been protected from burial by prominent riparian zones. In contrast, riparian corridors have protected few if any urban headwater streams. In suburban areas outside Baltimore City, smaller streams are also buried more extensively than larger streams but, overall, stream burial in suburban areas is less extensive than in the densely urban Baltimore City. Headwater stream burial within low-density developments may also consist of less "connected impervious area" (Walsh *et al* 2005), thus allowing runoff to filter through to groundwater, rather than directly entering stormwater systems.

The inverse relationship between stream size and fraction of buried stream reaches might be a simple consequence of the expense of burying larger streams. However, there could be more complex factors at work. In particular, results for Baltimore City suggest a significant change in slope at a catchment size of 260 ha ($P = 0.028$), which represents the size limit beyond which floodplain development restrictions apply (via FEMA). Beyond this threshold, larger streams appear to be more effectively protected than smaller streams. Although restrictions imposed by FEMA or even the Clean Water Act might play a role, perhaps more plausibly, a catchment size of 260 ha may coincide with the size at which streams in this region become permanently running waters (instead of ephemeral). Over several centuries of development, the residents of Baltimore may have incorporated this into their land development practices. Nevertheless, in Baltimore City, over 70% of headwater streams have been buried, and when we extend the definition of "headwater stream" to catchments as small as 1 ha, 73% of streams have been buried. It is therefore apparent that streams in catchments smaller than 260 ha are buried to virtually the same extent as dry ground. Nearly 30% of headwater streams still exist above ground, but this appears to be a consequence of ancillary land protection (eg creation of parks or large land tracts) that protects all land types (terrestrial and aquatic) equally.

To meet the challenges associated with watershed restoration, remote sensing and GIS could be used to effectively target heavily impaired stream reaches. For key regions of rapid development and poor water quality, the extent and pattern of stream burial would be used in combination with quantitative assessments of riparian buffer condition (Goetz 2006) to more accurately parameterize runoff and nutrient export models. As higher resolution data and land-cover maps become available, routine implementation of these modeling and analysis tools will be possible at the municipality and township level, possibly resulting in more consistent protection of headwaters across jurisdictional boundaries.

The structure and function of headwater ecosystems determine the quantity and quality of water in downstream rivers, lakes, and coastal waters (Freeman *et al.* 2007). The widespread occurrence of headwater stream burial probably contributes to the Patapsco River estuary's status as the most degraded tributary of the Chesapeake Bay, as assessed by indicators of water quality and biotic health (UMCES 2007). The conversion of natural channels to buried streams decreases habitat for critical species and interrupts patterns of dispersal and colonization (Meyer *et al.* 2005; Wigington *et al.* 2006). It may also increase roadway contaminant transport from impervious surfaces (Kaushal *et al.* 2005) and decrease interactions between streams and "hotspots" of nutrient retention in nearby riparian soils (Kaushal *et al.* in press). Stream burial alters ecosystem metabolism and food-web structure, due to changes in primary production versus respiration in dark conditions, and may influence thermal regimes due to runoff from pavement (Paul and Meyer 2001). Given the large extent of stream burial and the potential for increases therein, an important next step is to estimate habitat loss, alterations to channel structure, and watershed nutrient export due to stream burial. Maintenance of ecological function in streams is of national and global importance, extending far beyond the mid-Atlantic US. More uniform strategies and policies are necessary to protect against headwater stream burial. This will require research into how the alteration of headwater streams affects ecological processes at the entire drainage scale, coupled with measurements to quantify changes in the spatial extent and patterns of stream burial under current and future scenarios of urban development.

## Acknowledgements

We thank K Belt and B McCormick for inspirational conversation, and the Maryland Water Resources Research Center and NSF (DEB-9714835 and DBI-0640300) for funding. This is UMCES Appalachian Laboratory contribution #4105.

## References

Alexander RB, Boyer EW, Smith RA, *et al.* 2007. The role of headwater streams in downstream water quality. *J Am Water Resour As* **43**: 41–59.

Brakebill JW and Preston SD. 2003. A hydrologic network supporting spatially referenced regression modeling in the Chesapeake Bay watershed. *Environ Monit Assess* **81**: 73–84.

Claggett PR, Jantz CA, Goetz SJ, and Bisland C. 2004. Assessing development pressure in the Chesapeake Bay watershed: an evaluation of two land-use change models. *Environ Monit Assess* **94**: 129–46.

Freeman MC, Pringle CM, and Jackson CR. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *J Am Water Resour As* **43**: 5–14.

Goetz S J. 2006. Remote sensing of riparian buffers: past progress and future prospects. *J Am Water Resour As* **42**: 133–43.

Groffman PM, Boulware NJ, Zipperer WC, *et al.* 2002. Soil nitrogen cycle processes in urban riparian zones. *Environ Sci Technol* **36**: 4547–52.

Hothorn T, Hornik K, and Zeileis A. 2006. Unbiased recursive partitioning: a conditional inference framework. *J Comput Graph Stat* **15**: 651–74.

Jantz P, Goetz S, and Jantz C. 2005. Urbanization and the loss of resource lands in the Chesapeake Bay watershed. *Environ Manage* **36**: 808–25.

Kaushal SS, Groffman PM, Likens GE, *et al.* 2005. Increased salinization of fresh water in the northeastern United States. *P Natl Acad Sci USA* **102**: 13517–20.

Kaushal SS, Lewis WM, and McCutchan JH. 2006. Land-use change and nitrogen enrichment of a Rocky Mountain watershed. *Ecol Appl* **16**: 299–312.

Kaushal SS, Groffman PM, Mayer PM, *et al.* Effects of stream restoration on denitrification in an urbanizing watershed. *Ecol Appl*. In press.

Kemp WM, Boynton WR, Adolf JE, *et al.* 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. *Mar Ecol–Prog Ser* **303**: 1–29.

Meyer JL, Paul MJ, and Taulbee WK. 2005. Stream ecosystem function in urbanizing landscapes. *J N Am Benthol Soc* **24**: 602–12.

Meyer JL, Strayer DL, Wallace JB, *et al.* 2007. The contribution of headwater streams to biodiversity in river networks. *J Am Water Resour As* **43**: 86–103.

Paul MJ and Meyer JL. 2001. Streams in the urban landscape. *Annu Rev Ecol Syst* **32**: 333–65.

Peterson BJ, Wollheim WM, Mulholland PJ, *et al.* 2001. Control of nitrogen export from watersheds by headwater streams. *Science* **292**: 86–90.

UMCES (University of Maryland Center for Environmental Science). 2007. Chesapeake Bay report card: a geographically detailed and integrated assessment of Chesapeake Bay habitat health. www.eco-check.org/reportcard/chesapeake/. Viewed 1 Jun 2007.

Vayssieres MP, Plant RE, and Allen-Diaz BH. 2000. Classification trees: an alternative non-parametric approach for predicting species distributions. *J Veg Sci* **11**: 679–94.

Walsh CJ, Roy AH, Feminella JW, *et al.* 2005. The urban stream syndrome: current knowledge and the search for a cure. *J N Am Benthol Soc* **24**: 706–23.

Wigington PJ, Ebersole JL, Colvin ME, *et al.* 2006. Coho salmon dependence on intermittent streams. *Front Ecol Environ* **10**: 513–18.