Disappearing headwaters: patterns of stream burial due to urbanization

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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 10,000 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 mi²) were buried. In this densely urbanized city, headwater streams are buried to the same extent as is dry land.
protection of streams by studying variations in the pattern of stream burial for catchments smaller and larger than 260 ha (1 mi²). 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 (e.g., 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 hydrologic flow lines (streams/rivers; e.g., 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...
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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 10³ km² 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 10⁴ 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 mi²), 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 10⁴ 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.

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 50% 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 (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.

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**References**


