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Research Note

Research Note: Mapping spatial patterns in sewer age, material, and proximity to surface waterways to infer sewer leakage hotspots

Kristina G. Hopkins[a,*], Daniel J. Bain[b]

[a] U.S. Geological Survey, Eastern Geographic Science Center, 521 National Center, Reston, VA 20192 USA

[b] Department of Geology and Environmental Science, University of Pittsburgh, 4107 O'Hara Street, SRCC, Room 200, Pittsburgh, PA 15260, USA

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ABSTRACT

Identifying areas where deteriorating sewer infrastructure is in close proximity to surface waterways is needed to map likely connections between sewers and streams. We present a method to estimate sewer installation year and deterioration status using historical maps of the sewer network, parcel-scale property assessment data, and pipe material. Areas where streams were likely buried into the sewer system were mapped by intersecting the historical stream network derived from a 10-m resolution digital elevation model with sewer pipe locations. Potential sewer leakage hotspots were mapped by identifying where aging sewer pipes are in close proximity (50-m) to surface waterways. Results from Pittsburgh, Pennsylvania (USA), indicated 41% of the historical stream length was lost or buried and the potential interface between sewers and streams is great. The co-location of aging sewer infrastructure (> 75 years old) near stream channels suggests that 42% of existing streams are located in areas with a high potential for sewer leakage if sewer infrastructure fails. Mapping the sewer-stream interface provides an approach to better understand areas were failing sewers may contribute a disproportional amount of nutrients and other pathogens to surface waterways.

1. Introduction

More than one million kilometers of public sewer pipes connect homes and businesses to local treatment plants in the United States (ASCE, 2017). The likelihood of sewer leaks increases as sewer pipes surpass design lifetimes and maintenance is deferred. Recent research has shown sewer leakage inputs to urban stream are substantially underestimated (Divers, Elliott, & Bain, 2014; Kaushal et al., 2011). Patterns in stream impairment processes in urban watersheds can be clarified by reconstructing development trajectories using non-traditional data sources such as historical maps (Boone, 2003; Hopkins, Bain, & Copeland, 2014). Reconstructing spatio-temporal patterns in sewer infrastructure installation and deterioration in urban areas may provide insights to improve the detection and mitigation of underlying impairments to aquatic ecosystems associated with sewer leachate. Catchment nutrient and water budget approaches to urban ecosystem ecology have increasingly incorporated human-built infrastructure into both conceptual and quantitative models in an effort to better contain nutrient inputs and processing mechanisms (Broadhead, Horn, & Lerner, 2015; Divers, Elliott, & Bain, 2013; Divers et al., 2014; Kaushal & Belt, 2012). Recognition of patterns created by early water management decisions in urban systems should allow widely applicable and effective detection and mitigation of impacts associated with deteriorating sewer infrastructure.

This paper focuses on mapping potential connections between streams and sewers in the metropolitan region of Pittsburgh, Pennsylvania (PA). We present a method to 1) estimate the installation year of sewer pipes segments and map pipe deterioration based on pipe age, 2) map and identify areas where streams were likely piped into the sewers, and 3) map areas where connection between deteriorating sewer pipes and streams may occur. Reliable identification of areas where aging sewer infrastructure is in close proximity to streams can be used to identify hotspot for nutrient and contaminant inputs to surface waterways and guide restoration priorities aimed at addressing urban impairments.

2. Methods

2.1. Study area and context

The study area is located in the metropolitan area of Pittsburgh, PA, in the mid-Atlantic region of the United States (Fig. 1A). The study area covers the portion of metropolitan Pittsburgh that receives sewage treatment services from the Allegheny County Sanitary Authority

* Corresponding author.
E-mail addresses: khopkins@usgs.gov (K.G. Hopkins), dbain@pitt.edu (D.J. Bain).

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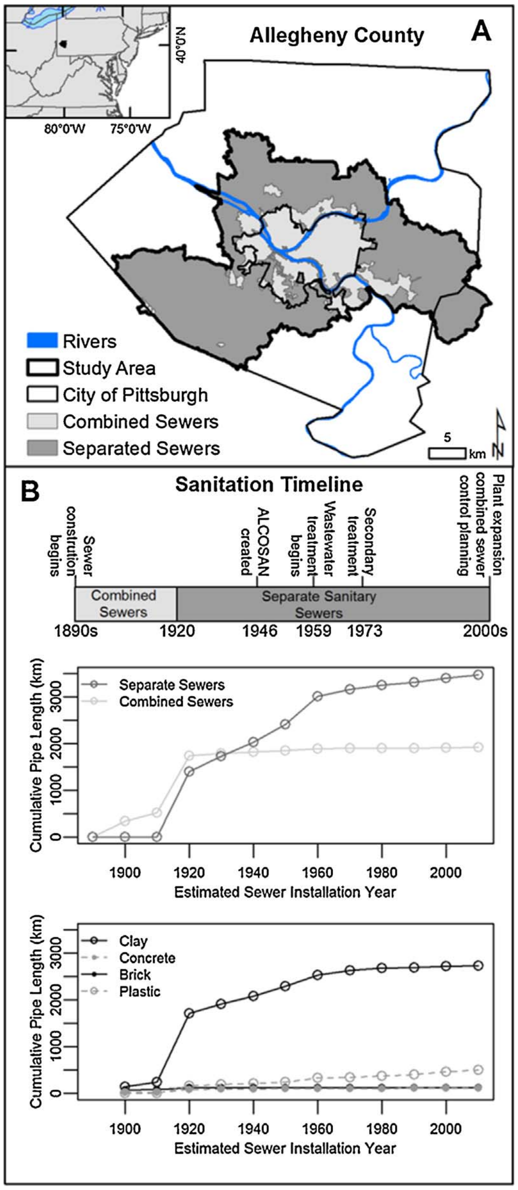

Fig. 1. Study area includes areas with combined or separate sewer systems in the ALCOSAN treatment area (A). Inset map shows the location of Allegheny County in southwestern Pennsylvania, USA. Sanitation timeline shows major sewage construction efforts within the study area and a timeline of sewer pipe type (combined versus separated sewers) and sewer pipe material (B). Cumulative pipe length estimated from reconstruction methodology presented in this study.

(ALCOSAN). The study area includes the City of Pittsburgh and 82 other local municipalities. ALCOSAN owns and operates over 140 km of interceptor sewers, but each customer municipality owns and maintains their local sewer network, spanning over 6400 km of pipe (ALCOSAN, 2012). The entire, multi-county study area covers 817 km^2, with 22% of the area served by combined sewers and 78% served by separated sewers (Fig. 1A). The portion of the study area in the City of Pittsburgh (151 km^2) is served by a combination of separated (23% area) and combined (73% area) sewers (Fig. 1A). Separated sewers have one pipe that conveys stormwater to nearby water bodies and one pipe that conveys wastewater to the sewage treatment plant. A combined sewer system has one pipe that conveys both stormwater and wastewater. When the capacity of the combined sewer system is exceeded during precipitation events excess water overflows untreated to the river. In a typical year, ALCOSAN estimates that approximately 34 million cubic meters (9 billion gallons) of combined sewer water, containing a mix of sewage and stormwater, discharges to streams in the study area (ALCOSAN, 2012).

2.2. Stream burial estimation

The existing stream network in the study area was defined from 1:24,000 scale National Hydrography Dataset (NHD) stream flow lines obtained from the Pennsylvania Spatial Data Access Clearinghouse (U.S. Geological Survey, 2004). The NHD stream flow lines were supplemented with Allegheny County stream lines for two streams, Panther Hollow Run and Nine Mile Run, to better represent urban streams located in the City of Pittsburgh. The locations of buried streams were identified by comparing the existing stream network to the historical stream network derived from a 10-m resolution 2000 U.S. Geological Survey (USGS) National Elevation Dataset digital elevation model (DEM) (Gesch et al., 2002). The historical stream network was delineated in ArcMap 10.2 (Esri, Redlands, California) using the DEM with sinks filled, hydrology tools within spatial analyst, and a threshold flow accumulation area of 0.25 km^2 for stream channel initiation. A sensitivity analysis of flow accumulation threshold from 0.1 km^2 to 0.5 km^2 indicated that an accumulation threshold of 0.25 km^2 provided the more reasonable and robust stream network that best aligned with the scale of the NHD network. The threshold flow accumulation value selected was similar to mean catchment areas (0.21 ± 0.06 km^2) reported for perennial stream flow origins in the Interior Plateau ecoregion in Hamilton County, Ohio (Roy, Dybas, Fritz, & Lubbers, 2009). Catchment areas for the Interior Plateau reported in Roy et al. (2009) represented watersheds composed of a mix of forested (mean 47.5% ± 6%) and urban (mean 42% ± 8%) land use. Using a conservative flow accumulation threshold of 0.25 km^2 may have underestimated stream burial, given the urban setting of our study area.

Streams from both current and historical drainage networks were intersected with municipal boundaries in the study area to calculate existing and historical stream length and density for each municipality. Statistics were estimated for municipalities to provide information at a scale comparable to local decision making. Stream burial rates were determined for each municipality by comparing the lengths of the existing and historical stream networks. Burial amounts were only determined for municipalities with greater than 1 km^2 of area within the study area and at least 5% of the total municipal area within the study area. Area criteria were required to ensure the municipality of interest had a large enough area to accurately assess stream burial rates. Of 82 total municipalities 76 met these criteria. Linear regression analysis and *t*-tests were conducted in R Studio (R Core Team, version 3.2.3) to assess relations between stream burial rates and sewer installation year and sewer density.

2.3. Sewer infrastructure dating

Two approaches were used to estimate the approximate installation year for sewer pipes in the study area. Sewer installations before 1910 were derived from Sewer System Maps in the Atlas' of the City of Pittsburgh published by Hopkins, Griffith, & Morgan from the years 1889–1910 (Hopkins, Griffith, & Morgan, 1889a, 1889b; Hopkins, Griffith, & Morgan, 1890a, 1890b, 1890c, 1890d, 1890e; Hopkins, Griffith, & Morgan, 1898; Hopkins, Griffith, & Morgan, 1899; Hopkins, Griffith, & Morgan, 1900; Hopkins, Griffith, & Morgan, 1901; Hopkins, Griffith, & Morgan, 1904; Hopkins, Griffith, & Morgan, 1910). Maps were georectified in ArcGIS 10.2 and overlain with the existing sewer network. Sewers shown on the Hopkins, Griffith, & Morgan map were attributed with the oldest matching map date. These sewers were then lumped into two age class categories dating 1900 (1889 − 1900) and 1910 (1901–1910), representing the first sewers installed in the study area. Total sewer length for 1900 and 1910 was cross-checked with data from the U.S. Census Statistics of Cities (U.S. Bureau of the Census, 1907).