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RESEARCH ARTICLE

# Reconstruction of a century of landscape modification and hydrologic change in a small urban watershed in Pittsburgh, PA

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**Abstract** Assessing the causes of stream impairments is challenging without a clear understanding of the spatiotemporal interactions among human infrastructure networks and hydrologic systems. Landscape change is often characterized using simplistic metrics that lump changes into generalized categories, such as impervious cover. We examined the evolution of human infrastructure in Panther Hollow, a small watershed in Pittsburgh, Pennsylvania to characterize the impacts of long-term (~100 years) landscape change on stream flow. Results show that impervious cover in the catchment grew from 3 % in 1900 to 27 % in 2010. Growth was non-linear, with 60 % of the development occurring between 1904 and 1930. We then compared two models that predict changes in annual water yield, one model based on watershed impervious cover and one based on human infrastructure arrangement. The model based solely on impervious cover predicts excessive amounts of surface runoff relative to the infrastructure model and monitored yield. This discrepancy occurs because the impervious model does not account for the diversion of 50 % of the watershed drainage through the combined sewer system to an adjacent basin. In the Panther Hollow watershed, hydrology is dominated by a reduction in water yield, contrasting typical hydrologic changes associated with urbanization. Our analysis reveals the value of quantifying additional landscape metrics, such as infrastructure pattern and connectivity, which provide a more complete understanding of how human development alters natural hydrology.

**Keywords** Impervious cover · Inter-basin transfer · Land use change · Sewer infrastructure · Urban hydrology

## Introduction

Conceptual models provide a powerful framework for predicting the impacts of urbanization on aquatic ecosystems from both ecological (Groffman et al. 2003; Walsh et al. 2005a) and geomorphological (Wolman 1967) perspectives. Prevailing models attribute aquatic degradation primarily to impervious surfaces, such as roadways and rooftops, which reduce infiltration and transport water and pollutants quickly to receiving streams (Schueler 1994; Arnold and Gibbons 1996). Degraded urban streams experience elevated nutrient and contaminant concentrations, flashy hydrographs, incised and widened stream channels, and altered plant and animal communities (Paul and Meyer 2001; Meyer et al. 2005).

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Landscape connectivity, particularly the connection of impervious surfaces and stormwater pipe networks to surface waterways, affects the quantity and quality of surface runoff contributions to a waterway. Refined frameworks such as effective impervious cover begin to account for the importance of infrastructure connectivity by examining only impervious surfaces connected directly to the stream (Walsh et al. 2005a). This metric is more strongly correlated with runoff volume (Alley and Veenhuis 1983; Driver and Troutman 1989) and stream health (Lee and Hearney 2003) than total impervious cover. While impervious based landscape metrics are used as management tools to evaluate the relative impairment of streams, they provide limited perspective on the history of the stressors that drive aquatic ecosystem decline.

Recent advances in conceptual frameworks expand our understanding of urban aquatic ecosystems by incorporating the importance of human infrastructure evolution through time and space. The urban watershed continuum provides a foundation to integrate watershed land use history into assessments of aquatic ecosystem decline (Kaushal and Belt 2012). The framework recognizes the impacts of short-term pulses and long-term presses on aquatic ecosystems (Collins et al. 2011; Bain et al. 2012a). Short-term pulses include quick events that input pollutants to a stream, while long-term presses can span centuries, encompassing the history of human landscape modifications and changes in development patterns.

We focus on the long-term impacts of urbanization on aquatic ecosystems. We hypothesize that the legacy of human landscape modifications, particularly the spatial arrangement of sewer infrastructure and neighborhood age, imparts lasting and unique impacts on urban aquatic ecosystems. Urban neighborhoods have unique development histories. For example, the timing of urbanization influences the type of sewer and water infrastructure constructed. Older cities that built sewer systems in the early 20th century typically designed systems as combined sewers, with stormwater and sanitary sewage sharing the same pipes, while newer cities designed separate sanitary and storm sewers (Tarr et al. 1984). Many of the original brick sewer mains remain in use today and many communities throughout the United States utilize sewers pipes that are over 50 years old (Wirahadikusumah et al. 2001). Evaluations of variation in watershed infrastructure age and arrangement can strengthen traditional analyses based on urban to rural gradients (Bhaskar and Welty 2012) and detect additional drivers of aquatic ecosystem decline.

Despite the importance of landscape change through time and space, retrospective assessments that include reconstructions of human water infrastructure expansion remain too rare. Retrospective assessments can uncover when human built infrastructure began disrupting natural hydrologic regimes and the rates of landscape conversion through time (Jennings and Jarnagin 2002). While challenging to reconstruct, examining long-term datasets that span the period of landscape urbanization can strengthen our understanding of the cumulative factors that lead to stream impairment and improve our ability to manage water resources in the future (Bain et al. 2011). We assess the implications of long-term landscape modification on aquatic ecosystems by examining the evolution of human infrastructure patterns in a small catchment in Pittsburgh, Pennsylvania throughout the last century.

We ask when and where were the buildings, roadways and sewers installed in the watershed? How does the spatial arrangement and connectivity of human infrastructure networks affect drainage patterns in the watershed throughout the last century? What are the relative impacts of deteriorating sewer infrastructure and changing tree canopy cover on the water balance? Particular attention is given to interactions among road, sewer, and stream networks and the resulting impacts on annual water yield. We evaluate the ability of two water yield models to predict hydrologic conditions; one model based on changes in impervious cover and one based on infrastructure connectivity. Examining the evolution of infrastructure and land use transitions allows us to characterize the connections between upstream development and downstream hydrologic effects. Moreover, this approach provides a contextual understanding of urban stream degradation that may guide and increase the success of restoration projects and improve decisions made during the repair and replacement of existing infrastructure.

## Methods

### Study area

The Panther Hollow watershed (147 ha) is a sub-basin in the Four Mile Run watershed (877 ha) located in

Pittsburgh, PA (Fig. 1). The basin lies in the western Allegheny Plateau and is underlain by the Casselman Formation, comprised of alternating layers of limestone, sandstone, and shale (Wagner 1970). Soils are predominantly formed from weathered shale and sandstone and are typically silty, clay loams (Newbury et al. 1981). Rainfall is evenly distributed throughout the year, averaging 970 mm per year.

The Panther Hollow watershed has 27 % impervious cover, with the eastern half of the watershed composed of a dense residential neighborhood (14 houses/ha) and business district, while the western half is parkland containing forest land and managed lawn areas including a golf course. Two small streams flow through the parkland portion of the watershed and drain into a human-made lake (Fig. 1). The stream network historically flowed to the Monongahela River. However, half of the reaches upstream of Panther Hollow Lake have been buried and streams downstream of the lake were connected to the combined sewer system (Fig. 1). The residential neighborhood is serviced by a combined sewer system with an overflow outfall to the Monongahela River. In 2010, 1.6 billion liters of sewage and stormwater were discharged into the Monongahela River from this outfall (ALCOSAN 2010).

The two streams that flow through the catchment are listed on the EPA's 303 (d) list of impaired waterways. The cause of impairment is sedimentation resulting from stream bank modification and slope destabilization. Elevated *E. coli* levels, ranging from 1,000 to 3,000 cfu/100 ml, were found in both streams during 2006 and 2007 (VanBriessen and Schoen 2007). Potential sources for *E. coli* include pet waste, goose and deer feces, and leaking sewer infrastructure.

## Human infrastructure reconstruction

Historical maps and aerial photography were used to reconstruct the expansion of roads and sewers and the loss of stream length in the Panther Hollow watershed. Aerial photographs and historical maps were rectified to 2010 USGS digital orthophoto quarter quads using image-to-image recognition techniques and a first order polynomial transformation in ArcMap10 (ESRI). Road, sewer, and stream networks shown on G. M. Hopkins Company Maps (1872, 1882, 1890, 1898, 1904, 1911, 1923, and 1939) were digitized and attributed with the earliest depiction of each segment (UPitt 2012b). In addition, infrastructure removed during reorganization were digitized and similarly attributed with the earliest indication of abandonment. Human infrastructure networks were clipped to the watershed area and totaled to provide an estimate of road, sewer, and stream length for each digitized map. Linear interpolation was used to estimate road and sewer length for years not included in map coverage.

Housing growth was reconstructed using a building description database obtained from the Pittsburgh Neighborhood and Community Information System

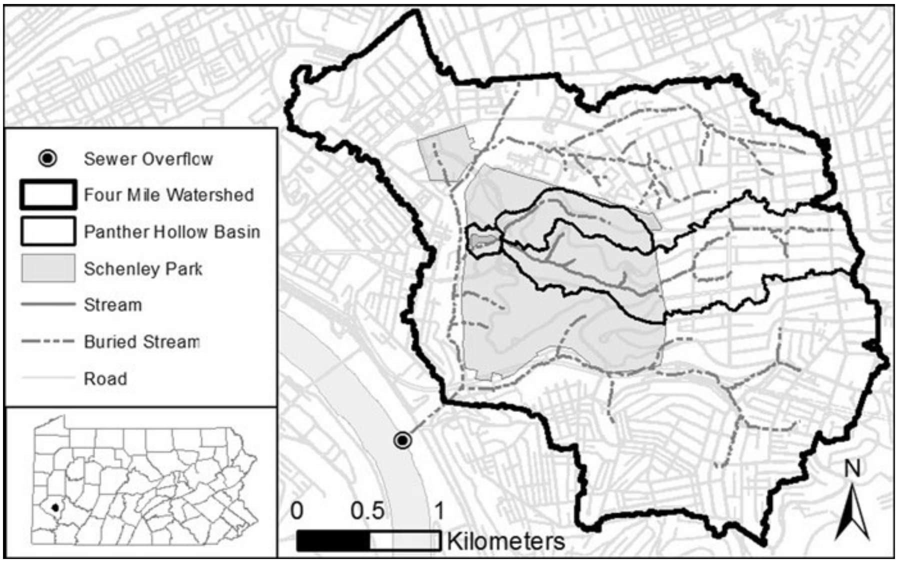

**Fig. 1** Panther Hollow sub-basin is nested within the Four Mile watershed. The majority of the historical stream network is buried and piped, except for two streams in Schenley Park. During wet weather, a mixture of stormwater runoff and sewage from the Four Mile run watershed is discharged into the Monongahela River at the combined sewer overflow point indicated on the map. The inset shows the location of the Four Mile watershed in the state of Pennsylvania (USA)

(PNCIS) and Allegheny County Property Tax Assessment Records from 2010. Parcels in the watershed were joined by map block number to the inventory of building descriptions. A housing construction date was assigned to each parcel in the basin. Building construction dates during the early 1900s appeared to assign uncertain housing construction dates to the start of the nearest decade. Therefore, our building inventory was generalized to decadal time steps from 1900 to 2010. To confirm housing estimates, trends in neighborhood growth were compared with watershed population estimates obtained from tract-level United States Census records. Linear interpolation was used to estimate annual changes in building densities and population between decades.

### Impervious cover reconstruction

Historical datasets were used to reconstruct changes in watershed impervious cover since 1870. Impervious cover was estimated using total roof and road area. Roads and roofs are the dominant hard surfaces in the watershed, comprising 82 % of present day impervious cover. Total roof area was estimated for each time interval by multiplying average roof area (164 $m^2$) by the total number of buildings. Total road area was estimated for each time interval by multiplying average road width (10 m) by total road length. Roof and road area were summed and divided by watershed area to determine percent impervious cover for each time interval. Impervious cover in 2010 was estimated using current PNCIS datasets for building footprints, edge of street pavement, and parking lots.

### Tree canopy reconstruction

Tree canopy cover was reconstructed in the commercial and residential portions of the watershed using aerial photography from 1938 to 2010. To conduct our analysis, we randomly selected 15 % of the parcels in the watershed. From this subset we eliminated parcels smaller than 200 $m^2$ to ensure that our sample included parcels with the majority of their area within the watershed boundary and excluded very small parcels from condominium units. Additionally, the resolution (1:20,000) of the aerial photographs limited canopy delineation in very small parcels. From our initial selection of 15 %, 27 parcels were smaller than 200 $m^2$, leaving 145 parcels or 13 % of the total number of parcels for the analysis. The parcel subset composed 25 % of the total commercial parcel area and 21 % of the total residential parcel area. Parcel areas average 1,010 and 714 $m^2$ (parcels >200 $m^2$) in the commercial and residential portions of the watershed, respectively. In our subset parcel areas averaged 1,669 $m^2$ (range 258–7,673 $m^2$) and 842 $m^2$ (range 209–6,720 $m^2$) for the commercial and residential sections, respectively. Within each zoning category our sample includes both large and small parcels.

Three aerial photographs taken during the growing season in 1938, 1956, and 1967 were obtained from the Penn Pilot archive (PSU 2013). Aerial photographs were rectified using image-to-image recognition techniques and a first order polynomial transformation in ArcMap10 (ESRI). All transformations had root mean square errors of 35 m or less. To quantify tree canopy cover in each photograph, parcel subset boundaries were overlain on the historical photograph. Using GIS we visually interpreted and digitized the tree canopy in each parcel for each of the three photographs. Overall canopy cover was estimated by summing tree canopy area in the parcel subset and dividing by total parcel subset area. Percent canopy cover was also calculated for the commercial and residential zoning groups for each year.

Canopy cover for 2010 was derived from canopy area data supplied by the Pittsburgh Urban Tree Canopy Cover (UTC) Assessment (UTC 2012). The UTC derived canopy cover from high-resolution aerial imagery from 2010 and LiDAR acquired in 2006. Parcel subset boundaries were overlain on the 2010 UTC tree canopy layer and tree canopy was clipped to the parcel boundaries. Overall canopy cover was estimated by summing tree canopy area in the parcel subset and dividing by total parcel subset area. The UTC was also used to estimate canopy cover in the entire watershed, and residential and commercial areas.

Rectification error was assessed by spot checking twenty current building footprints in each aerial photograph. Corner-to-corner distance errors between aerial photograph buildings and building footprints averaged 6.9 m (SD = 2.4 m). While the boundaries of parcels in each photograph may vary slightly due to rectification error, our estimated rates of canopy area expansion are extremely consistent, with an average expansion of the canopy area of 0.22 % per year.

Additionally, we cross-checked our parcel subset estimates with watershed-wide estimates of 2010. Parcel subset canopy cover estimates were 1.6 % higher than watershed-wide canopy cover for commercial areas and 1.7 % lower for residential area. Overall, the subset was 1.7 % lower than the watershed canopy cover. This consistency suggests that the sample subset captures the larger watershed-wide trend.

## Water yield model methodology

A simple water balance approach was used to reconstruct runoff proportions and annual water yield in the Panther Hollow watershed. We developed two models to predict water yield, 1) one based on runoff proportions associated with varying degrees of watershed impervious cover and 2) one based on stream flow monitoring results, infrastructure connectivity, changes in tree canopy cover, and leaking sewers.

The first model, the impervious cover model, estimated annual water yield using runoff proportions associated with impervious cover in the watershed. Runoff proportion is defined as the proportion of annual precipitation routed to the stream channel and is composed of baseflow contributions from shallow infiltration and storm flow contributions from direct runoff. The total water yield estimate assumes shallow infiltration will emerge in the stream as baseflow on an annual time-step. Runoff and shallow infiltration contributions commonly relied upon when estimating impervious impacts (Arnold and Gibbons 1996) were used to derive an equation to predict runoff proportion based on percent impervious cover. Using average runoff estimates from Fig. 1 in Arnold and Gibbons (1996) we derived a relationship between runoff contributions and impervious cover,

$$\mathrm{R} = 0.0032\ \mathrm{IC} + 0.34, \tag{1}$$

Runoff proportion (R), as a proportion, is a function of impervious cover (IC), as a percent. For each year between 1870 and 2012, we estimated annual runoff proportions in the Panther Hollow watershed using our historical impervious cover reconstruction and Eq. (1).

We then predicted annual yield by applying annual estimates of runoff proportion to the annual precipitation record (1870–2012) from the National Weather Service Pittsburgh Station. Annual yield in mm was calculated as,

$$\mathrm{Y} = \mathrm{R} \times \mathrm{P}, \tag{2}$$

where water yield (Y) equals the runoff proportion (R) times annual precipitation (P) in mm. This equation assumes the entire watershed area is contributing water to the streams (Fig. 2a).

The foundation for the second water yield model, the infrastructure model, is Panther Hollow's contemporary runoff proportion. Contemporary annual runoff proportions were determined using five years of stream flow and precipitation records from January 2008 to December 2012. Flow data was provided by the Allegheny County Sanitary Authority (ALCOSAN) from a discharge monitoring station at the bottom of the watershed, below Panther Hollow Lake (Fig. 2b). Discharge was recorded at 15-minute intervals using an area-velocity flow meter (American Sigma 920) installed in a 38.1 cm diameter overflow pipeline below the lake. Annual yield was calculated by summing annual stream flow volume and dividing by the watershed area. Annual runoff proportions were determined for each year by dividing annual yield by precipitation depth obtained from a rain gage located within 1 km of the watershed (Three Rivers Wet Weather Rain Gage Network). Annual runoff proportions averaged 0.209 (SD = 0.036) and the overall runoff proportion during 2008–2012 was 0.213 over the five year monitoring period.

For the infrastructure water yield model, we applied the contemporary runoff proportion of 0.21 to the annual precipitation record from 1911 to 2012. This runoff proportion reflects water inputs from groundwater sources and runoff from impervious surfaces directly connected to the stream from the western portion of the watershed (Fig. 2b). We apply a constant runoff proportion because impervious surfaces directly connected to the streams during this time period remained around 10 % of the directly connected watershed area. Runoff contributions from increased impervious cover in the upper, eastern portion of the watershed were routed out of the Panther Hollow watershed to an adjacent basin. Therefore, annual water yield from 1911 to 2012 was estimated using Eq. 2, where R = 0.21 and P is annual precipitation in mm.

From 1872 to 1911, the infrastructure model incorporates changes in watershed drainage patterns during the construction of the combined sewer system. During this time period we assume the main factor

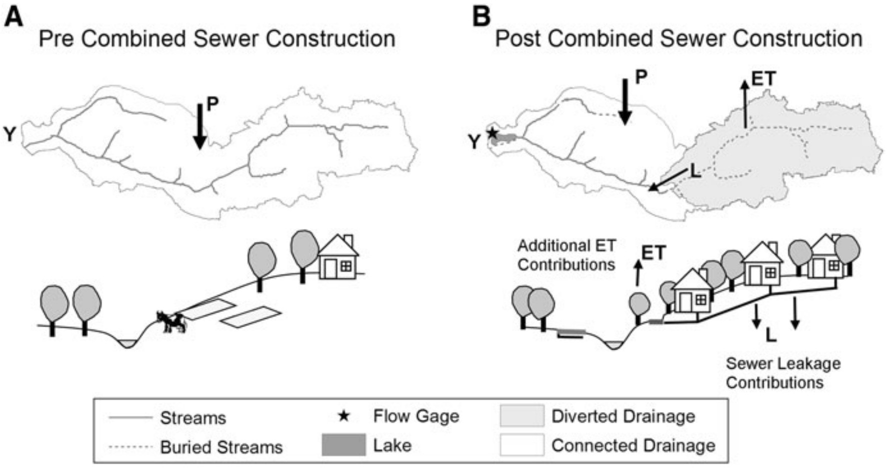

**Fig. 2** The infrastructure water yield model is based on the runoff proportion (*R*) determined from a 5 year stream flow record obtained from a stream flow gage at the bottom of the lake. Annual precipitation inputs (*P*) where multiplied by the runoff proportion to determine annual water yield (*Y*). *Panel A* shows the watershed prior to urbanization (pre-1900) when the entire watershed contributed drainage to the streams. *Panel B* shows the watershed post urbanization (post-1911) when the upper half of the watershed was connected to the combined sewer system, halving directly connected drainage. The infrastructure model also explored, additional contributions from water inputs from leaking sewer lines (*L*) and additional exports from increased evapotranspiration (*ET*)

influencing water yield in the watershed is the disconnection of the upper basin drainage during the eleven year period between 1900 and 1911 when the combined sewer was constructed. Our infrastructure reconstruction reveals ~50 % of the upper watershed was disconnected from the lower watershed during the construction of the combined sewer system (Fig. 2b). Impervious surfaces in the upper watershed are connected directly to the combined sewer system and runoff from these surfaces is routed out of the Panther Hollow watershed. To account for the transfer of water draining from 50 % of the basin, the runoff proportion was incrementally doubled from 0.21 to 0.42 over the course of 11 years spanning the construction of the sewer network from 1900 to 1911 and fixed at 0.42 prior to 1900. We then estimated annual water yield using Eq. (2), reconstructed runoff proportions, and annual precipitation.

### Infrastructure model: quantifying potential imported and exported water

To understand the role of other processes, the infrastructure model includes estimates of increased evapotranspiration due to the growth of the urban tree canopy and water imports from leaking sewer lines due to deteriorating infrastructure (Fig. 2b). Additional annual evapotranspiration was estimated from 1938 to present using the historical tree canopy reconstruction. Percent canopy increase was calculated for each year since 1938, using canopy cover in 1938 as the baseline. Additional water contributions from evapotranspiration were estimated for each year assuming that a 1 % increase in tree canopy cover would reduce the total water yield by 2.2 mm (Hibbert 1966). Sewer leakage was quantified by first estimating annual sewer flow and then applying a leakage factor between 0 and 5 % depending on pipe age (Ellis et al. 2004). Most of the combined sewer lines were installed in the watershed by 1910, making them 100 years old. Therefore, we applied a leakage factor starting with 0 % leakage in 1910 and adding 0.5 % more leakage each decade since 1910, ending with 5 % leakage in 2010. Annual sewer flow was estimated by multiplying watershed population by average daily water consumption, assuming water use of 379 liters/person/day (Gleick 1996) and that residential water use is the main component of sewer flow. To determine annual leakage yield, the leakage factor was applied to total annual sewer flow and divided by the watershed. These additional water balance components were incorporated into the infrastructure model by adding and subtracting evapotranspiration and leakage contributions, respectively, to the annual yield record. The bounds of this range in estimated yield provide a measure of infrastructure yield uncertainty.

## Results

### Infrastructure histories

#### *Road and sewer growth*

Prior to 1900, road and sewer infrastructure was limited in the Panther Hollow watershed (Fig. 3). Historical maps from 1872 show the Panther Hollow watershed as an agricultural landscape, with seven large parcels containing 29 structures (Fig. 4). The two main roads that ran through the upper basin were likely surfaced with dirt, gravel, or macadam since widespread asphalt paving did not occur until the 1920s (McShane 1979). Residents disposed of sewage on-site in privy vaults or pit-style outhouses (Buchan 1948). Households obtained water from wells, surface water, or precipitation harvesting with cisterns (Ogle 1996; Tarr 2005).

A transition from agriculture to urban land use occurred between 1890 and 1920. Development was concentrated in the upper half of the watershed, while the lower watershed remained mostly forest parkland with the exception of an eighteen-hole golf course that opened in 1902 (Fig. 4). Between 1890 and 1911, approximately 16.7 km of brick and vitrified clay sewer pipes were installed in the watershed. Sewer infrastructure diverted water drainage from the upper half of the watershed to an adjacent watershed (Fig. 4). The road network expanded from 4.5 km of dirt roads to 15 km of asphalt, brick, and block surfaces (Hopkins 1911). A network of curbs, gutters, and storm drains were installed during road construction, channeling runoff to the combined sewer (Tarr et al. 1984). Approximately 2.8 km of streams (42 % total stream length) were buried and piped during urbanization (Fig. 3). A 0.9 ha lake was constructed at the mouth of the watershed around 1904. The lake outfall was connected to the newly constructed combined sewer and discharged water to the Monongahela River (Fig. 1).

Rapid installation of road, sewer, and stormwater infrastructure during the urban transition significantly altered natural drainage patterns. Half of the natural drainage area was disconnected from surface water drainage and re-routed through the combined sewer to the Monongahela River. Raw sewage and stormwater flowed into the Monongahela River until 1959 when ALCOSAN installed sewer interceptors along the river to convey sewage to a centralized treatment facility (Tarr 2005). Minor changes in the spatial arrangement of the road and sewer networks occurred since initial construction.

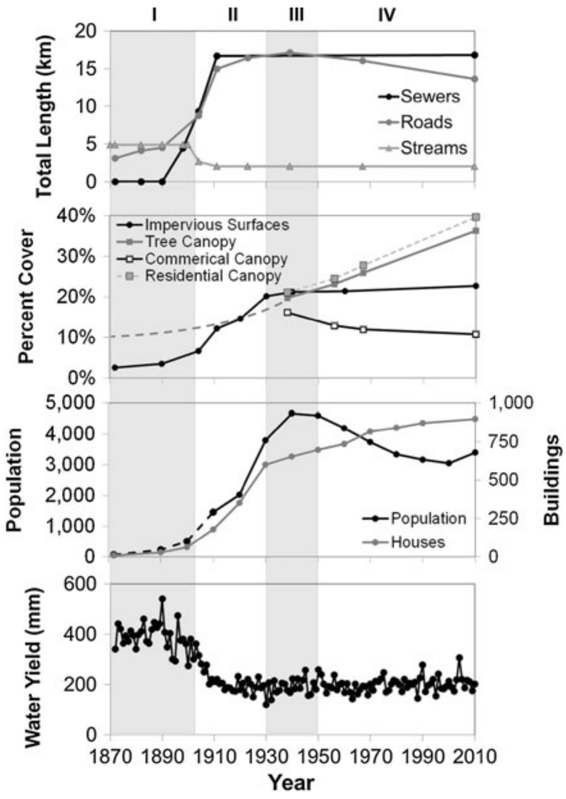

**Fig. 3** Four infrastructural phases were identified in the Panther Hollow watershed. *Phase I* is dominated by agriculture, with a limited road network and low population. *Phase II* is marked by the rapid expansion of the sewer and road networks, the loss of headwater streams and a decline in annual water yield. *Phase III* includes the growth and stabilization of the watershed population. *Phase IV* spans the decline of the watershed population and the growth of the urban tree canopy. The canopy in the residential portion of the watershed has increased from 21 to 40 %, while tree canopy cover in the commercial portion has declined from 16 to 11 %. Dashed lines indicate expected trends in population and overall canopy cover during data gaps

#### *Housing growth*

While the main road and sewer infrastructure in the basin was largely completed by 1911, the watershed

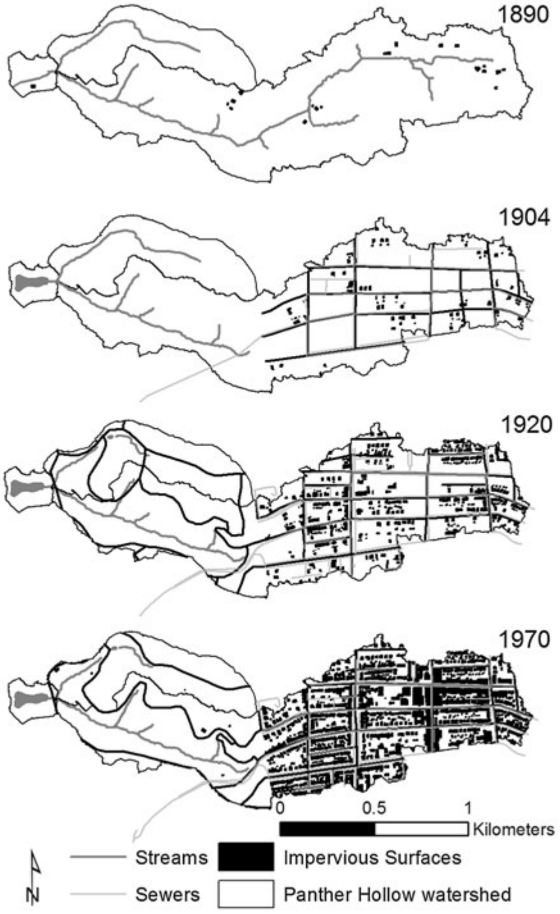

**Fig. 4** Infrastructure reconstruction reveals a century of landscape modification in the Panther Hollow watershed. Prior to 1900 the watershed was dominated by agriculture and contained very few impervious surfaces. Between 1900 and 1910 road and sewer networks expanded in the eastern portion of the catchment and a lake was constructed at the bottom of the catchment. From the 1920s to 1940s the majority of houses were constructed, with development concentrated in the eastern half of the catchment, while the western portion was preserved as parkland

contained only 179 residential houses, just 20 % of the current number (Fig. 3). The completion of the road network connected the eastern half of the watershed with economic activity to the north and west, making parcels in the Panther Hollow watershed attractive to potential buyers. Housing construction increased dramatically between 1920 and 1930, with 248 houses constructed in a single decade. The western portion of the watershed remained forested parkland or part of the golf course. Minor structures built in the park include picnic shelters, a boathouse, and golf clubhouse.

### *Expanding residential tree canopy cover*

Historical photographs indicate that much of the watershed's forests were cleared during early agricultural activity, leaving the eastern half of the basin mostly devoid of trees (UPitt 2012a). Parcel analysis revealed that overall tree canopy cover increased from 20 % canopy cover in 1938 to 36 % canopy cover in 2010 (Fig. 3). In residential parcels canopy cover expanded from 21 % in 1938 to 40 % in 2010, however commercial parcel canopy cover declined from 16 % in 1938 to 11 % in 2010. Between 1938 and 2010, overall average increases in canopy cover of 17 % per lot were observed, with an average canopy cover increases of 18 % in residential parcels and average losses of 4 % in commercial parcels. The entire Panther Hollow watershed, including the parkland, had 47 % tree canopy cover in 2010 (UTC 2012).

### Water yield model comparison

Monitored annual yield in Panther Hollow is roughly half that of yield predicted by the impervious model (Fig. 5). The impervious model predicts an increase in water yield over the past century, while the infrastructure model predicts a decline in water yield starting in 1901. In the infrastructure model, contributions from increased evapotranspiration from tree canopy growth and water inputs from leaking sewer infrastructure were relatively modest and offsetting. Since 1990, leaking sewer lines could be contributing an average annual input of 14 mm into the catchment, thereby subsidizing on average 7 % of total annual water yield. Since 1938, additional evapotranspiration from tree canopy growth is potentially removing an average of 18 mm of water annually (9 % of total yield) from the watershed (Fig. 5).

## Discussion

Effective restoration planning to improve aquatic health requires a complete understanding of how historical and contemporary infrastructure interacts with stream ecosystems. The reconstruction of a century of urbanization in the Panther Hollow watershed reveals fundamental lessons about the effects of human infrastructure networks on urban stream hydrology. This historical perspective allows

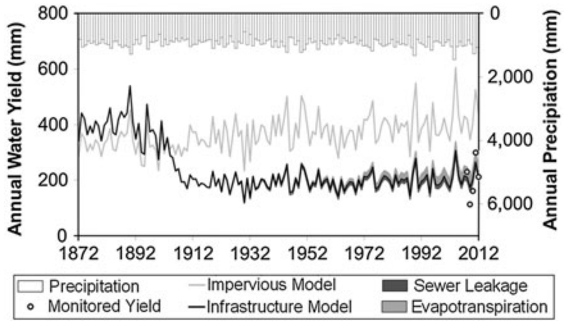

**Fig. 5** Impervious and infrastructure yield reconstructions for the Panther Hollow watershed. The impervious model predicted 50 % higher yield than the infrastructure model from 1910 to present. Potential contributions of other poorly characterized water budget components are shown. The dark grey shading indicates the potential contributions of leaking sewer lines, composing on average 7 % (14 mm) of total water yield since 1990. Similarly, the growing tree canopy transpires increasing amounts of water out of the catchment and removes on average 9 % (18 mm) total water yield since 1990

us to distinguish when urbanization began altering natural drainage networks and identify the onset of hydrologic changes that lead to aquatic ecosystem decline.

## Clarifying discrepancies in annual water yield

Both yield models predict similar pre-development water yields (Fig. 5). However, the impervious model predicts annual yield in Panther Hollow's streams has increased over the last century, while our infrastructure model indicates a decline in annual yield beginning in 1901. For example, the impervious model predicts contemporary yields in Panther Hollow that are twice that of monitored and infrastructure model yields. This discrepancy occurs because the impervious model does not incorporate interactions between the sewer and stream networks. Sewer infrastructure installed in the early 20th century hydrologically disconnected much of the upper watershed, transferring stream water and urban runoff through the combined sewer to an adjacent watershed (Fig. 2b). While this may seem a unique case, the importance of inter-basin transfer in urban areas has been recognized in catchments throughout the United States (Brandes et al. 2005; Claessens et al. 2006; Lookingbill et al. 2009).

Interactions among sewer and water infrastructure and stream networks may be much more common and significant than recognized in urban systems. The effects of inter-basin transfer can be particularly dramatic at the small basin scale, a scale roughly equivalent to many urban neighborhoods (Bain et al. 2012b). Refined urban water budgeting can clarify additions from municipal water from leaking water lines and exfiltration of sewage (Bhaskar and Welty 2012; Kaushal and Belt 2012). This case emphasizes the continued need to refine urban water budgets to include and characterize interactions between sewershed and watershed areas.

## Human infrastructure histories and watershed metrics

Results from our retrospective assessment reveal the importance of integrating human infrastructure histories into urban catchment models. Without this evaluation, traditional impervious-based models over estimate water yield in Panther Hollow's streams. Further, additional landscape metrics such as infrastructure connectivity and development age can clarify when urbanization began altering watershed hydrology and degrading aquatic ecosystems.

Applying general urban growth models results in the assumed associations between the growth of urban areas, impervious cover expansion, and the existence of identifiable thresholds (Arnold and Gibbons 1996; Booth and Jackson 1997). Initial studies hypothesized that stream impairment would be minimal in watersheds with less than 10 % impervious cover (Booth and Jackson 1997). However, recent work has refined linear thresholds to a continuous but variable gradient of impairment as impervious cover increases (Schueler et al. 2009). Our examination of infrastructure history in Panther Hollow agrees with this impairment continuum and corroborates urbanization's non-linear impact on aquatic ecosystems.

In Panther Hollow the onset of urbanization occurred around 1910 and the progression of infrastructure growth was non-linear, peaking in the 1930s. This non-linearity is exhibited in the four phases of Panther Hollow's development history (Fig. 3). During the first phase, the watershed was an agriculture landscape with a small population and very little impervious cover (<3 %). Large family farms were connected by a sparse network of dirt roadways and headwater streams remained intact (Fig. 4). Water yield in the streams was double contemporary yields.

Phase two, the construction phase, spans 1905–1930. During this phase, large parcels were subdivided into residential lots, around which the road and sewer network were built (Fig. 4). Housing development then in-filled the established street network and the watershed's population nearly doubled between 1920 and 1930. The construction of the street network and houses effectively created present day impervious cover in one step during the two decades between 1910 and 1930. This period of peak development had significant impacts on the aquatic ecosystem. Headwater streams were buried and piped into the new combined sewer system (Fig. 4). The diversion of headwater streams marks the onset of urbanization's impact on the aquatic ecosystems because it significantly reduced water yield through the catchment. Downstream aquatic ecosystems likely experienced reduced baseflow, nutrient and sediment inputs from surrounding roads, and a decline in aquatic communities.

The next phase spans 1930–1950 and is characterized by a plateau in watershed population and a slow in infrastructure construction. Increases in population led to increases in water use and flux through sewer networks. We estimate that water use at the height of Panther Hollow's population (4,700 residents in 1940) was roughly 645 million liters/year. This volume of water, combined with stormwater draining from the road network likely tested the capacity of early 1900s era sewer lines and increased the occurrence of sewer overflows (Tarr 2005). However, infrastructure arrangement focused these impacts along the Monongahela River, not the streams in Panther Hollow.

Phase four encompasses a decline in watershed population, continued deterioration of infrastructure networks, and the growth of the residential urban tree canopy (Fig. 3). While our historical estimates do not quantitatively incorporate these processes, we can estimate that between 1950 and 2010, sewer leakage and additional evapotranspiration fluxes constitute on average 6 and 10 % of total yield, respectively (Fig. 5).

Our results suggest that the evolution of neighborhoods, particularly sewer infrastructure deterioration and tree canopy recovery, is not well incorporated into our conceptual models of urban stream impairment. In addition, patterns of infrastructure development can result in surprising changes in stream hydrology. In this case, development has actually reduced, not increased annual water yield. While impervious cover in the upper portion of the catchment is substantial, the arrangement of sewer infrastructure routes stormwater runoff from 90 % of the impervious surfaces out of the catchment. Clarifying the interactions among these human and natural drainage networks can aid in assessing the causes of stream impairments and in prioritizing restoration efforts.

## Integrating landscape evolution into urban watershed frameworks

With stream restoration and stormwater management projects quickly becoming a multi-million dollar industry (Lavendel 2002), it is vital that we incorporate interactions among road, sewer and stream networks into planning processes. Consider the impacts of leaking sewer lines. Many of the brick and clay combined sewer lines in Panther Hollow were installed 100 years ago, and remain far beyond design lifetimes. As maintenance of sewer lines is deferred, deterioration rates increase (Micevski et al. 2002). Though not necessarily surprisingly with hind sight, sewer leakage is a potentially large and relatively under-characterized catchment input. Given data availability, it is impossible to trace the exact amount of water leaking from Panther Hollow's sewer lines. However, our estimates reveal that sewage exports to the streams should be characterized for accurate water and material budgeting. Leaking sewer lines subsidize baseflow and nutrients to downstream reaches. In Baltimore City, lawn irrigation and pipe leakage accounted for 14 % of catchment inputs, while infiltration of groundwater into sewer lines accounted for 41 % of catchment outflows (Bhaskar and Welty 2012).Without a clear understanding of this system's evolution, material budgeting approaches are prone to error (e.g. Divers et al. 2013).

Changes in the tree canopy also have implications for assessing the health of urban streams. During the late 1800s much of Panther Hollow's watershed was deforested. Residents and the city reforested portions of the watershed by planting trees during the 1930s and 1940s (Fig. 3). As the neighborhood matured, newly planted trees grew into a canopy covering 36 % of the upper watershed. The dramatic increase in canopy cover over the last century provides numerous hydrologic benefits to the catchment, including increased interception and evapotranspiration. However, impervious-based models do not fully incorporate the benefits of increased canopy cover, though these benefits are recognized in the literature (Sanders 1986; Xiao et al. 1998). During smaller precipitation events water is likely intercepted on tree leaves and evaporated before it becomes runoff (Xiao et al. 1998). For example, in Panther Hollow the current tree canopy covers 13.6 % of the total road area and 3.7 % of the total roof area, both the dominant impervious surfaces. In cities with extensive urban forests, the contribution of trees to stormwater reduction is likely substantial.

Just as impervious models have addressed connectivity with effective imperviousness, incorporation of inter-basin transfer, deteriorating infrastructure, and changing tree cover into conceptual models will enhance available approaches to assess hydrologic impairments. Additionally, effective planning for urban stream restoration often requires site history and infrastructure interaction data in addition to impervious cover.

### Implications for urban watershed management

The importance of watershed history is clear. Understanding these legacy impacts and interactions can help target watershed restoration to achieve goals that provide multiple benefits. For example, in Pittsburgh and Panther Hollow, focusing repair on deteriorating infrastructure and installing stormwater practices to slow down and store water in the eastern portion of the watershed likely provide substantially more benefits to the aquatic ecosystem than riparian restoration (Walsh et al. 2005b). Implementing stormwater management practices (e.g. rain gardens) in upper catchment could provide the neighborhood with multiple benefits including increased green space, reduced flooding, and increased infiltration. These improvements may also benefit downstream reaches by reducing peak flow events, increasing baseflow, and reducing sediment and pollutant inputs, thereby protecting any future investments in the stream channel. Effective restoration planning recognizes the limitations associated with site history and prioritizes practice placement within the broader context of the watershed as a whole (Bernhardt and Palmer 2007). This study demonstrates the fundamental importance incorporating watershed history into restoration planning efforts.

## Conclusions

Our analysis demonstrates that approaches based on impervious cover alone do not effectively quantify the hydrologic impacts of urbanization in Panther Hollow. Therefore, impervious cover models applied to catchments without regard for the history or spatial arrangement of infrastructure can overestimate urbanization's impacts on stream storm flow and underestimate impacts on other characteristics such as baseflow. Effective restoration of aquatic ecosystems requires clarifying the accumulated legacy impacts arising from changes in land use and land management practices. In addition it requires looking upstream to assess where restoration efforts can provide multiple benefits to both the community and water quality.

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