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CHARACTERIZING A MAJOR URBAN STREAM RESTORATION PROJECT: NINE MILE RUN (PITTSBURGH, PENNSYLVANIA, USA)[1]

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ABSTRACT: Urban stream restoration continues to be used as an ecological management tool, despite uncertainty about the long-term sustainability and resilience of restored systems. Evaluations of restoration success often focus on specific instream indicators, with limited attention to the wider basin or parallel hydrologic and geomorphic process. A comprehensive understanding of urban stream restoration progress is particularly important for comparisons with nonurban sites as urban streams can provide substantial secondary benefits to urban residents. Here, we utilize a wide range of indicators to retrospectively examine the restoration of Nine Mile Run, a multi-million dollar stream restoration project in eastern Pittsburgh (Pennsylvania, USA). Examination of available continuous hydrological data illustrates the high cost of failures to incorporate the data into planning and adaptive management. For example, persistent extreme flows drive geomorphic degradation threatening to reverse hydrologic connections created by the restoration and impact the improved instream biotic communities. In addition, human activities associated with restoration efforts suggest a positive feedback as the stream restoration has focused effort on the basin beyond the reach. Ultimately, urban stream restoration remains a potentially useful management tool, but continued improvements in post project assessment should include examination of a wider range of indicators.

(KEY TERMS: urban areas; rivers/streams; watersheds; geomorphology; streamflow; restoration.)

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INTRODUCTION

The "restoration" of streams has become an increasingly popular tool for management goals ranging from species diversity to flood control (Bernhardt *et al.*, 2005, 2007; Palmer *et al.*, 2007). Stream restoration projects attempt to reestablish the biological, physical, and chemical processes that connect aquatic, riparian, and terrestrial ecosystems (Kauffman *et al.*, 1997). Restoration of urban streams requires addressing additional challenges, particularly those arising from urban property valuation and ownership patterns (Bernhardt and Palmer, 2007) and the severe alteration of hydrologic and geomorphic systems following urbanization (Wolman, 1967; Hammer, 1972; Graf, 1975; Booth and Jackson, 1997), generally "diagnosed" as the urban stream syndrome (Walsh *et al.*, 2005a; Coles *et al.*, 2012). However, stream restoration as a policy option continues to suffer as clear documentation of reestablishment of biological, physical, and chemical processes over extended periods remains [3] relatively rare (Bernhardt *et al.*, 2005).

Despite the recognition that the data quality in post project evaluation continues to limit meta-evaluation of urban stream restorations (Miller *et al.*, 2010), site-based characterization of urban stream restoration has rapidly expanded over the last several years. Early work used multiple lines of evidence including visual habitat assessments, comparison of benthic macroinvertebrate communities with reference reaches, and a short neighborhood survey to evaluate a small urban stream restoration in California (Purcell *et al.*, 2002). More recent work has brought increased sophistication in evaluation of these indicators, including econometric evaluation of local resident response (e.g., Kenney *et al.*, 2012), examination of interactions among multiple biological communities (e.g., Stranko *et al.*, 2012), and even examination of interactions among sediment transport, chemistry, and biology (e.g., Schiff *et al.*, 2011). Throughout the literature, calls for continued increases in post project assessment rigor are universal. Less common, but seemingly as important, is the need for more comprehensive examination of restoration methods and outcomes, expanding to the entire drainage basin and to all of the biotic and abiotic processes acting on reaches of interest.

Often post project assessments focus on single integrative variables, such as macroinvertebrate communities. Furthermore, the vast majority of the time, restoration success is considered on a reach scale, outside of the context of responses by local residents and the larger watershed. Both tendencies are problematic, as indicators like macroinvertebrate communities recover slowly in isolated reaches without established upstream communities to recolonize the reach (Blakely *et al.*, 2006) and research results continually point to the need for adaptive management of the larger watershed (Walsh *et al.*, 2005a; Bernhardt and Palmer, 2011). In addition, focus on integrated biological indicators of stream quality does not account for the multiple bottom line benefits possible in urban systems (e.g., enhanced green space, water quality improvements, flood control, etc. [Taylor *et al.*, 2006]). The potential for multiple bottom line benefits is particularly important given the infrastructure crisis in the United States (American Society of Civil Engineers, 2009). Significant investments will be required over the near term to correct deferred infrastructure maintenance and repair and restore water and sewer systems in aging urban areas (American Society of Civil Engineers, 2009). The utilization of stream restoration as part of infrastructure repair and replacement represents a tremendous opportunity to maximize benefits from public expenditures. However, the effectiveness of urban stream restorations in addressing infrastructural deficiencies must be demonstrated before they can be reliably incorporated into our environmental and infrastructure management efforts.

While projects are ideally evaluated both before and after restoration (Kondolf, 1995), in the absence of pre-project characterization, a largely retrospective assessment can provide important lessons, particularly with a broad set of indicators. This study focuses on restoration of Nine Mile Run (NMR) (Pittsburgh, Pennsylvania) completed in 2006. Synthesis of relevant post project monitoring data enables evaluation of urban stream restoration over a relatively extended temporal period. Herein, we have collected and synthesized data including hydrological, biotic (fisheries, benthic macroinvertebrate), water chemistry, and local community activity characterizations to evaluate urban stream restoration at multiple scales. Together, these data document improvements in instream biotic communities with a continuing positive trajectory. In particular, the response of catchment residents to the restoration seem fundamental to the continued removal of instream stressors. Moreover, examination of hydrologic and geomorphic changes in the basin indicates the failure to address these catchment-wide impairments such as the altered hydrograph may limit the long-term sustainability of reach-scale urban stream restoration success.

STUDY AREA

NMR is a tributary of the Monongahela River draining 19.4 km^2 of eastern portions of the city of

Pittsburgh, Pennsylvania and adjacent communities (Figure 1). The basin drains a highly dissected portion of the unglaciated Appalachian Plateau Physiographic Province, with a total vertical relief in the drainage basin of 180 m and an average annual precipitation of 94 cm. The watershed was urbanized in the first half of the 20th Century, predominantly as residential streetcar suburbs to the City of Pittsburgh. It drains substantial portions of four separate municipalities (City of Pittsburgh, Swissvale, Edgewood, and Wilkinsburg, Pennsylvania) and relatively small portions of three others (Braddock Hills, Forest Hills, and Penn Hills, Pennsylvania). These municipalities and neighborhoods in Pittsburgh span a wide range of socioeconomic conditions; for example, between 5 and 38% of the residents in these communities were at or below the poverty line in 2009. This human landscape is challenging to manage due to heterogeneity in municipal governance exacerbated by extreme contrasts in socioeconomic status. Today, due to widespread stream burial during urbanization, many of the roughly 50,000 basin residents live distant from any open flowing water (Figure 1).

Previous research documents substantial impacts to NMR by road inputs, leaking sanitary sewer systems, combined sewer overflows, and leachates from a 22 Mm^3 steel slag dump located near its mouth (Abrams *et al.*, 2001; Koryak *et al.*, 2002; Divers *et al.*, 2013). Base-flow dry weather conductivity values along NMR average about 1,200 µmhos/cm and can drop as low as 60 µmhos/cm following summer storms. However, short duration winter thaw peak conductivity values as high as 32,000 µmhos/cm have been documented. This chemistry results from road salt runoff during periods of frozen precipitation (Williams *et al.*, 2000; Foos, 2003; Godwin *et al.*, 2003). Even during summer base-flow conditions, the major ion composition of the waters of NMR is dominated by sodium chloride, rather than calcium sulfate, the dominant ionic chemistry in nearby drainages (Abrams *et al.*, 2001). In addition, slag dumping (Figure 1) began in the 1920s and ended in 1972 covering the lower portions of the stream valley (Collins *et al.*, 1998; Tarr, 2002). Before these leachates were captured and diverted in 2005, the mean pH of the stream below the dump was 9.3, ranging between 7.7 and 11.1 (Koryak *et al.*, 2002).

In the late 1990s, an effort led by the Center for Creative Inquiry at Carnegie Mellon University resulted in the decision to restore rather than culvert and bury NMR (Tarr, 2002; Harnik, 2007). The $7.7 million stream restoration project was completed

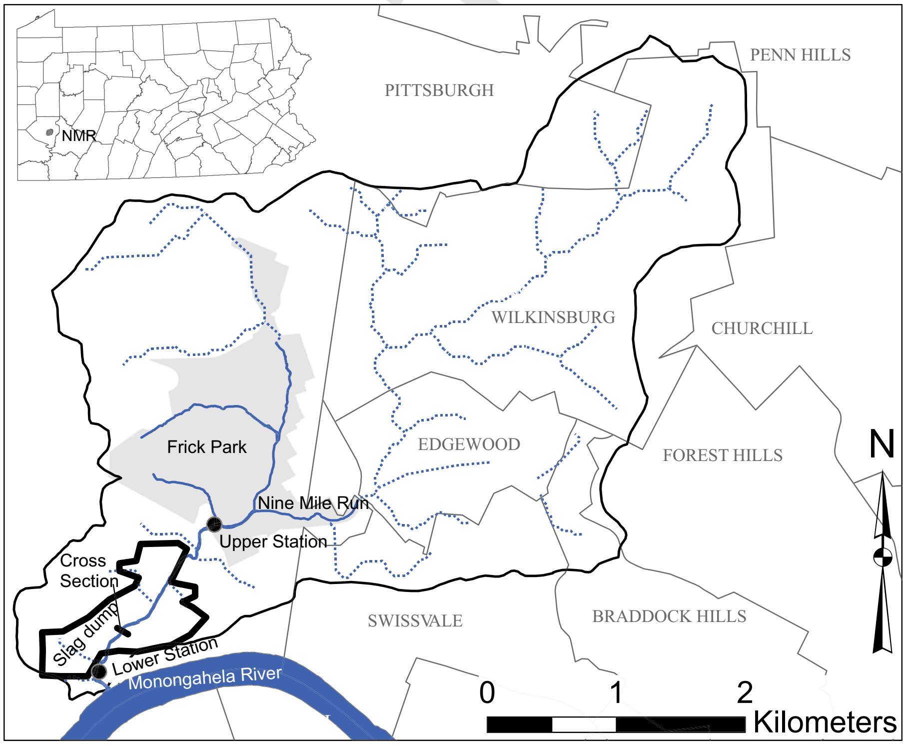

FIGURE 1. Map of Nine Mile Run Watershed Boundaries. Solid lines show contemporary intermittent and perennial streams. Dotted lines indicate historical drainages since buried. The extent of Frick Park is shown in solid gray and the historic slag dump with a heavy dark line. Municipal boundaries and municipality names are shown in gray. Inset map shows location of the Nine Mile Run watershed in the state of Pennsylvania. The USGS gage was located at the "Upper Station."

in July 2006, with additional reparation work in 2007 and 2009 (Table 1). The planning and implementation of the project was funded by the U.S. Army Corps of Engineers, with matches from a variety of agencies including the City of Pittsburgh, the PA Department of Environmental Protection, the Allegheny County Sanitary Authority and the Heinz Endowments (Harnik, 2007). The project was completed to: (1) improve stream stability and water quality; (2) diminish peak discharges resulting from urbanization; (3) improve the aesthetic quality of the valley; and to (4) enhance recreational opportunities (Camp, Dresser, & McKee, 2001). The restoration project removed barriers, both chemical and physical, throughout the hydraulically modified reaches. Perhaps the most important being removal of the slag leachates discharged upstream of the Lower Station, with leachate captured and rerouted to water treatment systems via a French-drain style engineered system (Table 1). The general nature and toxicity of highly concentrated slag leachates were examined in detail by the U.S. Army Corps of Engineers (1982, 1989), and their specific impacts to NMR by Koryak *et al.* (2002). In addition, eight significant hydraulic barriers to fish passage to the upper NMR existed prior to restoration. Six of these were scoured below concrete-encased sewerline crossings and two below concrete aprons protecting channel sections underneath bridges. Since the restoration project in the valley was completed in 2006, further stressor reduction efforts continue in the basin, including extensive repairs and upgrades of the basin's sewer system infrastructure; the capture and diversion of slag leachates; and an ambitious rain barrel project. The Nine Mile Run Watershed Association (NMRWA) was established in 2001 to engage citizens, implement demonstration projects, and advocate for the stream and watershed. In more recent periods, the watershed association has taken a more central role by advocating for additional restoration work, for example, pursuing funding for the 2009 channel re-reconfiguration.

METHODS

Hydrograph Extension

Only limited periods before and after the restoration have continuous records of instream flow, both collected at the "Upper Station" sampling location (Figure 1). Stream discharge was measured at 15-min intervals from June 1999 to March 2000 to guide restoration design (U.S. Army Corps of Engineers, 2000). Following the restoration, a USGS gauging station was installed in NMR (June 2006-September 2009; USGS station 03085049). To better understand these snapshots in context, the hydrograph was extended using a 49-year discharge record from Little Pine Creek as a reference (USGS station 03049800). The Little Pine Creek Watershed is located approximately 8 miles north-northwest of the NMR Watershed. The gauged catchments are similar in size (NMR: 14 km^2 and Little Pine Creek: 17 km^2);

TABLE 1. Major Components of Restoration Project and Repairs in Nine Mile Run.

Restoration Work	Period of Work	Description of Work
Phase 1a	Completed spring 2002	1. Initial rerouting of stream channel 2. Removal of hard surfaces (e.g., parking lots) in valley bottom 3. Construction of a soccer field in valley bottom
Urban Redevelopment Authority Seep Abatement	2005	Soil and groundwater discharging from steel slag pile captured and routed to sewage treatment plant, removing chemical barrier to fish passage
Phase 1b	Spring 2004-fall 2005	1. Stream channel work including installation of hydraulic structures in Nine Mile Run above the "Upper Station" (Figure 1) 2. Stream channel moved from the valley wall to the center of the valley 3. Large amounts of overbank sediment removed from system 4. Establishment of wetlands in floodplain areas
Phase 2	Fall 2005-June 2006	Installation of hydraulic structures in Nine Mile Run below the Upper Station (Figure 1), including moderation of physical barriers to fish passage
2007 Channel work	September 2007	Most hydraulic structures in main stem of stream rearranged
2009 Channel work	December 2009	Repair of damaged hydraulic structures, clast sizes in structures enlarged

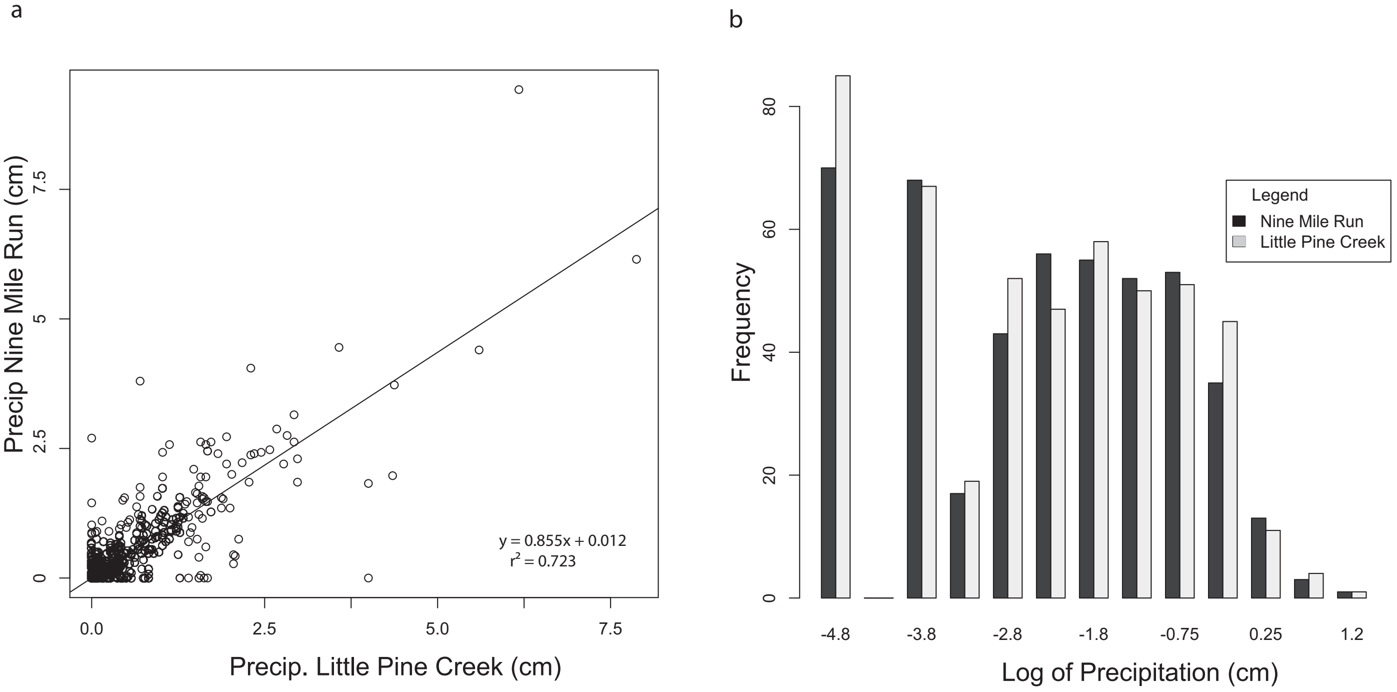

FIGURE 2. Comparative Precipitation in Basins Used for Hydrograph Reconstructions. (a) Daily precipitation for both Little Pine Creek and Nine Mile Run (NMR) (data from Three Rivers Wet Weather Rain Gauge Network). (b) Probability distribution function for both Little Pine Creek and NMR between June 2006 and September 2009).

however, the NMR basin is much more urbanized (Little Pine Creek impervious cover: <5% [Pennsylvania Environmental Council, 2009], NMR impervious cover ~38% [Homer *et al.*, 2007]).

The hydrograph extension used here related the distribution frequency of discharge in NMR with Little Pine Creek rather than reconstructing historic flow based on direct comparison of simultaneous flows. The high variance in real-time precipitation between the two watersheds (Figure 2a) limits precision of hydrograph reconstruction in real time. However, similar precipitation frequencies (Figure 2b) allow historical discharge frequency analysis for estimation of discharge in NMR. Daily discharge from 2006 to 2009 in each basin was arranged least to greatest, and the relationship between basins was fit as a linear model. Through this transformation, streamflow (base flow and storm flow) is more likely to be associated with atmospheric conditions (drought, small storms, and large storms) of similar magnitude. The linear model was applied to the discharge record in Little Pine Creek between 2000 and 2009 to estimate NMR flows during this period. This method of hydrograph extension, while appropriate for reconstructing the frequency of extreme events, is not intended to be used for more specific measures such as exceedance probabilities due to the confounding effects of contrasting impervious covers and sewer systems.

Surface Water Quality Sampling

Surface water sampling was conducted biweekly between April 2007 and August 2010 at the Upper Station (Figure 1). Sampling was based on the sampling schedule rather than weather conditions; therefore, sampling includes a range of flow conditions. For specific details on sampling methods, see Divers *et al.* (2013). Anion samples were filtered within 24 h of collection using 0.2 μm nylon filters and stored in the dark at 4°C until analysis. Anionic analyses were conducted on a Dionex ICS2000 Ion Chromatograph 4 at the University of Pittsburgh. Nitrate (NO_3^-) concentrations are reported here. Grab samples in 1999 were collected by the USACE at this same location and the sum of nitrate and nitrite concentrations were measured (U.S. Army Corps of Engineers, 2000).

Fish Assemblage Sampling Surveys

Fish surveys were performed by single-pass backpack electrofishing using direct current battery powered units. The two stations are intended to be representative of the upper and lower reaches of the 3 km above ground portion of NMR. The first station is colocated with the primary water quality and benthic macroinvertebrate “Upper Station” (Figure 1). It includes the stream reach between 1.7 and 2.3 km upstream of the mouth, and is located in the upper part of NMR, upstream of the slag dump and numerous historical obstacles to fish passage, but closer to the historical major sources of sewage and deicing salt runoff. This station was sampled for fish by the NMRWA in July 2006, September 2008, July 2009, and October 2010, and by the U.S. Army Corps of Engineers in September 1999. While these sampling events were conducted by a variety of institutions, the sampling team personnel and methods remained consistent.

The “Lower Station” (Figure 1), which extends from 0.1 to 0.8 km upstream of NMR’s mouth, was representative of the lower portion of NMR where transient fish from the nearby Monongahela River are most likely to be encountered. The Lower Station was sampled by the watershed association in June 2006, July 2007, and November 2010. This station was also electrofished by the Pennsylvania Fish and Boat Commission in June 1990 (Pennsylvania Fish and Boat Commission, 1990), by Pennsylvania State University in 1998 (Stauffer and Stecko, 1999), and by the U.S. Army Corps of Engineers in June 1999 (U.S. Army Corps of Engineers, 2000).

To characterize and summarize the changing fish community of NMR, index of biotic integrity (IBI) scores were computed from the data collected by electrofishing at the two reference stations over the period of record. Drainage area weighted IBI scores were determined from criteria established by the Ohio Environmental Protection Agency (1988), with some modifications for local conditions (Hoskin *et al.*, 2003; Koryak and Porter, 2011). IBI ratings of <14 are considered very poor, 15-24 poor, 25-34 fair, 35-49 good, and 50 or greater exceptional.

Benthic Invertebrate Sampling

Benthic macroinvertebrate samples were collected at the Upper and Lower Stations (Figure 1), using a Surber Sampler (a one square foot metal frame with a net attached to one side). Sampling was conducted at two to three stations in the stream along a transect perpendicular to a riffle and composited into a single sample. Transect stations were located near each bank and an additional station near the center if streamflow permitted. During Monongahela River high-flow events back waters cover the Lower Station, precluding sampling. Sampling occurred three times per year (June, July, and August) between 2000 and 2010. The invertebrate samples were taken to Chatham University and live-sorted, then preserved in alcohol for later counting and identification. Percent individuals as EPT (%EPT) was calculated as the number of individual organisms in a sample as a proportion of the total sample that were mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera). Higher index values indicate healthier stream water quality that can support more pollution-intolerant organisms.

Citizen Response Data

To address upland impairments (e.g., impervious surfaces), the NMRWA undertook a large effort to install rain barrels to intercept runoff at the gutter. Phase 1 began during the summer of 2004 and eventually installed 500 rain barrels in the course of a year. Phase 2 of the rain barrel program began in 2007, and as of December 2011 an additional 900 rain barrels were densely installed in four study watersheds. The locations, dates of installation, estimated roof drainage area, and other criteria were tracked by the NMRWA for each rain barrel. (Note, these data do not capture independent rain barrel installations by individual property owners.) Similarly, the Pittsburgh Parks Conservancy runs the Urban EcoSteward program in conjunction with partners like the NMRWA. This program pairs volunteers with specified locations in parks to remove exotic species, address erosion problems, and to remove litter. The Pittsburgh Parks Conservancy tracks the activities of Urban EcoSteward volunteers and the data for Frick Park are utilized for this analysis.

Stream Cross Section Surveying

As part of related investigations in the watershed (Divers *et al.*, 2013) elevations across stream channel cross sections were collected in Spring 2009. These sections were colocated with groundwater monitoring wells located in riparian areas (Figure 1). Sections were measured by leveling a measuring tape across the channel, using the well as a control point and measuring distance to line at regular intervals across the floodplain and channel. Following a major hydrologic event in summer 2009, substantial change was observed in floodplain and channel geometry (e.g., tens of centimeters of sediment accumulated around above ground portions of the well casing). This change was quantified with a resurvey of cross sections in the summer of 2012. This resurvey was collected measuring ground surface distance below a laser level at regular intervals across the floodplain and channel.

RESULTS

Synthetic Hydrograph

Discharge in NMR was 57% lower than discharge in Little Pine Creek from 2006 to 2009 (Figure 3). Two outlying points (Figure 3-open circles) were excluded from the analysis because of their high leverage on the overall relationship. The observation that mean daily discharge in NMR is significantly less than in Little Pine Creek suggests that a significant proportion of water may be diverted from the stream through storm sewers and/or there are large differences in evapotranspiration rates or water storage between the basins. High-density commercial and residential development in the upper part of the NMR watershed, a mostly separate sewer system, and NMR's first emergence in Frick Park from a stormwater tunnel, support the former explanation. Mean daily discharge in the extended hydrograph (Figure 4f) ranged from 0.014 to 9.3 m^3/s with average and median discharges of 0.091 and 0.046 m^3/s, respectively.

Water Quality (Nitrate)

Nitrate is a constituent particularly associated with urbanization (Baker *et al.*, 2001; Groffman *et al.*, 2004). Sampling campaigns pre- and post restoration reveal limited changes in nitrate concentrations. The highest nitrate concentration (20.2 mg/l) was observed on June 18, 2009 and the lowest (2.14 mg/l) on August 2, 2007 (Figure 4e). Nitrate concentrations follow an annual pattern with elevated concentrations during the winter and relatively lower nitrate concentrations during the summer months. Neither ammonium nor nitrite were a significant proportion of the total biologically available nitrogen pool on most sampling days with concentrations often 1-2 orders of magnitude less than nitrate concentrations (see Divers *et al.*, 2013, for details). Nitrate concentrations measured in the several years following restoration are at least equivalent to, if not greater than, the historic nitrate + nitrite sampling collected by the USACE prior to restoration (U.S. Army Corps of Engineers, 2000).

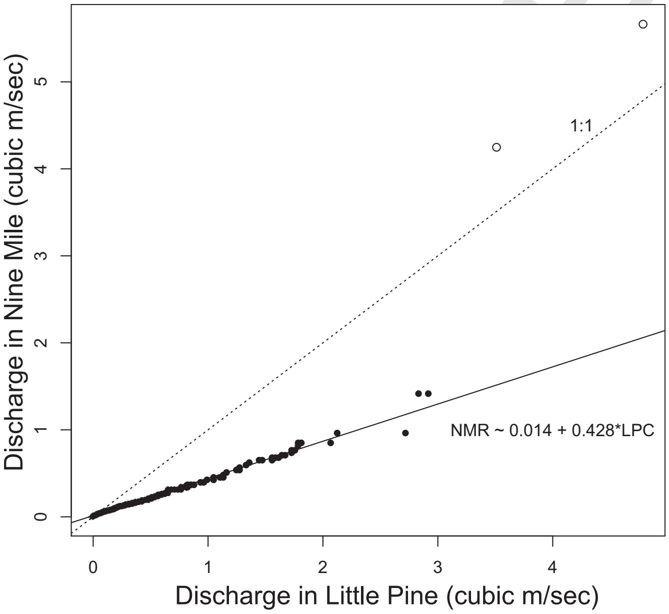

FIGURE 3. Comparison of Discharge Records in Nine Mile Run and Little Pine Creek.

Fish Sampling

Black (1947) found no fish in NMR between July 1946 and July 1947. In 1990, the Pennsylvania Fish and Boat Commission conducted an electrofishing survey of NMR and again found no fish in the stream (Pennsylvania Fish and Boat Commission, 1990). In 1998, Stauffer and Stecko (1999) sampled the Lower Station (Figure 1) and captured four creek chubs with a combined weight of 77 g. The U.S. Army Corps of Engineers (2000) found no fish in the upper reach of the stream in 1999, but at the Lower Station they collected a total of 19 fish of four species with a combined total weight of 348 g. The four species found in 1999 were pollution tolerant: white sucker, western blacknose dace, creek chub, and green sunfish. In every respect, species diversity, fish counts, biomass, or pollution tolerance, the ichthyofauna of NMR was severely impacted prior to the restoration.

Monitoring of the fish community by the NMRWA was initiated in 2006, shortly after completion of the final lower phase of the USACE stream restoration project. The results demonstrate a continual and substantial improvement in the fish community that corresponds to the overall period of restoration efforts (Figure 4b). The improvement is especially apparent along the lower reach of NMR. Between 2007 and 2010, the number of species of fish collected at the Lower Station increased from 5 to 14 (280%), the total number of individual fish increased from 313 to 1,617 (516%), sample biomass increased from 1,503 to 19,560 g (1,301%), and IBI values increased from 19 to 37. Less pollution-tolerant species such as northern hogsucker, pumpkinseed, bluegill, johnny darter, and spotfin, emerald, and mimic shiners appeared in the stream for the first time in 2010. These new species collected at the Lower Station were likely transient from the Monongahela River (Koryak *et al.*,

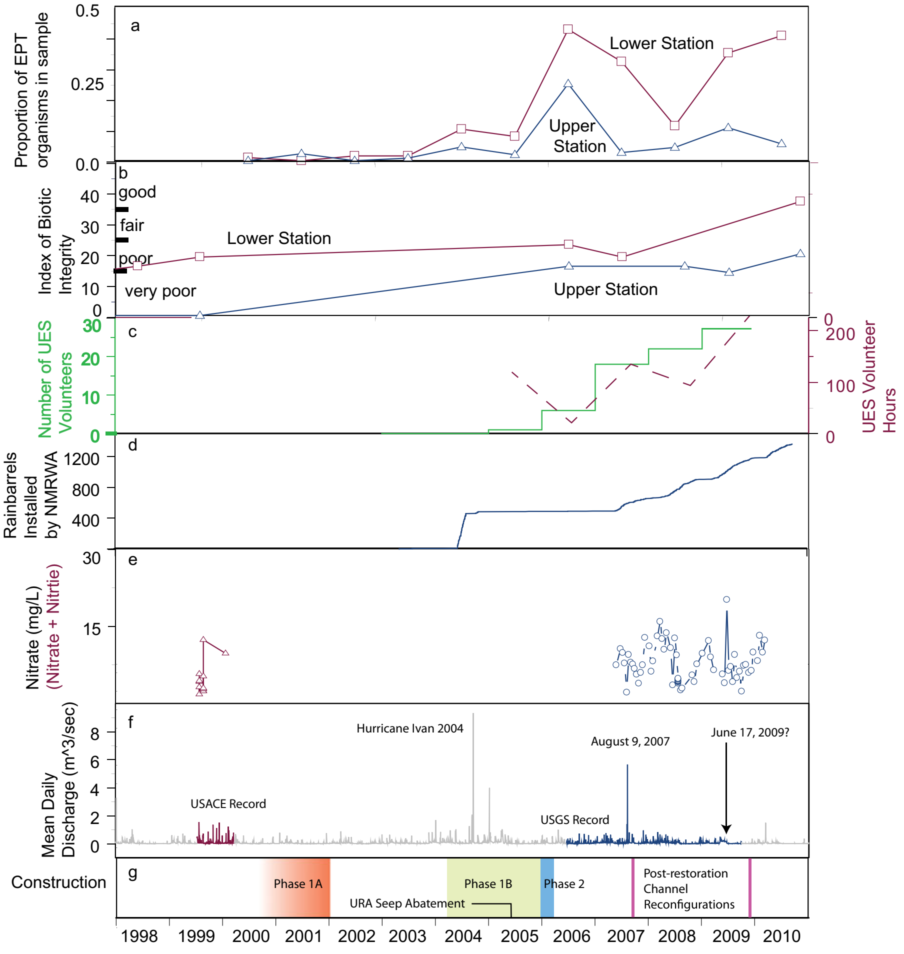

FIGURE 4. Timeline of Activities and Indicators in Nine Mile Run Restoration Work. (a) Changes in the %EPT individuals (i.e., Ephemeroptera, Plecoptera, and Trichoptera species) in macroinvertebrate samples collected at the upper (blue triangles) and lower (red squares) stations. (b) Changes in index of biotic integrity values for fish species at the upper (blue triangles) and the lower (red squares) stations. (c) Number of urban ecostewards working on portions of the restoration (green) for that year and the total number of person hours (red, dashed; right axis) these stewards contributed on an annual basis. (d) Cumulative number of rain barrels installed by the Nine Mile Run Watershed Association. (e) Available stream water nitrate concentration records from the upper station. The red triangle samples are from the US Army Corps of Engineers (2000) pre-restoration sampling for nitrate + nitrite. The blue circle series is data collected for this study. (f) Mean daily discharge records for Nine Mile Run. The red series is the US Army Corps of Engineers (2000) pre-restoration record. The blue line is the USGS record (gauging station 03085049). The gray line is the hydrograph reconstructed for this study. (g) Various stages of restoration work and repair, as described in Table 1.

2001). These changes in fish assemblage likely arise in part from the removal of barriers to fish passage.

In contrast, after some initial rapid improvement, the fish community of the upper reaches of NMR seems to have stabilized and remains overwhelming dominated by a now abundant but still limited assemblage of resident pollution-tolerant headwater species (blacknose dace, creek chub, white sucker, and green sunfish with occasional bluntnose minnows and spotfin shiners). IBI ratings are considered “poor.”

Benthic Macroinvertebrates

The pre-restoration samples from both sites showed an invertebrate fauna of very limited richness and heavily dominated by midges (Family: Chironomidae). Usually, 70-97% of the organisms collected were midges. The only other fairly abundant organisms were blackfly larvae (Diptera: Simuliidae: *Simulium*) which, on average, constituted 20% of the total organisms, and sludge worms (Haplotaxida: Tubiificidae: *Tubifex*) which constituted an average of 8.2% of the total organisms at the Upper Station. At the Lower Station, the blackflies constituted 19.4% of the organisms collected and sludge worms made up 3.3% of the organisms. These three taxa are indicative of poor water quality (U.S. Environmental Protection Agency, 1997) and constituted 96% (range 90-100%) of the organisms at the Upper Station and 93.4% (range 83-98%) of the organisms at the Lower Station pre-restoration. Other species were rare — usually fewer than 10 individuals (i.e., <5% of the total organisms collected). Samples from the Upper Station contained many more individuals (an average of 2,600 org/m^2) than the Lower Station (an average 610 org/m^2). Several organisms (amphipods [Amphipoda: Gammaridae*:* *Gammarus*], isopods [Isopda: Asellidae*:* *Asellus*], damsel flies [Odonata: Calopterygidae: *Calopteryx*], and water mites [Order: Hydrocarina]) were represented by only a few individuals. Observations during sampling suggest these organisms were probably washed into the stream from the small tributary at the site (Figure 1) and had not established permanent populations. Pre-restoration, %EPT averaged 1.6 for the Upper Station and 3.7 for the Lower Station.

Immediately following restoration (i.e., August 2006), the benthic macroinvertebrate assemblage began to change (Figure 4a). Although midges still dominated both sites in counts of individuals, blackflies became less common at both sites, decreasing from an average of 21% (SD = 29%) to 1.5% (SD = 1.5%) of sampled organisms at the Upper Station and 19% (SD = 26%) to 1% (SD = 1%) at the Lower Station (difference pre- and post restoration is not significant; *t*-test, $0.1 > p > 0.05$ in both cases). Similarly, sludge worms decreased from an average of 8.2% (SD = 10%) of sampled organisms at the Upper Station pre-restoration to an average of 1.6% (SD = 1.5%) of sampled organisms post restoration at the Upper Station (pre- and post restoration proportions not significantly different, *t*-test, $0.1 > p > 0.05$). The number of sludge worms at the Lower Station remained relatively unchanged, 3.3% (SD = 3.3%) pre-restoration to 6.3% (SD = 6.4%) post restoration. Post restoration, these three taxa comprised 82% of the organisms at the Upper Station (range 69-91%) and only 63% of the organisms at the Lower Station (range 56-71%). In addition, net-spinning caddisflies (Trichoptera: Hydropsychidae: *Hydropsyche*) and mayflies (Ephemeroptera: Baetidae: *Baetis*) became more common. When %EPT is averaged for the pre-restoration period (2000-2005) and the post restoration period (2006-2010), %EPT increased from 1.6 ($n = 6$, SD = 1.7%) to 9.6 ($n = 5$, SD = 9%) at the Upper Station (*t*-test, $p < 0.05$) and from 3.7 ($n = 6$, SD = 4.2%) to 32.2 ($n = 5$, SD = 12%) at the Lower Station (*t*-test, $p < 0.001$). Thus, % EPT increased significantly and substantially after the restoration.

Stream Channel Geometry

Substantial change in the stream channel geometry of a cross section in the lower section of the stream (Figure 1) was measured (Figure 5). Sediment accumulated in an inset floodplain on the left hand side of section during the period between surveys (an average of 22 cm between the 5 and 8 m stations shown in Figure 5). This accumulation occurred largely during the June 2009 storm. In addition, large amounts of sediment were mobilized from this channel (an average of 44 cm across stations 6 m through 20 m in Figure 5), despite deliberate armoring with large clasts (>20 cm diameter) in this portion of the channel. The change captured in this return cross section survey cannot represent dynamics in the entire restored length, but it demonstrates the powerful dynamics that continue to shape the channel, despite substantial effort to prevent these processes.

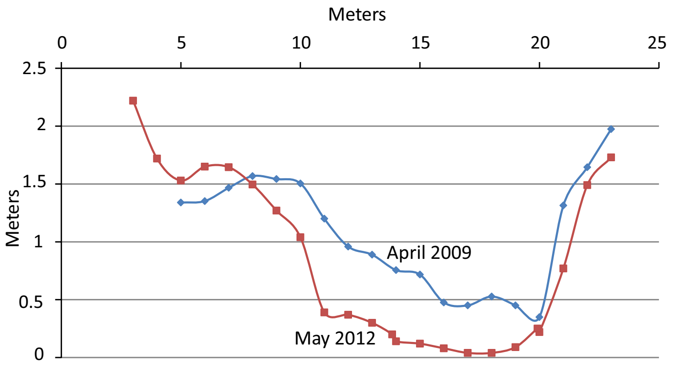

FIGURE 5. Changes in Nine Mile Run Channel Geometry Showing Post Restoration Channel Incision. The upper line shows a cross-sectional survey taken between the Upper and Lower Station in April 2009. The lower line shows a return survey conducted in May 2012.

Colour online, B&W in print

DISCUSSION

Stream Discharge and Sustained Restoration Success

Following the initial restoration project, resources have been focused on maintaining/altering hydraulic structures installed to maintain channel stability during extreme flows (Dickson, 2008). Given this focus, it is particularly important to understand the conceivable range of discharges in NMR. Stream restoration projects that do not anticipate appropriate hydrologic boundary conditions can fail (Smith and Prestegaard, 2005). At least two periods of stream discharge monitoring exist for NMR, June 1999 through March 2000 (USACE) and June 2006 through September 2009 (USGS Gage 03085049). Furthermore, utilizing the synthetic techniques described above, daily flow conditions over a much longer (1998-2010) period were approximated (Figure 4f), allowing insight into the timing of major regional hydrologic events.

Colour online, B&W in print

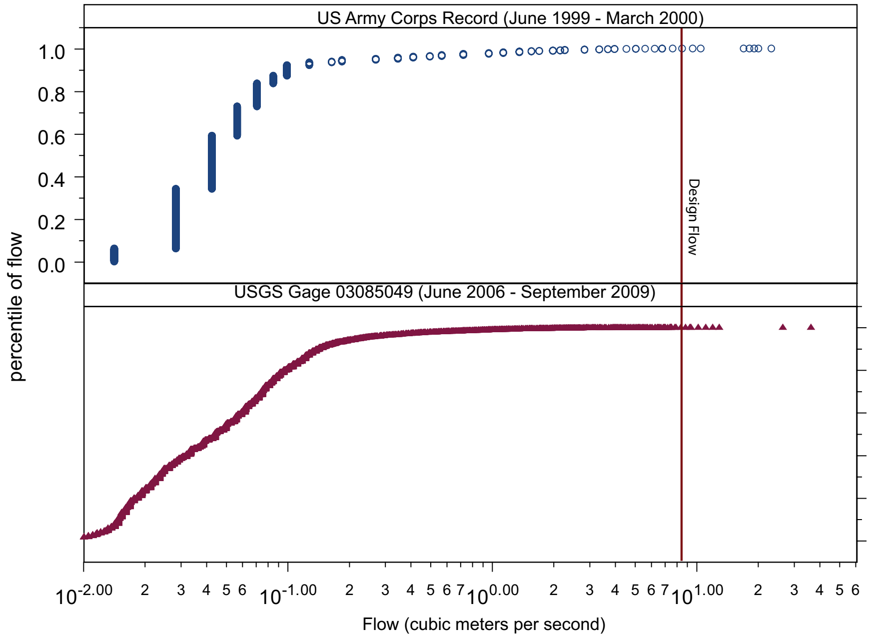

FIGURE 6. The Cumulative Distributions of Flows in the Two Available Discharge Records (top U.S. Army Corps of Engineers (2000), bottom, USGS gage 03085049). These data are average flows over 15 min intervals (Figure 4f shows average daily flows). The solid vertical line is the design flow used in stream restoration planning. The USACE record is discontinuous at lower flows, this is a result of rounding to limited significant digits in that record.

However, even with this relatively data-rich environment, the challenge of selecting a design hydrograph in a multiple stakeholder environment remains. The design flow chosen for the initial channel design work was 8.4 m^3/s (appendix 4 in U.S. Army Corps of Engineers, 2000). Yet, examination of the discharge data collected by the USACE prior to restoration efforts (Figure 6) reveals that this design flow is exceeded in eight separate 15-min intervals, sometimes by a factor of two, even over the course of less than a year of monitoring. The design flow used was a clear underestimate, which became clear when flows associated with Hurricane Ivan (2004, Figure 4f) occurred during early channel reconfiguration. Hydraulic structures were compromised during this flow and larger clasts were incorporated in the remainder of the construction. However, the increase in clast size was not sufficient, as later reports suggested impending catastrophic failures (Dickson, 2008). The Dickson report spurred modifications to the channel, work which largely rearranged existing hydraulic structural building blocks rather than increase clast size. Furthermore, the hydraulics were not reevaluated as part of this work (e.g., a new design flow was not established and HEC-RAS modeling to justify the modifications were not provided). Two years later, in 2009, when a similar or larger storm flow occurred (the official USGS record does not reconstruct the peak flows during this event), the underestimated design criteria again resulted in substantial damage to the hydraulic structures. Finally, during the third set of repairs, clast size was increased.

This retrospective assessment indicates fundamental flaws in this restoration design process. The design flow seems too low in light of the pre-planning flow monitoring conducted by the USACE (Figure 6). In this case, data were available, but were not effectively integrated into the planning process and an adaptive management cycle was never fully completed. This retrospective effort also highlights the critical need to rigorously scrutinize existing discharge records and utilize continuous discharge records as indicator of restoration progress. Too often the urban stream restoration evaluation literature does not incorporate continuous records of flow. Even in NMR, which has an uncommon amount of data, we are limited by widely separated temporal periods of data. If urbanization imparts a syndrome (Walsh *et al.*, 2005b), discharge is one of the fundamental vital signs to monitor during recovery, particularly as assumed benefits of restoration often depend on channel stability and therefore depend on reductions in storm flow.

Assessing Restoration Goals: Is "Reconnection" of the Floodplain Sustainable?

One of the hopes for urban stream restoration is that it can provide additional benefits by removing excess nutrients, and thus mitigating downstream nutrient impairments (Craig *et al.*, 2008; Kaushal *et al.*, 2008). In particular, there has been a recent push for transferring successes in "floodplain reconnection" to smaller scale urban alluvial systems (Kaushal *et al.*, 2008; Klocker *et al.*, 2009; Sivirichi *et al.*, 2011). Floodplain reconnection, in general, is the removal of barriers between the stream and historic floodplain (e.g., levees, deeply incised channels) to allow for flood and storm flows to interact with riparian wetland areas. Successful floodplain reconnection would garner nutrient assimilation benefits from restoration projects and help offset the considerable costs of stream restoration and restoration maintenance. During the NMR restoration, large volumes of overbank sediment were removed to reconnect the floodplain with the channel. Although this design feature was not completed explicitly to address nutrient impairments, available data allow examination of this potential benefit in NMR. It also created substantial expenses, inviting scrutiny in cost-benefit considerations.

At the reach to basin scale in NMR, there is little indication that floodplain reconnection and the establishment of wetland areas in the floodplain are contributing to substantial nutrient abatement (Figure 4e). Nitrate concentrations in waters sampled after the restoration, if anything, exceed those measured before the restoration (Figure 4e). While prerestoration data are limited, one would expect to see some change in reactive nitrogen concentration if floodplain reconnection provides such benefits. On the other hand, this result is not that surprising given the thoroughly altered hydrology in the system, providing pathways for water and contaminant loads to bypass areas of potential nutrient assimilation and abatement. Furthermore, it is consistent with observed restoration results in other human-dominated systems such as agricultural ditches where nitrogen uptake benefits appear to be relatively minimal (Roley *et al.*, 2012). If floodplain reconnection is to work in urban systems, it seems not only must barriers between the stream and the floodplain be removed, but in addition, existing drainage infrastructure should be interrupted or removed. For example, if there are abandoned sewer lines in the floodplain connecting near stream groundwaters to contemporary infrastructure, identification, and disconnection of these drainage structures are likely necessary.

A more important consideration in urban floodplain reconnection is how long simple reconnection lasts given the considerable impacts on the urban sediment cycle (e.g., Wolman, 1967; Hammer, 1972). Fundamentally, if streams re-entrench despite radical hydraulic control, effort devoted to reestablishing floodplain connectivity may be wasted. Incision would again disconnect riparia from the stream. The sustainability of such reconnection was examined in NMR. There are a limited number of repeat cross sections from the post restoration period (e.g., Figure 5) and those available indicate rapid and substantial channel incision in NMR. If this rate of change in channel form is representative, improvements in floodplain connectivity and any associated benefits are likely short-lived, as incised channels will once again isolate the floodplain. In addition, the substantial biotic community benefits from connectivity to the Monongahela River (cf. the Upper and Lower Stations for both fish and macroinvertebrates) can be lost with channel incision and the reestablishment of hydraulic barriers. Channel incision in the restored NMR raises some doubt about the sustainability of urban floodplain reconnection without concentrated effort to ameliorate the impacts of high flow events associated with densely urban watersheds.

Biotic Responses to the Restoration

While it seems to be growing increasingly clear that benthic macroinvertebrate communities recover relatively slowly, if at all, in urban systems (Blakely *et al.*, 2006; Matthews *et al.*, 2010; Meisenbach *et al.*, 2012), this remains an indicator of choice in the literature. As noted previously, there are emerging efforts to evaluate biotic integrity across communities (Stranko *et al.*, 2012); however, these often remain focused on instream communities and are similarly dismal in terms of recovery rates. Yet if a broader perspective is taken, in NMR substantial interest from the local citizenry in the urban stream restoration has emerged, and this interest can potentially enhance restoration resilience. Fundamentally, instream restoration allows a period of stabilization during which catchment characteristics such as riparian vegetation can be increased and impervious cover reduced. In general, any positive changes in biotic communities are more likely to persist with continued success in water management in the uplands (e.g., rain barrels) and vegetation management in the riparian areas (e.g., the Urban Ecostewards effort). Any feedback promoting positive community action to sustain restoration successes is a potentially powerful benefit that can be utilized to improve management of urban stream restorations. A sole focus on instream biotic indicators can obscure this feedback.

Fish Populations. The improvements in fish communities in NMR likely result from a variety of reasons, including the reconnection of the stream with the Monongahela River following removal of fish barriers. As discussed by Stauffer and Stecko (1999), one of the major components of elasticity and the ability of a system to recover once structural change has occurred is the proximity of refugia, from which recolonization as well as new growth and development can be initiated. In addition, Koryak *et al.* (2001) demonstrated that access for river transients can also greatly enrich fish assemblages of recovering small urban streams of the upper Ohio River Valley. Conversely, they showed that where access for transient fishes from larger downstream waters was denied, IBI scores declined 26-43%, and species diversity declined 39-69%. The importance of barriers to fish passage on assemblages in NMR is best illustrated by a series of surveys conducted by the U.S. Army Corps of Engineers (2000) in 1999. Fish were totally absent from the NMR embayment during a June 1999 low flow electrofishing survey, when a chemical barrier created by alkaline slag leachates (pH > 10) was present. However, in September 1999, during a rise in the flow and elevation of the river and a drop in pH, 26 species of fish were observed to enter the embayment. A large number of the estimated 92 fish species present in the Allegheny and Monongahela navigation systems (Koryak *et al.*, 2009) could at least occasionally utilize the waters of NMR and contribute to community richness. However, while the physical barriers received attention during maintenance work (Dickson, 2008), the persistence of extreme flow events makes reestablishment of similar barriers a remaining threat to sustaining improved ecological conditions.

Benthic Macroinvertebrate Recovery. Although recovery is slow, there is evidence of a healthier, more diverse benthic macroinvertebrate fauna in NMR. The significant increases in %EPT, particularly caddisflies and mayflies, indicates improving conditions. Furthermore, all life stages (small nymph to pupal) were collected during post restoration periods, indicating that these organisms are now completing their life cycles in the stream. Post restoration, while the macroinvertebrate community seemed to be affected by large hydrologic events, improvements in community health persists despite these events (Figures 4a and 4f). The lagging recovery of stream macroinvertebrates is consistent with many stream restoration assessments (Matthews *et al.*, 2010) and may arise, at least in part, from the lack of upstream refugia in NMR due to stream burial (Figure 1). In less impacted systems, upstream areas support important source populations allowing recolonization of downstream reaches (Gore, 1985).

Community Adoption of Restoration. Analysis shows a clear increase in rain barrel installations, number of Urban EcoStewards and their volunteer person hours in the NMR watershed (Figure 4c) following completion of the restoration. While these activities cannot be solely attributed to the presence of the restoration, timing suggests that the high level of volunteer involvement is at least somewhat associated with the presence of the restoration. The density of rain barrel installations (Figure 4c) is almost completely a result of a program sponsored by local foundations that placed large numbers of rain barrels in small sewersheds within the basin to evaluate impacts of dense rain barrel installation on stormwater sewage flow patterns. Without the downstream restoration to focus effort, it is likely this rain barrel activity would not have occurred in the NMR watershed. In addition, Urban EcoSteward volunteer hours have undergone substantial growth throughout the post restoration period (Figure 4c). These quantifiable efforts are at least two instances where this restoration has sparked human activity to address hydrologic and ecologic impairments in the basin. Community involvement is a promising and potentially crucial component in sustaining urban stream restoration. A well-executed, bottom up restoration effort can engender the work that is essential to sustaining channel restorations. While the data are not complete enough to demonstrate such a feedback, continued examination of this restoration and other urban restorations, with particular attention to these feedbacks is warranted.

Sustaining Hydrologic Characterization for Adaptive Management

This examination of retrospective data in both design and post restoration phases repeatedly reveals the fundamental importance of hydrologic and geomorphic characterization. Failure to incorporate existing hydrologic data can necessitate resource intensive maintenance work. Changes in stream channel geometry arising from large flows can potentially erase improvements in habitat connectivity and reestablish migratory barriers. Assessment, particularly comparison of datasets from before and after restoration, remains a glaring weakness of stream restoration science and its incorporation into larger management frameworks (Bernhardt *et al.*, 2005). Without an understanding of discharge changes in NMR, it is impossible to characterize rain barrel effectiveness at the catchment scale or detect other, potentially detrimental, changes in the watershed. Simultaneously, this study demonstrates that urban restoration has the potential to spawn changes in catchment management that improve restoration sustainability. The artful application of this human response to collection of simple, continuous data (e.g., channel cross section resurveys) may provide a resource to overcome the post project assessment challenges inherent in urban stream restoration.

CONCLUSIONS

The spatial scope of urban stream restorations should extend beyond the stream valley and into the upland. Urban stream restoration must address the symptoms of the "urban stream syndrome" (Walsh *et al.*, 2005b), and further, adapt as the surrounding urban areas evolve. This study utilizes a wide variety of indicators to document positive changes in NMR following restoration. Despite this progress, positive changes are threatened by the persistence of extreme flow events from the urbanized watershed, as continued channel geometry dynamics can reestablish disconnects in habitat connectivity removed during restoration. Encouragingly, the parallel evidence for human involvement in the process (e.g., rain barrels and EcoStewards) suggests the urban residents are an under-tapped resource in sustaining restoration success. Ultimately, stream restorations that address multiple urban challenges will, by definition, be more successful in the long run. The examination of interactions among biology, hydrology, and geomorphology seem essential for separating ephemeral species dynamics from long-term system improvements and making sure the instream challenges are met.

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