Stormwater infrastructure controls runoff and dissolved material export from arid urban watersheds

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Response to Reviewer Comments

Reviewer: 1

General comments

Overall I was quite happy with the quality and scope of this paper. It is very well written and contains some important findings. Some general and more specific comments are provided below. I think the authors should have the opportunity to think about a few of my comments below; this calls for minor revision.

While the paper concerns both hydrology and water quality, I think more attention is given to the latter. I would have liked to seen more results on hydrology. Maybe you could provide a graph (with associated discussion in the text) showing mean event runoff coefficients for each catchment? Given that the paper is already fairly long, this might not be possible. In any case, I recon you could expand your hydrological findings in a separate journal paper.

- Response: We are planning a separate paper that details the hydrologic results of this work. However, since both reviewers requested more hydrologic data, we have added a table in the appendix that provides more details on runoff and storm characteristics (Table A1)

In the discussion, you present a conceptual model of urban watershed ecosystem function and describe four periods of change. You suggest that the model is for arid urban catchments. I think it would be worth fleshing this section out a bit more. In doing this, maybe you could firstly describe in a general way, what is natural arid catchment hydrology.

- Response: We have limited space to add more discussion here, and we already have some information on arid hydrology in the introduction (lines 191-194), and we reference key literature (Osterkamp and Freidman, 2000. We have however, included a bit more discussion about how this model might differ in other regions (now lines 611-618).

Where I'm from, the "third" phase in your diagram is very different. We have been installing distributed stormwater infrastructure for the last 15 years. But, our systems are generally designed for pollutant-load reduction—aimed to protect our largest receiving water (a bay). These systems are not designed to restore/protect natural hydrology. Because of this, runoff/ratios tend to still be closer to the "second" phase (post-development). Our trouble is to try and build the sort of retention systems common in Phoenix (which retain most inflows). I am not suggesting that you contrast the arid context with others. I am suggesting though, that perhaps you further emphasize that this model is applicable to the arid regions.

- Response: The reviewer makes a great point here. We've updated the text (now lines 611-618) to emphasize that these phases are context-specific and that stormwater infrastructure that looks similar (e.g., basins) may have very different functional consequences depending on the intended purpose (e.g., flow vs pollutant control).

In your work, you quantify impervious area and the location/length of stormwater pipes. Did you quantify the connectivity of these impervious areas to the drainage system (i.e. calculate effective imperviousness)? Research is pointing to effective imperviousness (or similar variants which consider the stormwater conveyance system) as an important predictor of urban impacts on hydrology, water quality and stream ecology. Are most impervious areas in your region connected to the drainage system? It might be worth discussing this point in your paper.

- Response: While we did not originally calculate connected imperviousness for this work, we have recently made these calculations and have added the data to Table 1. In response to your comment, we assessed whether effective imperviousness is a better predictor of runoff than total imperviousness (results included in new Table A6), and found that it was not. Correlations between connected imperviousness and other variables have also been included in the correlation matrix (now Table A5). We added this information to the results (now lines 408-410) and the discussion (lines 523-529).

Specific comments

• Change some of your keywords which also appear in the title.

- Response: We have changed our keywords, deleting “stormwater infrastructure” and adding “stormwater management,” “ecosystem heterogeneity,” and “path analysis.”

• In the abstract, you suggest that it is “unknown” how variation in urban stormwater management affects flow and water quality. There are however, at least two studies I can (quickly) think of which do get at this question. Hatt et al. (2004) show how differences in drainage connection affect water quality. And, Walsh et al. (2012) show how differences in drainage connection affect ecology, hydrology, and water quality. In the abstract, I would suggest rephrasing the relevant text to something like “Little work has shown how variation…etc”. More broadly, I think the Walsh et al. (2012) paper needs some attention in the text.

- Response: We agree that these previous papers have addressed stormwater management, but they focused on variation in drainage density, rather than variation in infrastructure design (e.g., basins vs channels vs storm sewers). We have rephrased this sentence as “It is unknown, however, how variation in urban stormwater infrastructure design …” (now lines 24-25) to clarify this point, and have added a sentence to the introduction as well (lines 91-94). We’ve also included some discussion of Walsh et al. (2012) (lines 502-508).

• In the abstract, I would suggest bringing in some of your results on hydrology.

- Response: We’ve rephrased some of the sentences on the results to emphasize the hydrologic patterns (“We found that retention basin density decreased and imperviousness increased runoff, which in turn increased nutrient and DOC delivery.” now lines 37-38), but have not been able to expand much beyond that due to word limitation in the abstract.

• In the introduction on lines 122, give the depth of rainfall for this storm.

- Response: This information has been added (now lines 162-163).

• In the introduction near the bottom of page 6, I would suggest giving a bit more description of “your” retention basins. They would appear to be infiltration systems. With this, state the infiltration rate of underlying soils.

- Response: We have added more detail about the design standards for retention basins in the study area. The percolation rates of underlying soils vary, but retention basins are drained by infiltration only if percolation rates exceed 0.5 inches (13 mm) per hour, otherwise they are drained by dry wells. These details have been added (now lines 179-180)

• In the methods at the top of page 8, I found the sentence “To identify…”confusing. Could this be rephrased?

- Response: We have rewritten the sentence as “To assess how the use of different infrastructure designs has changed over time relative to the area of new development, we normalized the length (for pipes, channels, and washes) or area (retention basins) of newly employed infrastructure to the area of new development for each year.” (now lines 206-209).

• In the methods, you used Manning’s equation to estimate flow. What roughness values did you use? Did you do any “manual” calibration or validation of discharge? You could potentially use your approach to estimate flow for the two sites with data from USGS and compare these values with their discharge measurements.

- Response: We did not do any manual calibration of discharge and for channels of this size it was not possible to validate. However, our ISCO Bubbler modules were manually calibrated to ensure correct depth measurements and were checked at the start of each season. We actually used the data from the USGS site at IBW (and therefore cannot test our data against theirs, as suggested). At SGC we used our depth data along with the USGS rating curve (note that our flow gauge was adjacent to theirs). However, the USGS gauge at SGC didn’t collect measurements until flow reached a specific depth, therefore missing all of the smaller events captured in our study, and furthermore measured flow at a coarser resolution (15 min vs 1 min). As we had high confidence in our high resolution depth measurements due to our depth calibration procedure and repeat checking of this, we carried out no further comparison with USGS gauge data at this site. We’ve included details on the discharge calculation methods, including parameters used in Manning’s formula, in a new table in the appendix (Table A7).

Hatt, B. E., Fletcher, T. D., Walsh, C. J. & Taylor, S. L. 2004. The Influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. Environmental Management, 34, 112-124. DOI: 10.1007/s00267-004-0221-8.

Walsh, C. J., Fletcher, T. D. & Burns, M. J. 2012. Urban stormwater runoff: a new class of environmental flow problem. PLoS ONE, 7. DOI: 10.1371/journal.pone.0045814.

Reviewer: 2

Comments to the Author(s)
This paper discussed a very interesting topic and created some new knowledge. The research study focus is quite new and not many previous researchers have paid attention. Authors investigated the relationship among stormwater treatment infrastructure characteristics, land cover, storm characteristics and pollutant loads using a range of data analysis techniques and models. Additionally, it is well written and easily understood. Therefore, this paper should be accepted once the following comments are attended.

1. This research study had some new and important conclusions. But they haven't been well reflected in the abstract. It is suggested that more important findings should be added into the abstract.

- Response: We have rewritten the conclusions in the abstract to try to address this (now lines 37-42).

2. Authors discussed the influence of storm characteristics on pollutants export in watersheds. However, information regarding these storm characteristics hasn't been provided in the paper such as the number of rainfall events monitored, rainfall intensity, duration and dry period. It would be good to provide these details. This also applies to other factors discussed such as land cover. More detailed information needs to be given.

- Response: We have added a table with mean storm characteristic information in the appendix (Table A1). The land cover information used for the analysis is provided in Table 1.

3. When discussing Table A1, authors mentioned that some pollutant EMCs varied significantly across watersheds while others didn't (line 311-312). In my opinion, relative standard deviation is a better parameter to compare the variability of dataset than standard deviation. This is particularly significant when dataset is not in a same magnitude like the case in this research.

- Response: The significance of differences across and between watersheds was determined using an analysis of variance with a Tukey's HSD post-hoc test on data that was transformed to meet the assumptions of normality and equal variance. The standard deviations are reported for the information of the reader. We've kept these as is because standard deviation is a common statistic to report in the literature and relative standard deviation can be easily calculated by any interested readers using the standard deviation and the mean, which are both given. (Note that this is now Table A2).

4. Table A1 and A2 are not clear. What do those letters (superscript) mean? What do F, df and P mean? These need to be clarified.

- Response: The superscript letters indicate significant differences between sites; this is stated in the table caption ("Means with different letters are significantly different at $p<0.05$ using Tukey's HSD.") We've changed this to "Means with different superscript letters are significantly different at $p<0.05$ using Tukey's HSD" for clarity. F, df, and P are standardly reported values for analysis of variance (ANOVA). (Note that these are now Tables A2 and A3).

Stormwater infrastructure controls runoff and dissolved material export from arid urban watersheds

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Author contributions:

RLH conceived of or designed the study, performed research, analyzed data, and wrote the paper; LT conceived of or designed the study, performed research, analyzed data, and wrote the paper; SRE conceived of or designed the study, performed research, and wrote the paper; DLC conceived of or designed the study and wrote the paper; NBG conceived of or designed the study, analyzed data, and wrote the paper.

ABSTRACT

Urbanization alters watershed ecosystem functioning, including nutrient budgets and processes of nutrient retention. It is unknown, however, how variation in ~~urban~~ stormwater ~~management~~ infrastructure design affects the delivery of water and materials from urban watersheds. In this study, we asked: 1) How does stormwater infrastructure design vary over time and space~~What is the degree of spatial and temporal heterogeneity in stormwater infrastructure design~~ in an arid city (Phoenix~~ metropolitan area~~, AZ, USA), and 2) How does variation in infrastructure design affect fluxes of dissolved nitrogen (N), phosphorus (P), and organic carbon (DOC) from urban watershed ecosystems? From 1955 to 2010, stormwater infrastructure designs shifted from pipes, to engineered channels and retention basins, to natural washes. We monitored 10 nested watersheds, where small (5-141ha) watersheds had medium-density residential land use but differed in stormwater infrastructure ~~characteristics~~ while larger watersheds (1662-20247ha) had a variety of land use and infrastructure. We measured rainfall in each watershed and discharge and dissolved N, P, and DOC concentrations in flow at each watershed outlet for runoff-generating rainfall events between ~~August~~ 2010 and ~~August~~ 2012. We used path analysis to test hypotheses about the relationships among infrastructure characteristics, land cover, storm characteristics (including antecedent conditions), and nutrient and DOC loads. We found that ~~r~~retention basin density decreased and imperviousness increased runoff, which in turn increased nutrient and DOC delivery. Concentrations varied with antecedent conditions and rainfall but did not vary with watershed characteristics~~ Infrastructure and land cover affected nutrient and DOC delivery via control on runoff but did not affect concentrations, which varied with antecedent conditions and rainfall~~. We show that stormwater infrastructure creates heterogeneity in the hydrologic and biogeochemical function of urban watersheds and that stormwater management may represent a major source of ecosystem heterogeneity within and across cities. ~~Our results suggest that variation in stormwater infrastructure within and across cities may be an important source of heterogeneity in urban ecosystem functioning over time and space.~~

Keywords: ~~Stormwater infrastructure, n~~Nitrogen, phosphorus, dissolved organic carbon, urban ecosystems, watershed, ecosystem heterogeneity, stormwater management, path analysis

INTRODUCTION

Urbanization dramatically alters watershed ecosystem functioning, including processes of nutrient (nitrogen (N) and phosphorus (P)) retention and nutrient budgets (Groffman and others 2004; Wollheim and others 2005; Raciti and others 2008). Altered watershed function has consequences for downstream ecosystems, largely due to changes in the delivery of water, nutrients, and other materials (Dunne and Leopold 1978; Paul and Meyer 2001; Walsh and others 2005). Many urban watershed studies have focused on land-use change, comparing urban watershed ecosystems with non-urban watersheds (Groffman and others 2004; Kaushal and others 2008). Land-use change is associated with increased inputs of nutrients to watersheds via human activities, and is therefore strongly tied to nutrient and carbon (C) cycling in watershed ecosystems (Paul and Meyer 2001; Groffman and others 2004; Lewis and Grimm 2007).

However, human activities also alter the hydrology of watersheds, with implications for the cycling and fluxes of nutrients and C within and from urban watersheds (Arnold and Gibbons 1996; Paul and Meyer 2001; Groffman and others 2003; Walsh and others 2005). The most noted cause of altered urban hydrology is land-cover change, particularly the proliferation of impervious surfaces, which decrease infiltration and increase surface runoff from urban watersheds (Arnold and Gibbons 1996; Brabec and others 2002; Shuster and others 2005; Jacobson 2011). These changes not only affect the delivery of water~~; they~~ but also have implications for opportunities (i.e., hot spots and hot moments) for biogeochemical transformations within watershed soils and flowpaths (Groffman and others 2003).

In addition to altered hydrology due to land-cover change, humans have also deliberately engineered flow paths through and from urban watershed ecosystems. ~~The literature to date has largely focused on the burial and simplification of streams and the subsequent loss of their ecological function (Grimm and others 2005; Elmore and Kaushal 2008; Roach and others 2008). In much the same way, s~~Storm sewers create a highly connected system that can exacerbate water quality problems of high nutrient inputs and altered surface water balances (Paul and Meyer 2001; Hatt and others 2004; Walsh and others 2005; Kaushal and Belt 2012). Most of the existing research on urban stormwater infrastructure has addressed characteristics of storm sewer networks (e.g., density, connectivity of impervious surfaces; Hatt and others 2004; Walsh and others 2012) and has not addressed different types of stormwater infrastructure design: storm sewers, open channels, retention basins.

Engineering paradigms for urban hydrology have evolved substantially over time – in part due to research on the detrimental effects of highly connected conveyance-based systems on downstream ecosystems – such that the purpose of newer stormwater infrastructure designs is to minimize the effects of urban land-cover change on water quality and quantity (Ellis and Marsalek 1996; Chocat and others 2001; Delleur 2003). As a result, spatial and temporal variation in stormwater infrastructure has the potential to be a major source of heterogeneity in urban watershed functioning, including hydrological and biogeochemical processing. Thus, to determine if spatial and temporal variation in stormwater infrastructure is an important source of heterogeneity in urban watershed functioning, ~~in this study~~ we asked: (1) How does stormwater infrastructure design vary over time and space~~What is the degree of spatial and temporal heterogeneity in stormwater infrastructure design~~ in an arid city, and (2) What are the effects of this heterogeneity in infrastructure design on fluxes of dissolved N, P, and DOC from urban watershed ecosystems?

Objectives and Hypotheses

In order to answer these questions, the objectives of this research were to: (1) characterize spatial and temporal changes in urban stormwater infrastructure design for Scottsdale, AZ, USA (part of the Phoenix metropolitan area and the Central Arizona–Phoenix Long-Term Ecological Research Program: ~~(~~CAP LTER~~) program)~~); (2) characterize nutrient and DOC loads from urban watersheds with similar land use but different stormwater infrastructure designs; and (3) determine relationships among infrastructure, land cover, storm characteristics, and nutrient and DOC loads. Our goal was a better~~, toward an~~ understanding of the underlying mechanisms that control the fluxes of these materials from urban watersheds to downstream, recipient ecosystems.

We developed hypotheses on the roles of infrastructure, land cover, and storm characteristics in determining dissolved N, P, and DOC delivery (i.e., loads) as part of a model of potential drivers (Fig. A1). We hypothesized that these three sets of variables would control delivery via (1) the control of runoff (transport) and, (2) nutrient and DOC concentration (a proxy for the supply of nutrients and organic ~~carbon (~~C~~)~~ within the watershed). Our overall expectation was that watershed features that increase stormwater conveyance (e.g., imperviousness and pipes) would positively affect delivery, whereas features that decrease conveyance (e.g., channels, retention basins, and percent grass cover) would negatively affect nutrient and DOC delivery by reducing runoff. We expected that nutrient and DOC concentrations would be controlled by variables that affect supply within the watershed, such as rain-free days (time over which nutrient and DOC can accumulate (Welter and others 2005; Lewis and Grimm 2007)), as well as possible biogeochemical transformations and removal in channels (Gallo and others 2012), retention basins (Zhu and others 2004; Larson and Grimm 2012), and grass lawns (Hall and others 2009).

For the purposes of this paper, we focus our analyses on total dissolved nitrogen (TDN), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), soluble reactive phosphorus (SRP), and DOC. Both N and P may be limiting nutrients in downstream recipient ecosystems, and concentrations are typically elevated in urban stormwater (Paul and Meyer 2001; Grimm and others 2005; Walsh and others 2005), whereas DOC concentrations and loads are neither consistently higher nor lower in urban runoff compared with non-urban streams (Paul and Meyer 2001; Walsh and others 2005). We also ~~studied patterns~~used ~~of~~ chloride (Cl^-) as a biologically conservative tracer.

Site Description

The Phoenix, AZ metropolitan region (Fig. 1) is a rapidly growing urban area in the Sonoran ~~D~~desert. With 4.3 million residents, the Phoenix metropolitan area (hereafter Phoenix) is the 12th most populous urban area in the United States. Phoenix has developed and expanded across the alluvial plain of the Salt River above its confluence with the Gila River, from small agricultural communities in the late 1800s to today's 1700-km^2 urban–suburban matrix. Accompanying that expansion was the replacement of pre-urbanization natural ephemeral washes with extensively modified urban drainage systems ~~that is characterized by extensive hydrological modification~~ (Larson and others 2005; Keys and others 2007; Roach and others

2008; Larson and Grimm 2012). Although many older areas of Phoenix are serviced with underground stormwater drainage pipes, developments built since the 1970s have been required to retain all runoff from a storm with a 100-year recurrence interval and a 2-hour duration (FCDMC 2007), which is a storm ranging from 53 to 79 mm, depending on location (FCDMC 2013).

There are four primary stormwater infrastructure designs used in Phoenix: stormwater drainage pipes, engineered channels, natural washes, and retention basins. Stormwater drainage pipes (hereafter "pipes") are simply buried pipes that drain urban land, with streets and parking lots as headwaters. In Phoenix (and in other urban areas in the US Southwest), this pipe system is separate from the sanitary sewer system. Engineered channels (hereafter "channels") are linear, open channels that are typically concrete, gravel-lined, or planted with grass. Natural washes (hereafter "washes") are not designed features, but rather~~,~~ relict desert ephemeral streams that have gravel or sandy beds and tend to be more sinuous than channels. Retention basins are engineered depressions with xeric (i.e., landscaped with gravel and desert vegetation) or irrigated grass landscaping that are designed to retain all stormwater during rain events, but that must drain all retained water within 36 hours (they are therefore, by design, dry features most of the time). Drainage is by infiltration if percolation rates are more than 13 mm/hr and by dry well otherwise.

The climate of the Sonoran d~~D~~esert is hot and dry. Precipitation falls primarily as rain and is highly variable within years (monthly mean 2 mm [min=0 mm] – 26 mm [max=141 mm]) and between years (min=71 mm, max=390 mm, std. dev=76 mm), but averages 190 mm annually (Western Regional Climate Center, period of record 1933–2012, http://www.wrcc.dri.edu). The study years had annual precipitation slightly above (2010: 232

mm)~~,~~ and well below average (2011: 118 mm, 2012: 109 mm). Within years, precipitation falls during the summer monsoon and winter rain seasons (long-term average ~50% in each season). Summer monsoon storms are typically convective events characterized by brief, intense, and highly localized rainfall, with moisture originating in the Gulfs of Mexico or California. Winter storms, in contrast, are Pacific frontal storm systems with lower-intensity, longer-duration rainfall. In contrast with many other urban studies in more mesic settings, the non-urban reference stream conditions for Phoenix experience higher flood peaks and flash flood potentials due to the rainfall, soil, and vegetation characteristics of the Sonoran d~~D~~esert (Osterkamp and Friedman 2000).

METHODS

Objective 1: Characterize spatial and temporal changes in urban drainage infrastructure

We obtained data from the City of Scottsdale on the locations of stormwater pipes, channels, and washes. Retention basins were identified manually from a 0.6-m contour digital elevation model in ArcGIS 10.0, and validated using aerial photographs. We assigned a year of construction to each individual stormwater structure based on the construction year of adjacent residential development (obtained from the Maricopa County Assessor subdivision dataset (http://mcassessor.maricopa.gov/assessor)). To assess how the use of different infrastructure designs has changed over time relative to the area of new development, ~~To identify temporal changes in the use of different infrastructure designs,~~ we normalized the length (for pipes, channels, and washes) or area (retention basins) of newly employed infrastructure ~~each year~~ to the area of new development for each year.

Objectives 2-3: Characterize nutrient and DOC loads from watersheds with different stormwater infrastructure designs and determine relationships among infrastructure, land cover, storm characteristics, and nutrient and DOC loads.

To understand the effects of stormwater infrastructure design on nutrient and DOC fluxes, we sampled stormwater runoff from the outlets of 10 watersheds that experience ephemeral flow and vary in stormwater infrastructure and drainage area (Table 1). Nine of these watersheds are nested within the Indian Bend Wash (IBW) watershed that drains most of Scottsdale, AZ into the Salt River (Fig. 1; see also Roach et al. (2008)). The 10th watershed (Kiwanis Park; KP) is located in Tempe, AZ, outside of the IBW watershed, but is comparable to other watersheds in terms of its land use. Watersheds were selected to capture a range of stormwater infrastructure types (pipes, retention basins, and engineered channels), drainage areas, and land covers (Table 1). Seven watersheds (including KP) are <150 ha in drainage area, contain only medium-density residential land use, and are drained primarily by a single type of infrastructure (Table 1). The two smallest of these (<10 ha) are drained only by surface runoff (i.e., they have no stormwater infrastructure). The remaining three larger "integrator" watersheds drain areas with mixed land use and multiple forms of stormwater infrastructure.

Sampling

We measured stage height at all sites with ISCO®720 bubbler modules, which were installed in concrete channels, concrete box sections (in the case of engineered channels), or pipes, to facilitate development of depth-discharge rating curves. Rating curves were developed using Manning's Equation to calculate discharge (Q) from flow stage measurements:

$$Q = (1.0/n)A(R^{2/3})(S^{1/2})$$

where n is Manning roughness coefficient (empirical constant; dimensionless), A is channel cross-sectional area (m^2), R is hydraulic radius of channel (m) and S is channel slope (Table A7).

For ~~two of the~~the ~~larger~~ largest integrator sites, IBW, ~~and Silverado Golf Course (SGC),~~ discharge data were obtained from U.S. Geological Survey (USGS) ~~and Flood Control District of Maricopa County (FCDMC) flow gauges, respectively~~. At the same locations used to measure stage height, we used ISCO®6700 automated pump samplers to collect discrete stormwater samples during every storm from August 2010 to August 2012. The pump samplers were programed to collect samples at flow depths at or above 1.5 cm (the lowest depth at which it was possible to sample flow) and to sample more frequently on the rising limb of the storm hydrograph, when changes in nutrient and DOC concentrations were expected to be most dynamic due to first-flush effects (Lee and others 2002). We measured rainfall at each site using ISCO®674 tipping-bucket rain gauges that recorded at 1-minute intervals, though rainfall data (15-minute intervals) were obtained from the Flood Control District (http://fcd.maricopa.gov/Rainfall/Raininfo/raininfo.aspx) for three sites (PIE, LM, and SGC) where rainfall was already being monitored. To account for the spatial variability of rainfall across the study area, we supplemented measurements of rainfall from our rain-gauge network with data from Flood Control District gauges and the wunderground.com volunteer network of rain gauges. Rainfall depth measured at this full set of gauges was spatially interpolated to a 50-m grid using the natural-neighbor interpolation method (Sibson 1981) of the “griddata” function in Matlab R2012b. The natural-neighbor interpolation method was used as it is an ‘exact interpolator’, preserving the observed values at each gauge. These interpolated rainfall surfaces for each rainfall event were then used to calculate average event rainfall depth over each watershed.

Stormwater samples were collected from the field within 12 hours of an event and transported to the laboratory for processing. Samples for TDN and DOC were filtered through ashed Whatman® GF/F filters, acidified to pH=2 with HCl, and analyzed within 7 days by combustion on a Shimadzu TOC-VC/TN analyzer (detection limit 0.04 mg DOC/L and 0.004 mg TN/L). Samples for Cl^- and SRP were filtered as above and analyzed on a Lachat Quick Chem 8000 Flow Injection Analyzer (detection limit 0.19 mg Cl^-/L and 0.000139 mg SRP/L). Samples for NO_3^-, NO_2^-, and NH_4^+ were centrifuged to remove particulates and analyzed on a Lachat Quick Chem 8000 Flow Injection Analyzer (detection limit 0.00085 mg NO_3-N/L and 0.00301 mg NH_4-N/L). Samples for NH_4^+, NO_3^-, NO_2^-, SRP, and Cl^- were either analyzed immediately or frozen for later analysis.

Data analysis

Event load (L_e) was estimated as:

$$L_e = \left(60 \sum_{t=1}^{n} C_t \times Q_t\right) \div 10^6$$

Where C_t is the analyte concentration in mg/L, Q_t is the instantaneous discharge in L/s, 60 is a conversion factor to calculate load per minute, and 10^6 is a conversion factor to obtain load in units of kg. Concentrations were linearly interpolated between observed values. Event-mean concentration for each analyte (EMC, in mg/L) was calculated as:

$$EMC = \frac{L_e}{Q_e} \times 10^6$$

Where Q_e is the total discharge in L and 10^6 is a conversion factor to obtain concentration in units of mg/L.

All load data are expressed per unit watershed area (kg/km^2). Rainfall and runoff are expressed as a depth (mm). Data were transformed as necessary to achieve normality and homoscedasticity. Unless stated otherwise, all analyses were conducted using R (version 2.15.1, http://cran.r-project.org/).

To test for differences in nutrient and DOC loads and concentrations from watersheds with different stormwater infrastructure designs (Objective 2), we used a one-way analysis of variance (ANOVA) with site as the factor. We used Tukey's HSD post-hoc test to evaluate between-group differences. Ten events had runoff coefficients (runoff/rainfall) > 1, indicating uncertainty in rainfall and discharge data (in some instances due to the bubbler line becoming blocked). Six of these events were at a piped watershed (KP; Table 1) and 4 events were at a channel-drained watershed (MR; Table 1). These events were excluded from all analyses.

Watersheds were delineated by topographic analysis in ArcGIS 10.0 using a 0.6-m digital elevation model obtained from the City of Scottsdale in combination with stormwater-infrastructure data layers. We used a land-cover classification dataset created by the Environmental Remote Sensing and Geoinformatics Lab~~CAP LTER~~, in which land cover was characterized from 4-band National Agriculture Imagery Program (NAIP) imagery using object-oriented classification at a ~~(~~0.8-m resolution ~~)~~(Li and others 2014). Land cover was classified as building, road, bare soil, shrub canopy, tree canopy, grass, lake, canal, pool, cropland, and fallow cropland. For the purposes of understanding stormwater dynamics, only the type of surface cover was considered important (e.g., we reclassified tree and shrub canopy to the surface cover class below the canopy), and we reclassified the original categories into the following cover classes: bare soil, grass, impervious (=roads + buildings), water (=canal + pool + lake), and agricultural (=cropland + fallow). We assumed that the surface cover below tree and shrub canopies was in the same proportion as the surface cover not below canopies within each watershed. We also calculated the area of impervious cover that was directly connected to the storm sewer network by overlaying the storm sewer network with land cover. The proportion of each land-cover class within each watershed was calculated in ArcGIS 10.0.

Stormwater infrastructure data were developed as described above, with additional data from the City of Phoenix and City of Tempe. Spatial layers of infrastructure data were clipped to watershed boundaries to calculate the total length of each infrastructure type and the total area of retention basins. Lengths and areas were then normalized by watershed area to obtain a measure of drainage density (m/m^2 or m^2/m^2).

We used path analysis, a type of structural equation modeling, to characterize relationships among infrastructure, storm characteristics, land cover, and event load for each analyte (Objective 3). We excluded the three large integrator watersheds from this analysis because we were interested in isolating the roles of land cover and infrastructure on event load. Separate structural equation models were constructed for each analyte. Path analysis allowed us to test the hypotheses, shown in Figure A1, about the indirect effects of variables on load via their effects on runoff and concentration. We therefore constructed path models in which event-scale load was directly affected by runoff and EMC and indirectly affected by land cover, infrastructure, and storm variables via runoff and EMC (Fig. A1). Land-cover variables considered in the path analysis included imperviousness (%), connected imperviousness (%), grass cover (%), and soil cover (%). Infrastructure variables included retention-basin density (m^2/m^2), pipe drainage density (m/m^2), and channel density (m/m^2). Storm characteristics included rain-free days (RFD, days since the last rain event), flow-free days (FFD, days since the last discharge event), rainfall (mm), and season (binary: winter [November to March] or summer [June to October]; spring and fall storms can be from either winter or summer storm systems and were excluded from the analysis). We also included watershed area (ha)~~,~~ since previous research has found relationships between this variable and nutrient loads (Lewis and Grimm 2007).

We used a Pearson correlation matrix and our hypotheses to guide the selection of variables for each load model. All variables with significant correlations were included in our base model. The base model was fit to raw data using maximum-likelihood estimation in Amos 20 (SPSS). Any weak and insignificants paths (path coefficient < 0.1; $\alpha = 0.05$) were removed, one at a time, re-evaluating the model between each removal until all path coefficients were > 0.1 and significant ($p < 0.05$). Model fit was then evaluated using multiple goodness-of-fit metrics (chi-square, root mean square error of approximation, Tucker-Lewis Index, and Normed Fit Index;~~,~~ ~~(~~Hu and Bentler 1999; Kline 2010)~~)~~. If model fit was unacceptable, additional paths were removed until an acceptable fit was reached. In the case of multiple acceptable models, the model with the best fit metrics was selected. Once a best-fit model was selected, interaction terms between watershed characteristics (land cover and infrastructure) and storm characteristics were evaluated. Interaction terms were introduced to the model only if there was a direct effect of both a watershed and storm characteristic on runoff, concentration, or load. Weak and insignificant paths were then removed from the model if necessary to achieve a final best-fit model.

RESULTS

Spatial and temporal heterogeneity in stormwater infrastructure design

The design of stormwater infrastructure in the City of Scottsdale varied substantially from 1955 to 2010. Pipes were the predominant design for linear stormwater infrastructure in newly urbanizing areas until the late 1970s (Fig. 2). The use of engineered channels in newly urbanizing areas increased from 1970-1980, peaking in 1980, after which the use of engineered channels declined. As urban expansion continued, natural washes made a substantial contribution to new linear stormwater infrastructure after 1980, and were the dominant design type for new construction by the mid-1990s. The use of retention basins in Scottsdale was also variable, with the highest density of retention basins built in the early-1970s, after which the density of newly constructed retention basins declined, returning to pre-1970 levels by 2000 (Fig. 2).

The City of Scottsdale has grown peripherally (mostly to the north)~~,~~ rather than via infill development, and therefore, changes in stormwater infrastructure design through time are mirrored in the spatial patterns of infrastructure use. Retention-basin density is highest in the middle part of Scottsdale corresponding to the area developed between 1976 and 1995 (Fig. 2c). Similarly, there is a distinct north-south transition from the predominance of pipes in the southernmost part of the city, then a shift to engineered channels, and a sharp transition to washes in the newest northern-half of the city (Fig. 2d).

Fluxes and concentrations of dissolved N, P, and DOC from watersheds with different infrastructure types

We sampled TDN, DOC, Cl~~$^{-}$~~, and SRP for 115 events, NO_3^-, NH_4^+, and NO_2^- for 121 events, and Cl^- and SRP for 115 events over the two-year study period (August 2010–July 2012) across all of the watersheds. A variable number of runoff events was sampled for each watershed owing to spatial variability in rainfall and the varying responsiveness of our study watersheds (resulting from the different types of stormwater infrastructure, Table A1).

Event-mean concentrations of TDN, NH_4^+, DOC, and Cl^- varied significantly across watersheds, but those of NO_3^- and NO_2^- did not (Table A2~~1~~). Patterns of concentrations were not consistent across analytes and were unrelated to watershed infrastructure. The exception was the largest integrator watershed (IBW), where concentrations of nutrients and DOC were consistently the lowest, and Cl$^-$ concentrations were the highest.

Loads (kg/km^2) were significantly different across watersheds, and patterns were similar among analytes (Table A3~~2~~). Loads were consistently lowest from SW (retention basin) and SGC (integrator) for all analytes, and consistently highest from the surface- and pipe-drained sites for all analytes (Table A3~~2~~).

Effects of land cover, infrastructure, and storm characteristics on N, P, and DOC loads and concentrations

Best-fit path models showed good agreement with the data according to a variety of metrics (Table A4~~3~~). However, we were not able to validate the models with independent data due to the limited number of observations. Models for all analytes included land cover, infrastructure, and storm characteristics (Fig. 3). Both runoff and EMC were significant covariates of loads in all models (Fig. 3). The total effects of concentration on loads were positive and moderate, while the effects of runoff on loads were positive and strong.

Watershed area was significantly correlated with runoff and loads (except Cl$^-$) across all sites (Table A5~~4~~) but was not retained in any of the best-fit path models when the larger integrator sites were excluded. Imperviousness and grass cover were the most important land-cover variables, correlating significantly with runoff and loads. On the other hand, land-cover variables were generally not correlated with concentrations, except weakly with Cl$^-$ (Table A5~~4~~). Imperviousness was not retained as an independent variable in any of the best-fit models, yet the interaction term between imperviousness and rainfall was the strongest covariate with runoff across all models (Fig. 3). Total and connected imperviousness were equally well correlated with runoff and loads (Table A5), but total imperviousness produced path models with slightly better fits (Table A6). The interaction between imperviousness and rainfall also had a dilution effect on concentrations in all models except for SRP and NO_3^-. However, this dilution effect was overwhelmed by the effect of increased runoff on load; therefore, the total effect of the imperviousness–rainfall interaction on loads was positive (Fig. 3).

Total infrastructure effects on loads were moderate (total effects ~0.45 to ~0.68; Fig. 3). Increased retention-basin density was associated with decreased loads of all analytes. The effects of infrastructure on loads were almost exclusively via effects on hydrology, due to reduced runoff associated with increased retention-basin density. Retention-basin density had a negative effect on loads via EMC for DOC and Cl^-, although these effects were small relative to effects via runoff (Fig. 3).

Nutrient and DOC concentrations were most strongly related to antecedent and storm characteristics: number of rain-free days prior to runoff-generating rainfall event, number of flow-free days prior to runoff-generating rainfall event, season, and event rainfall. Rain-free days had weak to moderate positive effects on concentrations of nutrients and DOC, but not Cl^- (Fig. 3). While rain-free days was important for reactive nutrients and DOC, flow-free days was a moderate covariate with only Cl^- concentration (Fig. 3). Season had moderate effects on concentrations of DOC, NH_4^+, NO_2^-, and NO_3^-, with higher concentrations during summer months than winter months.

DISCUSSION

Spatial and temporal heterogeneity in stormwater infrastructure design

We found clear evidence of spatial and temporal variation in local stormwater infrastructure design that matched~~es~~ patterns that have been described broadly at the national scale (Ellis and Marsalek 1996, Burian et al. 2000, Chocat et al. 2001, Delleur 2003). Most researchers have concluded that urbanization increases hydrologic connectivity (Elmore and Kaushal 2008, Kaushal and Belt 2012). H~~; h~~owever, the heterogeneity in infrastructure design we report indicates that this is not the case in Scottsdale, AZ. Although there may be important regional differences in stormwater management, there is some evidence that the patterns we found are not unique to the arid Southwest. ~~Although they only studied 3 watersheds,~~ Meierdiercks et al. (2010) also reported that stormwater infrastructure in 3 watersheds in Baltimore, MD was related to the time of development, with newer developments having a higher density of stormwater detention ponds.

The changes in stormwater infrastructure design we have observed we~~a~~re driven by social learning at local and global scales (i.e., large-scale paradigm shifts). At local scales, infrastructure transitions may have been~~be~~ related to flooding events or observations of local watershed hydrology. At larger scales, paradigm shifts may ~~be~~ have been driven by scientific research on urban watershed hydrology and function that informs, then changes, regulations and policy (e.g., early works that documented “flashy” urban hydrology and altered sediment dynamics (Wolman 1967; Dunne and Leopold 1978)). These large-scale paradigm shifts may then have filtered down to local watershed managers. Importantly, existing conceptual models of how urbanization affects watershed and downstream ecosystem functioning (Paul and Meyer 2001; Walsh and others 2005; Kaushal and Belt 2012) do not incorporate feedbacks from urban ecosystem research to policy and practice, yet our research suggests that such feedbacks may be an important aspect of how urban watershed ecosystems change over time and space.

Drivers of urban watershed ecosystem function

Our second objective was to understand whether variation in stormwater infrastructure design le~~a~~d~~s~~ to heterogeneity in watershed ecosystem functioning (and resulting potential for heterogeneity in downstream impacts). Overall, we found that stormwater infrastructure design was significantly related to fluxes of nutrients and DOC from urban watershed ecosystems. Other watershed features were also important, such as imperviousness and grass cover, and watershed features interacted with storm characteristics to determine fluxes of dissolved nutrients and DOC from these ecosystems.

Unlike previous work that has found urban hydrology and water quality to be related to stormwater pipes (Paul and Meyer 2001; Shuster and others 2005; Walsh and others 2005; Ogden and others 2011) and channels (Gallo and others 2013 a), we found that retention-basin density was the strongest infrastructure predictor of fluxes of water, nutrients, and DOC. Stormwater infrastructure design was significantly related to stormwater runoff and fluxes of N, P, and DOC, but did not affect their concentrations. Previous work on decentralized stormwater designs (e.g., retention basins, stormwater ponds) and engineered channels has focused on nutrient retention at the scale of individual features (Zhu and others 2004; Bettez and Groffman 2012; Gallo and others 2012; Larson and Grimm 2012), and has suggested that these features have ~~a substantial~~considerable potential to remove nutrients, particularly N, from stormwater. However, at the watershed scale, we found no relationships between infrastructure and concentrations of NO_3^-, NH_4, or SRP, and only ~~although~~ a weak relationship ~~existed~~ between retention basin density and DOC and Cl^- concentrations. This ~~is in~~ contrasts with ~~to~~ the results ~~from~~ of Gallo et al. (2013 a), who reported that channel density correlated with concentrations NH_4^+, NO_2^-, SRP, dissolved organic N, and DOC at the watershed scale. The mechanisms underlying the negative relationship between retention basin density and DOC and Cl^-

concentrations in our study are unclear, but they are unlikely to be biogeochemical ~~mechanisms,~~ given the similar patterns with both bio~~between~~ reactive DOC and conservative Cl^-. Our results suggest that stormwater infrastructure design does affect fluxes of nutrients and DOC, but~~,~~ importantly, that the mechanisms underlying these patterns are hydrological rather than biogeochemical.

Our results are consistent with previous findings that imperviousness tends to be a good predictor of urban hydrology (Brabec and others 2002; Jacobson 2011), but a poor predictor of urban water quality (Brabec and others 2002; Cadenasso and others 2007; Schueler and others 2009; Gallo and others 2013 a). Again, however, imperviousness did not affect nutrient or DOC concentrations, only their delivery via runoff. This suggests that imperviousness affects nutrient delivery solely via effects on the surface water balance (decreased infiltration and increased runoff)~~,~~ rather than via effects on nutrient storage or biogeochemical cycling within watersheds. In contrast to previous work (Booth and Jackson 1997; Lee and Heaney 2003; Walsh and others 2012), we found that connected imperviousness did not improve our models of runoff or nutrient loads. We posit that this is because the effects of stormwater infrastructure overwhelmed the effects of small differences in imperviousness. Most previous work on connected (or effective) imperviousness has focused on watersheds with relatively low total impervious area, usually less than 20% (Walsh and others 2012), whereas even connected impervious area at our sites was greater than 20% and total impervious area ranged from 42-69% (Table 1).

Despite a wealth of literature that documents the high potential for yards and other grassy areas to remove N via denitrification (Zhu and others 2004; Raciti and others 2008, 2011; Hall and others 2009; Larson and Grimm 2012), we did not find any relationships between grass cover and nutrient or DOC concentrations. Instead, it appears that grass cover reduced nutrient and DOC delivery by reducing runoff. Although grass was not included in any of the best-fit path models, it was significantly and negatively correlated with runoff, and nutrient and DOC loads.

Across climatic regimes, the effects of land cover on watershed behavior appear to be strongly mediated by precipitation (Kaushal and others 2008; Gallo and others 2013 a, 2013 b). In our study, rainfall (in combination with imperviousness) also had a negative effect on nutrient and DOC fluxes via dilution of concentrations. Storm characteristics (including antecedent conditions) were also ~~the best~~good predictors of concentrations. Concentrations of NO_3^-, NO_2^-, NH_4^+, and DOC were higher during summer storms than ~~during~~ winter storms. These seasonal effects have been reported for other arid watersheds, both urban (Lewis and Grimm 2007) and desert (Welter and others 2005). These seasonal patterns are likely related to seasonal differences in N concentrations in rainfall that have been observed in the Sonoran d~~D~~esert (Welter and others 2005; Lohse and others 2008), as well as differences in rainfall intensity between summer and winter storms which is related to the transport of nutrients in runoff (Welter and others 2005).

Previous research in a variety of biomes has shown that antecedent conditions are important to concentrations of nutrients in runoff (Brabec and others 2002; Austin and others 2004; Welter and others 2005; Lewis and Grimm 2007). We found that ~~T~~the number of rain-free days preceding a storm event was related to concentrations of nutrients and DOC ~~in our study~~, supporting previous research in mesic urban systems (Brabec and others 2002), arid urban systems (Lewis and Grimm 2007; Gallo and others 2013 b), and natural desert systems (Welter and others 2005). While the number of rain-free days was an important correlate of nutrient and DOC concentrations, the number of flow-free days was an important correlate of Cl^-

concentrations. This~~ result~~ suggests that rainfall events that did~~o~~ not generate discharge at the watershed outlet did~~o~~ not alter the supply of Cl^-. In contrast, nutrients and DOC were more strongly controlled by rain-free days than flow-free days, indicating that storm events that did~~o~~ not generate flow still affected nutrient and C storage and transformation, likely via biogeochemical mechanisms. This interpretation is consistent with results from desert and urban studies that have found pulses of biogeochemical activity following wetting events (Austin and others 2004; Belnap and others 2005; Hall and others 2009) and strong relationships between rain-free days and dissolved inorganic N concentrations in both desert and urban stormwater runoff (Welter and others 2005; Lewis and Grimm 2007; Gallo and others 2013 b). The absence of a relationship between rain-free days and concentrations of the conservative tracer, Cl^-, further supports the ~~hypothesis ~~conclusion that biogeochemical processing within these watersheds alters watershed nutrient and C supply between events rather than during them.

Heterogeneity in urban watershed function over time and space

~~R~~Our results ~~from this study ~~suggest that the process of urbanization is dynamic and leads to heterogeneity in urban watershed ecosystems within cities and over time. We developed a conceptual model to illustrate how urban watershed functioning may have changed in our ~~southwestern ~~study area during urbanization (Fig. 4). We describe 4 major periods of change: (1) initial urbanization, (2) centralized management (e.g., the~~,~~ “Sanitary City”, ~~(~~*sensu* Melosi (2000)), (3) decentralized infrastructure, and (4) ecological infrastructure that ~~, the ~~uses~~ of~~ natural features.

During initial urbanization, changes in human activities increased nutrient inputs and availability in urban watershed ecosystems. Inputs included atmospheric deposition, fertilizer, and food for humans and pets. As people built~~d~~, impervious surfaces increased runoff and the transport of nutrients and other materials from urban watersheds (Fig. 4). During the second period of urbanization, development increased~~s~~ to the point where centralized services beca~~o~~me necessary for the protection of property, human health, and safety. Centralized storm-sewer systems increased runoff further, exacerbating the effects of land-cover change. Furthermore, the burial and channelization of streams decreased~~s~~ the ability of soils and vegetation to remove or retain nutrients and C from runoff (Fig. 4). During the third period of urbanization, the use of decentralized or green stormwater designs emerged~~s~~, reducing runoff to below that of the natural desert ecosystem. These infrastructure designs increased contact between nutrient- and C-rich stormwater runoff and vegetation and soils, potentially increasing nutrient and C cycling within urban watersheds. Regardless of the biogeochemical retention of nutrients and C in these systems, delivery of nutrients and C from urban ecosystems wa~~i~~s substantially reduced via hydrologic mechanisms (Fig. 4). Looking towards the future, the use of remnant desert features – washes – to drain urban watersheds continues to increase in Phoenix. While the use of decentralized retention basins continues, their density is reduced relative to older developments, and more runoff is directed to washes. We suggest that these changes will increase runoff relative to decentralized stormwater designs, bringing urban watershed hydrology closer to native desert hydrology. We also suggest that the use of desert washes for stormwater runoff will increase nutrient and C fluxes from urban watershed ecosystems via both hydrologic and biogeochemical mechanisms. Increased runoff will increase the delivery of nutrients and C, and desert washes are expected to have reduced biogeochemical capacity to remove nutrients and C from stormwater relative to engineered stormwater retention basins~~infrastructure features~~ (Fig. 4).

We developed this conceptual model specifically for arid urban watershed ecosystems, and future work is needed to determine how applicable the model is across arid urban areas and in other climatic regimes where trajectories of social learning may be quite different. Furthermore, management priorities may also vary across cities (e.g., pollution vs flood reduction), and local constraints may limit the types of infrastructure used (e.g., infiltration basins are not feasible in areas with high water tables). As a result, stormwater infrastructure that looks similar (e.g., basins) may have different functional consequences depending on the intended purpose (e.g., flow vs pollutant control) and local context. Regional context is therefore critical in evaluating and making recommendations for infrastructure design (Booth and Jackson 1997; Grimm and others 2008; Pitt and Clark 2008), and it is likely that new patterns will emerge in other climates and in cities with ~~variable~~ a diversity of stormwater management systems.

CONCLUSIONS

In contrast to recent focus on the homogenization of urban ecosystems (Groffman and others 2014; Steele and others 2014), urban stormwater management may represent a major source of ecosystem heterogeneity within and across cities. We ~~report~~ found that stormwater infrastructure design varied~~s~~ substantially over time and space in an arid southwestern city, and show evidence that infrastructure design strongly affected watershed hydrology and fluxes of dissolved N, P, and DOC. As a result, stormwater infrastructure in this urban ecosystem created heterogeneity in the hydrologic and biogeochemical function of urban watersheds over time and space.

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Table 1. Characteristics of study watersheds.

Site	Watershed Name	Drainage Area (ha)	% Impervious Surface Cover	% Connected Impervious Surface Cover	% Soil Cover	% Grass Cover	Retention Basin Density (m^2/ha)	Pipe Density (m/ha)	Channel Density (m/ha)	Total Drainage Density (m/ha)
ENC	Encantada	6	48	41	46	4	0	6	0	6
PIE	Pierce	10	57	48	38	5	0	0	0	0
MR	Martin Residence	18	42	23	45	12	0	1	21	22
BV	Bella Vista	57	69	59	18	13	559	16	33	49
KP	Kiwanis Park	106	57	31	34	9	0	24	0	24
SW	Sweetwater	118	49	21	39	12	531	15	9	24
MS	Montessori	141	49	21	39	12	455	14	41	55
LM	Lake Marguerite	1662	57	37	33	9	170	12	25	37
SGC	Silverado Golf Course	15455	46	26	42	10	46	4	5	9
IBW	Indian Bend Wash	20247	49	29	39	11	48	7	4	11

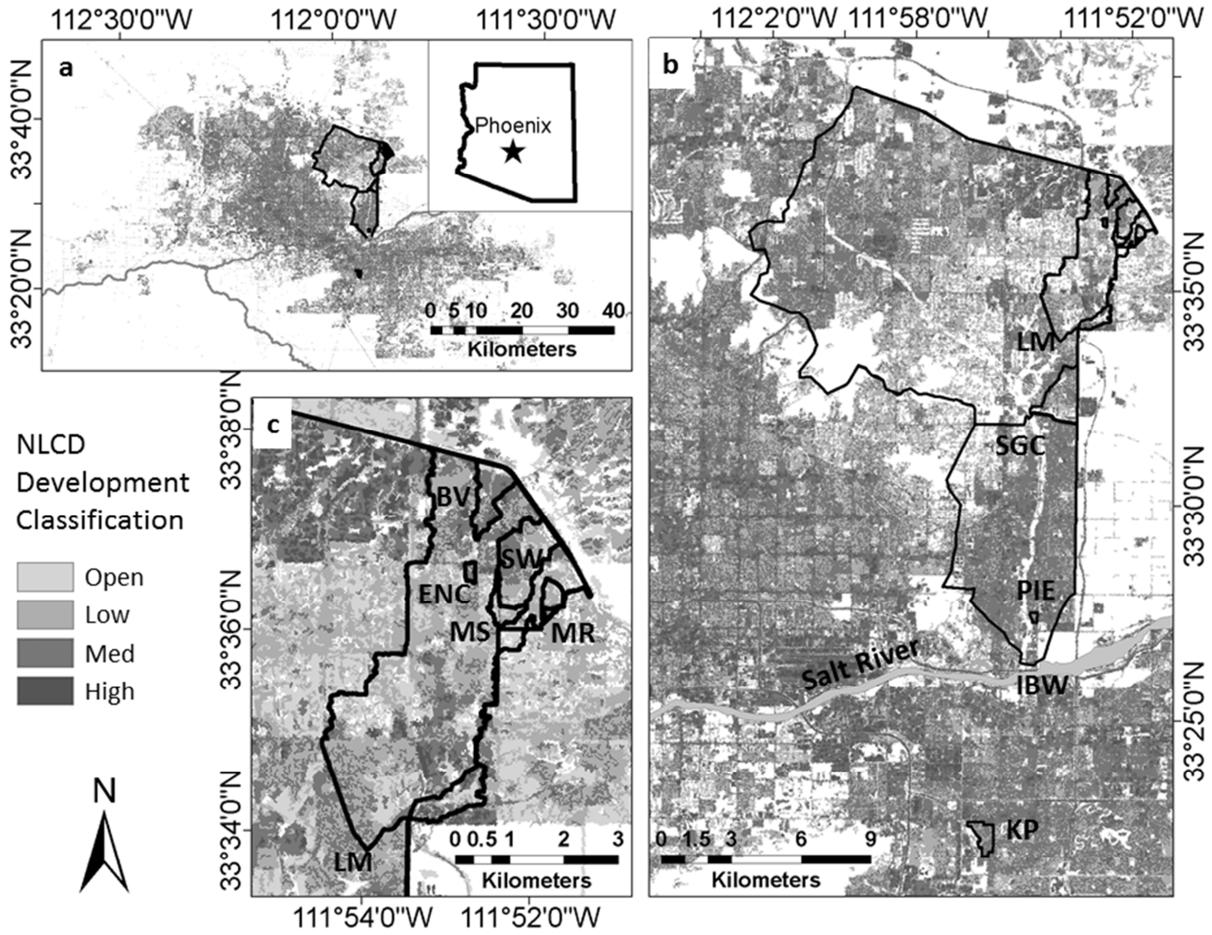
FIGURE LEGENDS

Figure 1. Location of study watersheds. (a) Location of watersheds within the Phoenix metropolitan region (inset: Phoenix location within Arizona); (b) Location of watersheds within Indian Bend Wash Watershed (IBW); (c) Location of small watersheds within Lake Marguerite (LM) watershed. Background indicates the intensity of development based on 2001 National Land Cover Database classification.

Figure 2. Temporal and spatial changes in stormwater infrastructure design for the City of Scottsdale, AZ. (a) area of new retention basins per total new infrastructure length from 1955 to 2010, (b) length of newly constructed pipes, washes, and improved channels as a proportion of total new infrastructure length, (c) location of retention basins, and (d) location of linear drainage features (data from City of Scottsdale).

Figure 3. Total and direct path coefficients for all best-fit models.

Figure 4. Conceptual model of urban watershed ecosystem function (runoff and nutrient fluxes) as a function of time of urbanization. Changes in runoff and nutrient fluxes are plotted relative to a desert watershed ecosystem.



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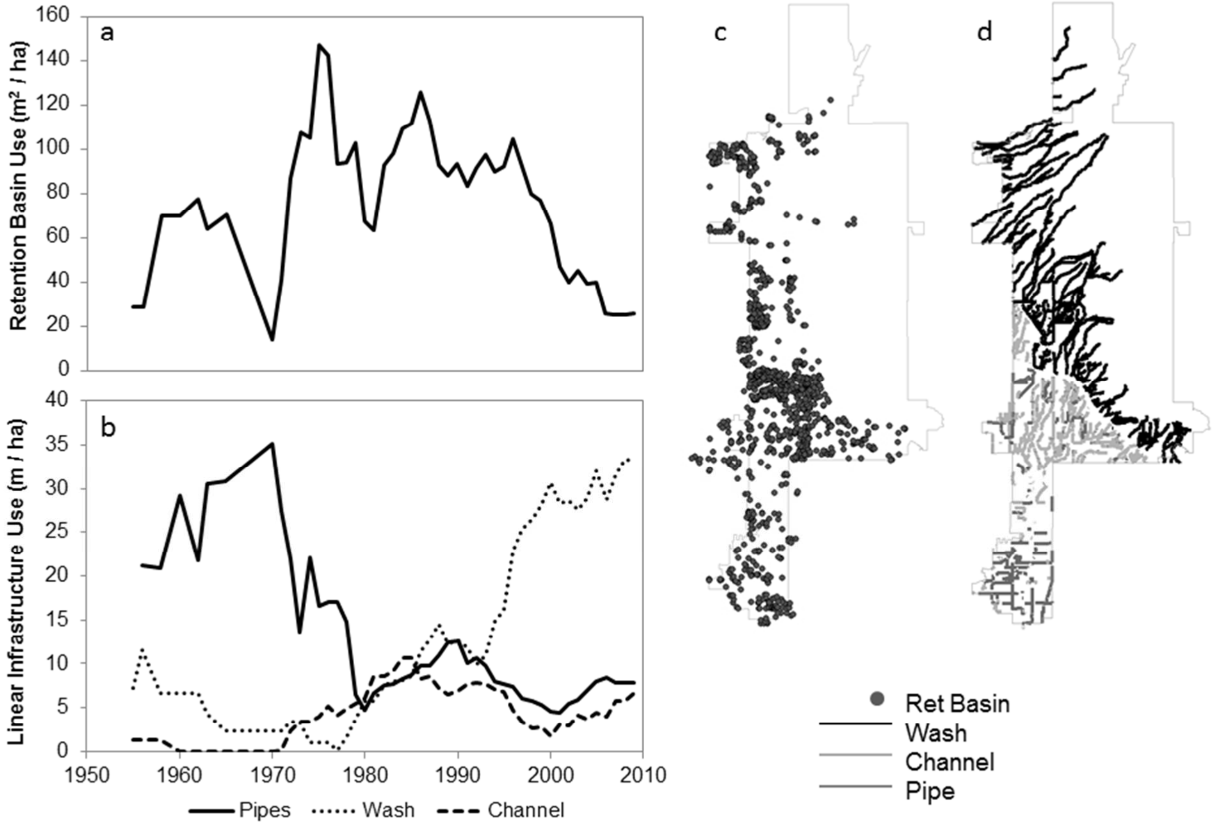

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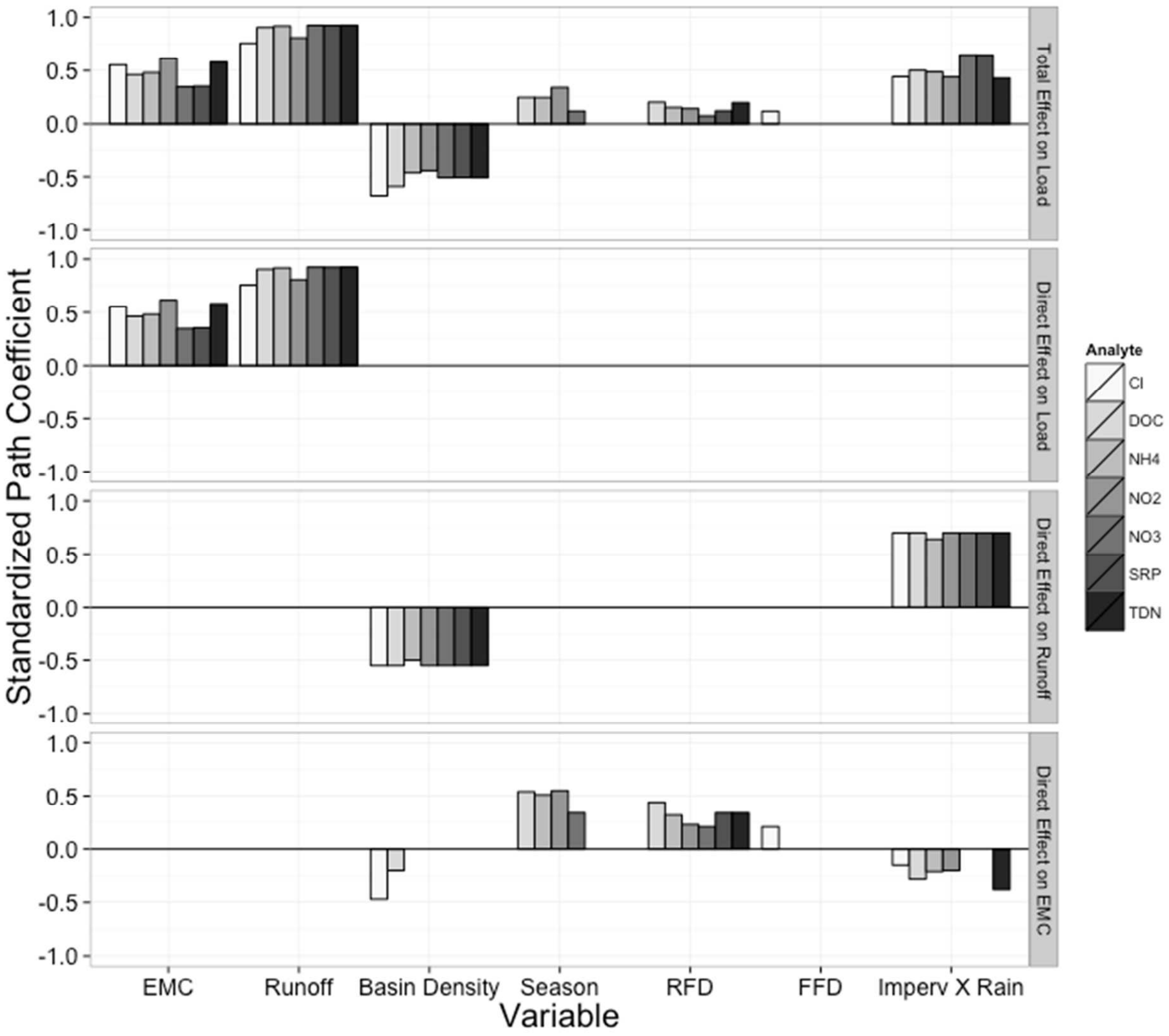
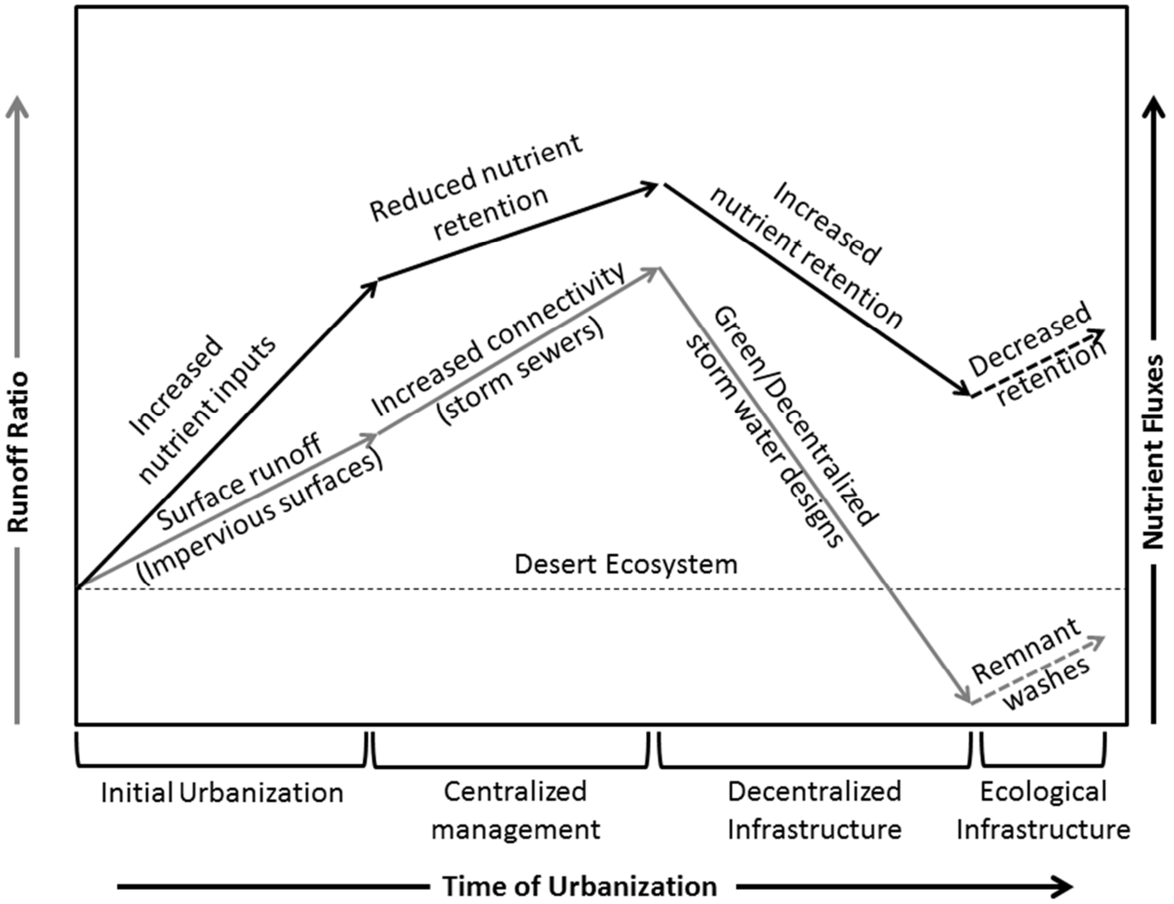


Figure 3. Total and direct path coefficients for all best-fit models. EMC is event mean concentration, RFD is antecedent rain-free days, FFD is antecedent flow-free days, Imperv X Rain is the interaction between impervious cover (%) and rainfall depth.



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