Local Environment

The International Journal of Justice and Sustainability

ISSN: 1354-9839 (Print) 1469-6711 (Online) Journal homepage: http://www.tandfonline.com/loi/cloe20

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To cite this article: Erik Porse (2018): Open data and stormwater systems in Los Angeles: applications for equitable green infrastructure, Local Environment, DOI: 10.1080/13549839.2018.1434492

To link to this article: https://doi.org/10.1080/13549839.2018.1434492

LOCAL ENVIRONMENT, 2018
https://doi.org/10.1080/13549839.2018.1434492

Open data and stormwater systems in Los Angeles: applications for equitable green infrastructure

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ABSTRACT

Urban stormwater systems traditionally used "grey" infrastructure to manage runoff. Contemporary designs now incorporate "green" infrastructure, which offers additional potential benefits such as urban amenities and health. Understanding how green and grey infrastructure investments are distributed across urban areas is important for new goals of promoting environmental justice in planning. In California, for instance, public investments increasingly require a percentage of funds to be spent in disadvantaged communities. Recent advancements in the availability of high-detail geographic data in cities can support prioritising investments to fulfil these multiple benefits. This paper analyses the distribution of stormwater infrastructure in Los Angeles (LA) County in relation to design criteria, urban structure and sociodemographic information. It demonstrates an approach for identifying projects that simultaneously address engineering needs and promote equity. Statistical analysis of high-detail sewer locations reveals geographic correlations with key local design parameters, urban characteristics and sociodemographic indicators. Watershed areas in LA County were identified that support multi-benefit projects, meeting dual criteria for infrastructure improvements and disadvantaged community status. As stormwater systems are increasingly designed for multi-benefit outcomes, new design frameworks can emphasise both performance and social equity.

ARTICLE HISTORY
Received 27 May 2016
Accepted 23 January 2018

KEYWORDS
Urban drainage; low-impact development; environmental justice; big data; California

Introduction

Cities have highly altered landscapes that change the timing, duration, magnitude and velocity of runoff from rainfall and irrigation (Hollis 1975; McCuen 1979; Duncan 1995a; Zoppou 2001; Shuster et al. 2005). This leads to increased pollution in urban watersheds (Ellis 1986; Duncan 1995b; Zoppou 2001; Brabec, Schulte, and Richards 2002; Howard 2010). Traditional stormwater systems used pipes and gutters, so-called grey infrastructure, to quickly convey runoff to local watersheds. In response to regulatory and fiscal pressures, urban stormwater planners increasingly look to "green" infrastructure approaches such as swales and local retention basins to cost-effectively improve water quality (Low Impact Development Center 2000; Shuster et al. 2005; Dietz 2007; Bedan and Clausen 2009). Doing so offers the potential to justify projects based on multi-benefit criteria, as well as privatise some improvement costs to land developers and property owners (Sedlak 2014; SWRCB 2015). Figure 1 illustrates examples of stormwater management infrastructure, including emerging green infrastructure.

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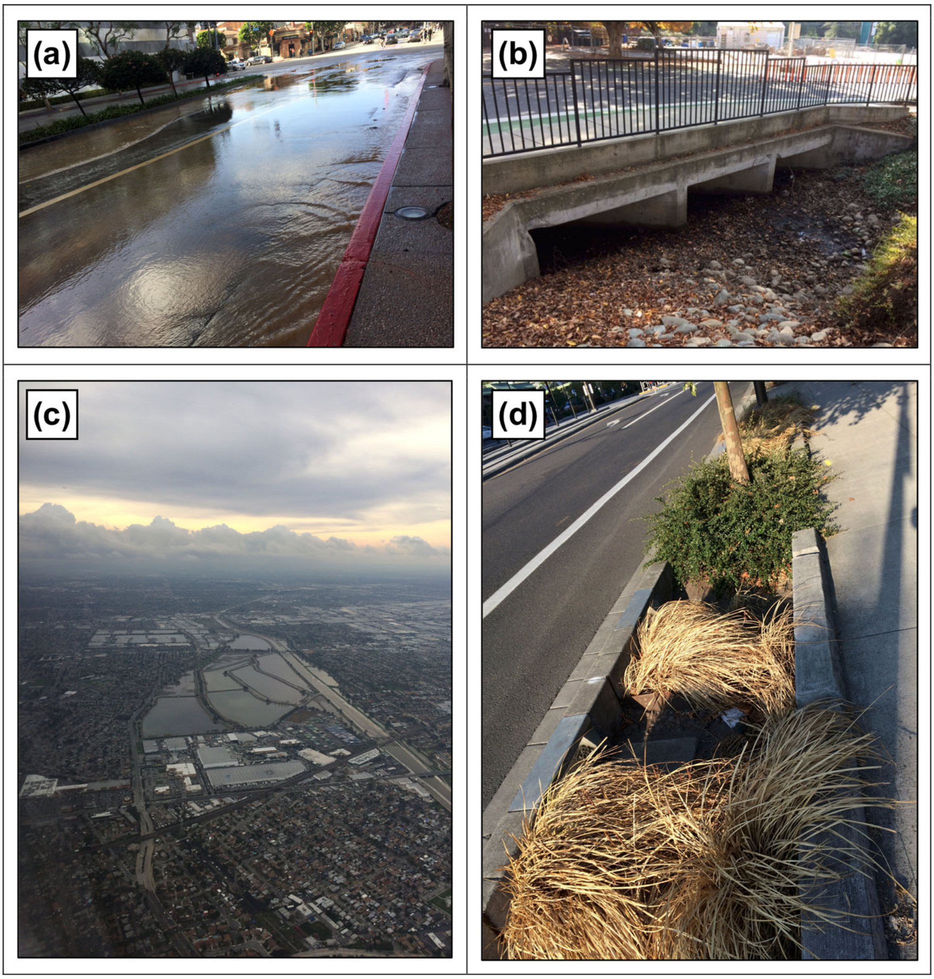

Figure 1. Examples of green and grey infrastructure for managing stormwater: (a) Street conveyance to storm sewers (Los Angeles, CA); (b) Concrete culvert underlying a bridge (California State University Sacramento); (c) Rio Hondo Spreading Grounds in Los Angeles for capturing and infiltrating stormwater; (d) Streetside infiltration swale (Portland, OR) (Source: Author photographs).

Among potential benefits, green infrastructure may contribute to improved *ecosystem services* in cities (Bolund and Hunhammar 1999; MEA 2003; Oberndorfer et al. 2007; Lundy and Wade 2011; Moore and Hunt 2012; Gómez-Baggethun et al. 2013; Jose, Wade, and Jefferies 2015). Such services can include pollution reduction, carbon sequestration, groundwater recharge, recreation and aquatic species diversity. Stormwater systems are one of many large-scale, complex urban infrastructures that facilitate urban life and are the products of past decisions (Tarr 1984; Hughes 1993). Large reconfigurations of infrastructure systems, which also require wide bureaucratic innovations, are often incremental and have unintended consequences (Tarr et al. 1984). For stormwater, building newly hybrid systems that not only reduce urban flood risk, the historic goal, but also provide additional ecological and social benefits such as pollution mitigation, requires better land-use planning and monitoring of actual ecological processes over time (Pataki et al. 2011; Porse 2013; Miguez, Rezende, and Veról 2014). Many stormwater planning assessments have limited incorporation of broader ecological benefits (Visitacion, Booth, and Steinemann 2009).

For multi-benefit projects, future stormwater designs should also strive to include sociodemographic considerations alongside ecology and engineering criteria, maximising the multi-benefit outcomes. For instance, the construction of urban stormwater controls is influenced by social attitudes and contemporary design techniques, as well as economics such as land prices (Tarr 1979; Tarr et al. 1984; Sample et al. 2003; Thurston 2006). The rise of the environmental justice (EJ) movement, which first identified how lower income and minority communities often face disproportionate exposure to environmental hazards, provides rich additional criteria for evaluating success. EJ researchers and practitioners advocate for more equitable distribution of built infrastructure to mitigate exposure risks, increase access to amenities, improve public health and promote sustainable communities (Bullard and Johnson 2000; Bullard 2007; Wolch, Byrne, and Joshua 2014).

Such equity considerations are seeping into actual planning guidance and funding (EPA 1998). For instance, in California, Senate Bill 535 and Assembly Bill 1550, passed in 2012 and 2016, require that 25% of funds spent on sustainable community projects through the state's Greenhouse Gas Reduction Fund (Cap and Trade) occur in disadvantaged communities (De Leon 2012; Gomez 2016). In support, the California Environmental Protection Agency's Office of Environmental Health Hazard Assessment (CalEPA OEHHA) developed a ranked index of environmental risk for California communities, *CalEnviroScreen* (OEHHA 2016). *CalEnviroScreen* provides a rich compilation of data to investigate geographic aspects of environmental hazard mitigation.

But empirical investigations of equitable infrastructure planning have not fully embraced the use of large, integrated data analysis. Merging the sociodemographic and environmental risk data contained in *CalEnviroScreen* and similar sources with data for existing infrastructure placement can inform municipal investments in green infrastructure. It also provides an opportunity to understand the outcomes of past infrastructure development, including evident factors that influenced where existing infrastructure is currently located, along with how the infrastructure may have shaped urban development. This paper presents an analysis of the distribution of stormwater infrastructure in Los Angeles (LA) County and the correlation with sociodemographic trends and the built environment. It examines factors that correlate with the location of current grey infrastructure. Looking forward, it demonstrates a procedure for integrating EJ considerations into stormwater planning with green infrastructure by ranking communities with high potential for improving both equity and infrastructure performance through new stormwater investments. The paper presents maps for LA showing communities with high potential for multi-benefit investments. It concludes with a discussion of relevant findings and insights for future planning. The case study for LA offers methods that can be applied to other cities.

Methods

The LA Metropolitan Statistical Area (MSA), covering LA and Orange counties, has a total population of nearly 13 million people across 4850 square miles (Census 2013). The study area used for this analysis focused on the urbanised region of LA County south of the Angeles and San Bernardino National Forests, which includes more than 9 million residents.

The study used compiled datasets to support two analytical procedures. First, linear regression with Ordinary Least Squares (OLS) was used to investigate correlations between: (1) a response variable for density of stormwater infrastructure in a sub-watershed and (2) explanatory variables including design parameters (runoff coefficient, density of buildings) and sociodemographic indicators (land value, median income, percent of rental households, percent of multi-family households and population density) for small watershed areas. These variables are listed in Table 1. The OLS model was developed to test the hypothesis that density of existing grey stormwater infrastructure correlates with both design parameters and urban form characteristics, such as building density. The outcome of the procedure helps understand factors that correlate with existing stormwater infrastructure, correlations that may be either intentional (by design) or unintentional.

Second, a ranking procedure was used to prioritise watersheds according to potential for multi-benefit green infrastructure projects. Specifically, indices quantified values of the density of existing grey stormwater infrastructure (sewers) and status as an environmentally at-risk community based on the *CalEnviroScreen* data set. The sections below describe the data and procedures in further detail.

Table 1. Explanatory and response variables investigated through linear regression models for stormwater infrastructure in LA County.

Variable	Description	Unit	Source
Explanatory variables			
Length of sewers	Total length of sewers in a sub-watershed, based on length (calculated) of gravity main sewer pipes	Ft	LA County Department of Public Works shapefile, accessible through the LA County geospatial library
Length of surface channels	Total length of surface channels, both natural and engineered in a sub-watershed as reported by LA County. Area is based on length (calculated) of channels	Ft	LA County Department of Public Works shapefile, accessible through the LA County geospatial library
Area of sewers	Total area of sewers in a sub-watershed, based on length (calculated) and width (estimated or reported) of sewer pipes	Ft^2	LA County Department of Public Works shapefile, accessible through the LA County geospatial library
Area of surface channels	Total area of surface channels, both natural and engineered in a sub-watershed as reported by LA County. Area is based on length (calculated) and width (estimated or reported) of channels	Ft^2	LA County Department of Public Works shapefile, accessible through the LA County geospatial library
Response variables			
Unit land cost	Cost of an acre of land in a sub-watershed, including land value and improvements. The value is calculated by correlating the value of a building and parcel with its geographic location in a watershed using a unique identifier	$ per acre	LA County property tax geospatial database
Average runoff coefficient	Average coefficient of runoff in the sub-watershed	n/a	LACDPW WMMS Database
Building density	The number of buildings in a watershed (determined using polygon-point analysis in GIS) divided by the total watershed area	Buildings/ acre	LA County parcel geospatial database
Population density	Population density within a sub-watershed, calculated as the mean of population densities among census tracts comprising the sub-watershed	Persons per sq-mi	US Census
Percent rental households	Percent of households in a sub-watershed that rent, calculated as the mean number of total rental households divided by the mean number of total households across census tracts	n/a	US Census
Percent multi-family households	Percent of multi-family households in a sub-watershed, calculated as the mean number of total multi-family households divided by the mean number of total households across census tracts	n/a	US Census

Data sources

High-resolution geographic data for land cover, groundwater recharge, sewer pipe networks and topography are essential components of stormwater analysis (Lai et al. 2007; DHI 2014). The Watershed Management Modeling System (WMMS) from the LA County Department of Public Works (LACDPW) is a comprehensive hydrologic model for LA County. Its database delineates 2655 small watersheds across the county, ranging in size from 3 to 11,500 acres (LACDPW 2013). The WMMS model database contains values in each sub-watershed for urban design characteristics that are key parameters of stormwater system design, including the percent of impervious surfaces, average runoff coefficient to estimate the amount of precipitation that runs off a property, watershed land area and design storm rainfall used to estimate the required volume of stormwater infrastructure (Table 1). From the full WMMS database, we used 2230 sub-watersheds for which sociodemographic and other factors could be identified through calculations. When merging spatial datasets, some areas may not be calculable because data do not exist or spatial discontinuities prevent direct attribution across layers of different geographic boundaries.

Locations of stormwater sewers and surface channels, which can both convey stormwater, were derived from the LACDPW's shape files of stormwater infrastructure locations (LACDPW 2012). The sewer shape file includes both smaller "lateral lines" that convey stormwater from small areas and larger "gravity mains" in which stormwater from many lateral lines collects and flows to treatment plants or discharges to rivers and oceans. Statistical models tested the response variable of sewer length as both the combined (lateral lines and gravity mains) and separate.

Estimates of building density, number of buildings and land costs were derived from the 2008 LA County Tax Assessor's database. Property tax records provide the value of land and improvements for all parcels in the county, along with additional building characteristics such as recorded square-footage and age (LA County Office of the Assessor 2008). Property boundaries and associated building locations were derived from the LA Region Imagery Acquisition Consortium's imagery-derived data (LARIAC 2012).

Additional sociodemographic indicators, including median income, percent of rental households, percent of multi-family households and population density, were derived for census tracts in LA County from the U.S. Census Bureau's American Community Survey (ACS) database (ACS 2014). This database is compiled from a statistically representative sample of households located within a Census Block group, which can be aggregated to census tracts. The time period for the collected sociodemographic information corresponds to the period ranging from 2010 to 2014.

Finally, the numerical index of environmental risk in an area was derived from the *CalEnviroScreen* rankings, which quantifies risks of California residents to many sources of pollution at a small geographic scale (OEHHA 2016). *CalEnviroScreen* ranks all census tracts in California into percentiles, with high percentiles values (85–100%) corresponding with at-risk communities.

Compiling data

The open-source Geographic Information System (GIS) software *QGIS* was used to calculate statistics for each sub-watershed (QGIS Development Team 2014). The LA County GIS database provides a shape file with stormwater pipe and channel locations, along with pipe and channel widths for some, but not all, line segments. The length of stormwater pipes and channels was determined using the *Sum Line Lengths* function in *QGIS* to calculate the linear distance of line segments in a sub-watershed. The surface area of pipes and channels, which is the area only associated with the pieces of grey infrastructure (not the collection basin area), was estimated by multiplying: (1) the length of sewer and channel line segments in a watershed and (2) an assumed or noted width. In cases where the width was not identified or infeasible in the database, the analysis estimated 2-foot diameter pipes, a reasonable assumption for engineering practice and 100-foot wide channels, based on analysis of available data in the LA stormwater shape file. The area of channels is the estimate land surface area, while for sewer pipes it would be an estimate of sub-surface area.

Average statistics for sociodemographics, building characteristics and environmental risk in sub-watersheds were determined using the *Join Attributes by Location* function, which calculates summary statistics of features within each polygon of a target layer. The analysis procedure calculated the number of buildings, summary characteristics for buildings (average square-footage and average building age) and average unit costs of land in a watershed based on the LA County Tax Assessor's database and LARIAC data. Sociodemographic values were aggregated from ACS census tract data to sub-watersheds by first determining centroids of census tracts to place them within a sub-watershed, and then calculating the mean value of a variable, such as population density, in all the census tracts comprising a sub-watershed.

For summary calculations of property and building characteristics in a watershed, buildings had to be placed within a watershed. Addresses were associated with the parcel shape file using a common parcel identifier, which allowed for connecting home values from the LA County Tax Assessor and spatially distinct building polygons from the LARIAC data. In total, there were approximately 2.4 million records. The total value (land and improvements) of all buildings in a watershed was summed and divided by the area of that sub-watershed, which yielded average land value per acre. Building locations were pinpointed within in a single sub-watershed by creating centroids of building polygons that retained the full attribute list. Sociodemographic indicators and the *CalEnviroScreen* scores were attributed to the watershed areas using a spatial join procedure. For instances where the census tract boundary was larger than a watershed, the attributes associated with the largest tract were given to a watershed.

Linear regression

Linear regression was performed using the open-source statistical package *R* (R Core Team 2014). Tests for multicollinearity among dependent variables were performed and a linear model was fit to test statistically significant relationships between response and explanatory variables. Explanatory variables with multicollinearity or lacking statistical significance were removed using a backward stepwise procedure to improve model fit. Two statistical models tested relationships between a response variable (length or area of sewers/channels) and explanatory variables of: (1) *design factors and property characteristics*, including runoff coefficient, imperviousness, building density, number of buildings, land costs, maximum elevation change and average building age or (2) *sociodemographic factors* including median household income, percent of renters and owners, percent of single-family and multi-family households, population, population density and percent of families above and below the poverty line. Reported models included statistically significant variables.

Ranking watersheds for multi-benefit investments

Once the spatial database for sub-watershed characteristics was compiled, including attributes for existing stormwater infrastructure density, sociodemographic factors, and property and building characteristics, all the LA County sub-watersheds with statistics (2203) were ranked according to scores for existing stormwater infrastructure and environmental risk. Sub-watersheds of high interest for potential multi-benefit investments were identified as those in both: (1) the top 15th percentile of average *CalEnviroScreen* ranking and (2) the bottom 15th percentile of existing stormwater infrastructure coverage, calculated as the ratio of stormwater sewer length divided by population density. Mapping showed the 30 watersheds in LA County where the two chosen score rankings of interest corresponded. In these areas, communities are potentially at risk from both environmental hazards (not necessarily hydrologic) and limited existing stormwater systems that could exacerbate flood risk and water quality impacts. These would be candidates for future stormwater investments using contemporary methods for green infrastructure.

Results

Based on analysing geospatial data from the LA County Department of Public Works, there are over 4604 miles of sewers and 835 miles of surface channels designated for stormwater conveyance in LA County. This does not count any roads designed to convey water during large rainfall events. The distribution of sewer pipes and surface channels varies throughout the metropolitan region (Figure 2(a, b)). Sewer pipes are prominent in urbanised areas, especially in downtown LA, coastal cities, and along major thoroughfares of the coastal plain. Surface channels are more dispersed in the outskirts and the Upper San Gabriel Valley, as well as in less urbanised areas of northern LA County. The length estimated using GIS is greater than the recorded length estimated of underground storm drains (3300 miles) and open surface channels (481 miles) per the LA County Management Maintenance System, potentially due to the GIS layer including additional municipal stormwater sewer infrastructure systems that are not directly maintained by LA County (LACDPW 2015).

A general linear model by OLS revealed statistically significant relationships for the response variable *length of sewers*, which is the length of gravity main sewers in a sub-watershed ($R^2 = 0.67$). Variables that were statistically significant and positively correlated to sewer length included *average runoff coefficient* ($\beta = 1.063e^4$), *building density* ($\beta = 3.43e^2$) and *percent impervious area* ($\beta = 5.69e^1$).

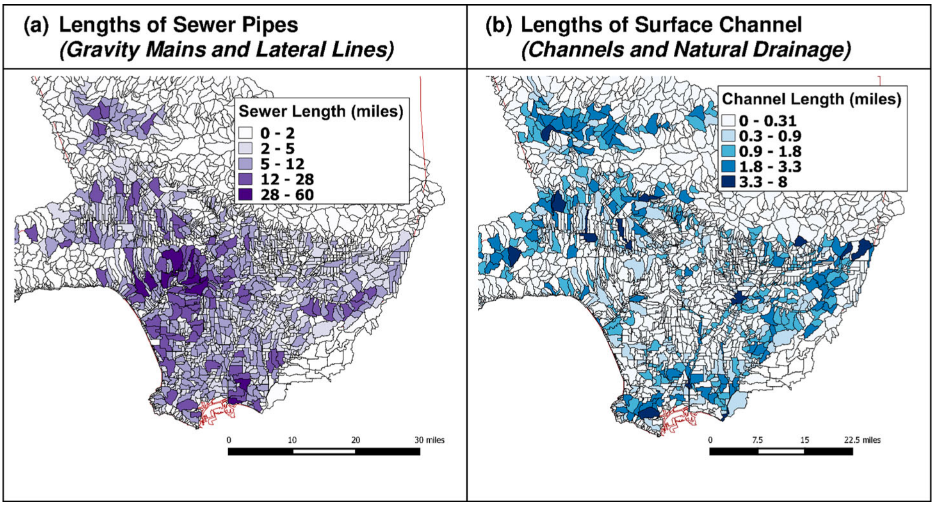

Figure 2. Geographic distribution of sewers and channels in LA County small watersheds defined by the LA County WMMS model. Darker areas indicate a greater length of (a) sewer pipes and (b) channels.

Unit land costs were not statistically significant. Replacing the explanatory variable of *building density* with the *number of buildings* increased the goodness of fit further for the model ($R^2 = 0.75$). Using the response variable of estimated *area of sewers*, statistically significant relationships with the same explanatory variables are preserved ($R^2 = 0.46$). If both gravity main and lateral line sewers are included in the *length of sewers*, statistically significant relationships remain among the three positively correlated variables but the goodness of fit reduces ($R^2 = 0.44$). For a response variable of *length of surface channels*, however, the same explanatory variables resulted in a linear model with poor fit ($R^2 = 0.09$). Table 2 lists the model parameters and statistical levels of confidence for comparable models of infrastructure area. Topography, determined as the maximum elevation change in a sub-watershed, was not a statistically significant predictor.

The geographic distribution of storm sewers and channels reflects findings from the statistical analysis of urban and design factors. Many areas with more buildings, including downtown LA

Table 2. Results from linear regression models to assess relationships between: (1) explanatory variables for building characteristics, design criteria and sociodemographic indicators and (2) response variables for density of storm sewer and channel infrastructure.

Explanatory variables	Coefficient	Standard error	*t*-value
Response variable: length of sewers (gravity mains) in sub-watershed ($R^2 = 0.74$)			
Intercept***	$-5.020e^{3}$	$1.282e^{3}$	−3.92
Unit land cost	$-3.049e-^{5}$	$3.079e-^{5}$	−0.991
Average runoff coefficient***	$6.570e^{3}$	$1.585e^{3}$	4.15
Number of buildings***	$3.550e^{0}$	$1.437e-^{1}$	24.71
Impervious area***	$3.446e^{1}$	$1.220e^{0}$	28.25
Response variable: length of surface channels in sub-watershed ($R^2 = 0.09$)			
Intercept	$3.411e^{3}$	$4.994e^{2}$	6.83
Unit land cost	$-5.546e-^{6}$	$1.209e-^{5}$	0.65
Average runoff coefficient**	$-1.760e^{3}$	$6.231e^{2}$	−2.82
Building density***	$-2.435e^{2}$	$2.943e^{1}$	−8.27
Impervious area***	$4.068e^{0}$	$3.11e^{-1}$	13.08
Response variable: length of sewers (gravity mains) in sub-watershed ($R^2 = 0.20$)			
Intercept***	$4.809e^{3}$	$7.35e^{2}$	6.54
Population density***	$1.535e^{0}$	$9.16e-^{2}$	16.75
Percent rental households***	$-2.230e^{4}$	$4.04e^{3}$	−5.52
Percent multi-family households***	$1.944e^{4}$	$33.47e^{3}$	5.61

***Significant at <0.001 level, **significant at 0.01 level.

and coastal areas, also have more sewers. Visually, areas with more surface channels inversely correlate with buildings, though the statistical model of this relationship fit poorly.

Sociodemographic indicators were less correlated with stormwater infrastructure in sub-watersheds ($R^2 = 0.20$). Population density and percent of multi-family households were positively correlated and statistically significant, while the percent of rental households was negatively correlated. Median household income, home ownership rates and percent of households above and below the poverty line were not statistically significant.

For the multi-benefit prioritisation procedure, 30 sub-watersheds were identified as being in both the highest 15th percentile for average *CalEnviroScreen* scores and the lowest 15th percentile for the ratio of storm sewer length to population density. The areas were primarily located east of downtown LA, with many in the San Gabriel Valley that comprises most of the area overlying the "Upper" groundwater basins. In these upstream areas, water accumulates from urban streets and mountain runoff, and is conveyed to several main rivers that have been hardened with concrete channels to control floods. Mapping the districts shows clustering of priority areas (Figure 3).

Most clusters of identified priority watersheds for multi-benefit projects are located in areas along the region's channelised rivers and creeks, including the LA River, San Gabriel River, Luguna Channel and Rio Hondo. This result is intriguing and may stem from historical urban development patterns. The rivers in LA County have highly seasonal flows. In summer and early Fall, river channels would be nearly empty in the absence of urbanisation given the region's long dry summers. Most flow is likely anthropogenic, related to runoff from irrigation (Manago and Hogue 2017). The LA River was rare in retaining flow year round, leading to its use as an early source for drinking and irrigation (Davis 1993; Desfor and Keil 2000; Gandy 2006). But all regional rivers can quickly swell and flood during the handful of winter rainstorms, collecting runoff from upstream and sending it towards the ocean. The advent of imported water to the region reduced the perceived value of regional water sources, which instead became flood control liabilities. In the face of regular destructive flooding, the Army Corps of Engineers and LA County embarked on a massive, decades-long building

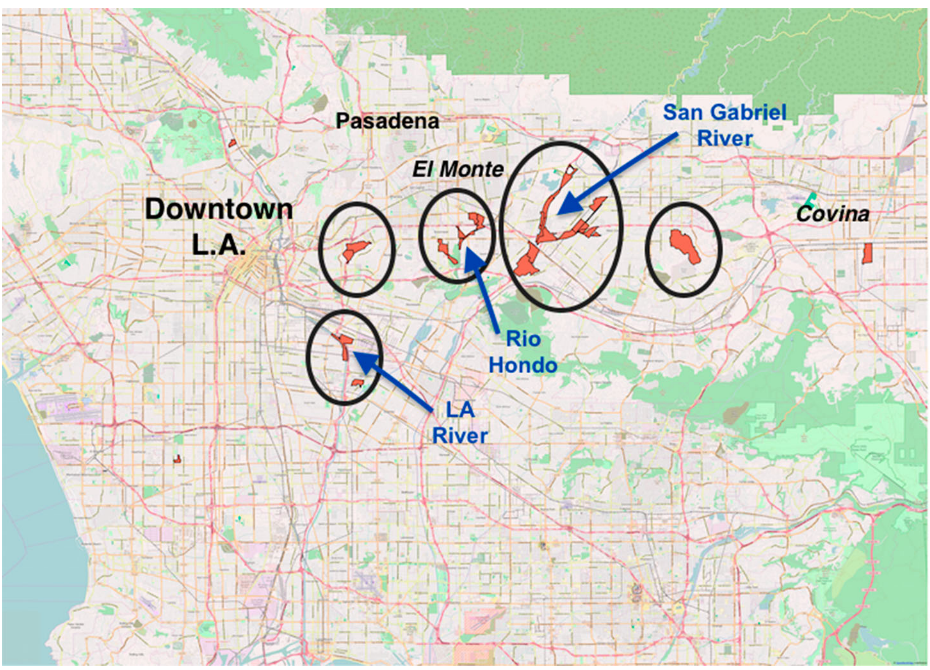

Figure 3. Mapping sub-watersheds with high average *CalEnviroScreen* scores (top 15%) and low ratios of stormwater infrastructure to population density (bottom 15%). Prioritised areas are highlighted in circles, along with corresponding local rivers.

campaign to harden rivers using concrete channels and underground tunnels (Desfor and Keil 2000; Gandy 2006). Riverfront property was not an amenity, instead often dedicated to industrial zones or working class communities only after hardening the channels (Desfor and Keil 2000).

Continued urbanisation created new flood risks in the 1970s and 1980s as more imperviousness created even larger peak flows. The regional conversations, however, changed, slowly moving from an engineering-dominated perspective of flood protection through built reinforcements, to one of broader ecological restoration and multi-use land planning (Desfor and Keil 2000; Gumprecht 2001; Gandy 2006). The many instances of at-risk communities located along concreted rivers and drainage channels are a legacy of past practices emphasizing channelization of rivers and land redevelopment, which was driven by political processes (Desfor and Keil 2000). Urban expansion built up to the edges of channelised rivers, which was useful land but not prime real estate. As a caveat, however, the prominence of priority investment communities alongside rivers could stem instead from the index of storm sewer density that was one-half of the ranking procedure. More detailed site investigations, or a broader index with more variables, would be useful for operationalising the method further. But balancing site-specific knowledge and broad geographic analysis is a consistent tradeoff when studying trends in cities.

The identified areas that rank highly for both environmental risk and limited existing infrastructure are distant from the coast and its many affluent communities. Several are located in unincorporated areas outside of chartered city boundaries where LA County is a primary service provider for infrastructure and public programs. But the areas of East LA are quickly gentrifying, as soaring regional property values drive existing and new residents inland in search of more affordable housing. The long effort in recent decades to redevelop the LA River, too, is leading to the massive development and land speculation. With increased growth and higher land values, influxes of new residents will likely drive infrastructure improvements. For stormwater, this likely means local projects based on green infrastructure, especially given a countywide ordinance to promote new buildings to capture and infiltrate on-site up to a uniquely high volume of stormwater (LA RWQCB 2016).

Discussion

The ranking procedure used to identify priority areas for investments is demonstrative. Adapting it to other regions would require a survey of available data and regional goals. In practice, for a given region or watershed, developing a ranking procedure would necessarily include stakeholders such as government agencies, non-profits, community organisations and others in devising an agreed-upon procedure for identifying how to evaluate potential projects in the face of many needs and limited funds. Data availability in LA and California is also unique. Los Angeles is a highly modelled urban basin with excellent open-source data for land use, hydrology and infrastructure. The *CalEnviroScreen* tool provides an important resource for standardising rankings of sociodemographic information from the US Census and more difficult to compile data on environmental hazards and pollution. But, most urban areas have some sort of model to support regional stormwater planning, and US Census data are easily available in high detail. Thus, performing a similar analysis for other major metropolitan areas and sectors of infrastructure planning, tailored to support planning needs, is quite feasible. Improving open-source data availability and municipal expertise in basic statistical and geospatial analysis would significantly improve metropolitan planning capacity to promote EJ and equity.

Interpreting results requires contextual understanding. Stormwater systems are intuitively related to design parameters such as runoff coefficient. These parameters would result from both human actions to change landscapes and natural features such as topography. For instance, humans increase runoff coefficients by creating impervious surfaces, but more water will run off of hilly areas. Stormwater systems that correlate with building density also make sense, as urban development requires more engineered infrastructure of all types, including stormwater mitigation, to augment natural capacities that are altered or diminished through urbanisation.

Curiously, however, only underground sewers, and not surface channels, yield a model with a strong fit for design parameters and characteristics of buildings and land use. This could imply that past stormwater infrastructure decisions predominantly emphasised underground sewers, while surface conveyance channels were built by augmenting natural drainage channels. Indeed, many of the stormwater system outflows (for large storms) are natural channels that have been hardened, indicating how natural environments intimately influenced the development of urban infrastructure and morphology.

Environmental risks, such as living beside a natural flood channel that fills during large storms, are inherently tied to landscapes, even in urban areas. Risks can be mitigated, though not entirely prevented, through infrastructure. Decisions regarding placement of infrastructure are critical to creating equitable cities. As stormwater systems evolve, they will slowly change from centralised systems, relying primarily on runoff conveyance, to hybridised systems with green and grey infrastructure that emphasise on-site retention and infiltration to reduce large flows. During the investments that drive this shift, equity considerations will become even more important. Who controls, funds and maintains stormwater systems are critical. Municipalities facing budget constraints hope to offload some portion of stormwater management costs to the private sector through building codes, wrapping construction costs into long-term amortised mortgages that are paid off over decades. Yet, system maintenance costs are significant. Households and commercial building owners may not have financial resources or expertise to maintain landscapes. If on-site systems fall into disrepair, environmental degradation and flood risks ensue. Thus, distributing costs and responsibilities for stormwater system management can have unintended consequences for individual property owners, as well as localities that must meet stormwater management regulatory targets. Planning processes that address EJ in locating distributed stormwater infrastructure can help mitigate risks, but only through thoughtful involvement by municipalities and regulatory agencies.

The statistical analysis identified positive correlations between building density and sewer length, but not economic indicators such as land costs. This may have several explanations. The analysis used tax assessment data, which can be less accurate than actual real estate sales data (Sample et al. 2003; Thurston 2006). In addition, building density and land values are only moderately correlated in the region (Spearman's correlation: 0.55). Economic efficiency, i.e. building underground sewers in areas of high land costs, does not entirely explain the locations of storm sewers in LA County. Instead, standardised engineering practices likely emphasised sewers as the modern industrial metropolis expanded. As cities update stormwater systems with green infrastructure, however, land costs are often a major component of design discussions, especially comparing costs of green and grey designs.

Conclusions

An analysis of stormwater infrastructure in over 2000 sub-watersheds of LA County revealed explanatory variables correlated with storm sewer density and identified priority areas for multi-benefit stormwater investments. Statistically significant correlations exist between storm sewer infrastructure locations and hydrologic design parameters, land use and buildings, and sociodemographic indicators. Stormwater system design variables were intuitively a strong predictor of stormwater infrastructure locations. But sociodemographic variables were statistically significant though with lower R^2 values. Together, results imply that while engineering and hydrologic parameter estimates are strong factors in stormwater planning, sociodemographic variables, which are not often considered designing urban stormwater controls, also influence resultant systems. The analysis was limited in using estimates of design parameters based on empirical model inputs from the LA County WMMS model, which delineates small watersheds and associated hydrologic and land cover parameters.

The procedure for prioritising multi-benefit stormwater project investments revealed high-detail watershed areas with strong potential for multi-benefit outcomes that include reducing environmental risks faced by residents, both flooding and exposure to pollutants. Analysis with GIS identified small watersheds in LA County with high exposure to environmental risks but limited existing stormwater infrastructure. Several areas in central and eastern LA County have clusters of small watersheds that meet these criteria. Targeted implementations of green infrastructure designs and technologies could help reduce the risk of exposure to certain environmental hazards, making projects both equitable and economic.

The analysis framework can be extended by using more detailed rainfall-runoff modelling to identify areas of high flood risk, not just low presence of stormwater infrastructure, which correlate with areas of high exposure risk to pollutants. Broader, multi-disciplinary approaches such as these will be increasingly necessary as design goals for more sustainable stormwater infrastructure expand beyond reducing flood risks to include urban amenities, ecosystem services and social equity.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the U.S. National Science Foundation, Water Sustainability and Climate Program under Grant number 1204235.

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