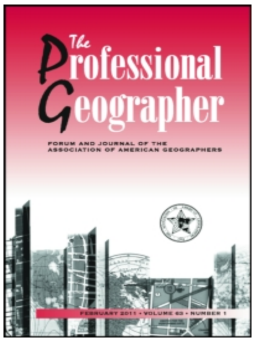


The Professional Geographer

ISSN: 0033-0124 (Print) 1467-9272 (Online) Journal homepage: https://www.tandfonline.com/loi/rtpg20

Assessing the Potential of Low-Impact Development Techniques on Runoff and Streamflow in the Templeton Gap Watershed, Colorado

Jeremy C. Tredway & David G. Havlick

To cite this article: Jeremy C. Tredway & David G. Havlick (2017) Assessing the Potential of Low-Impact Development Techniques on Runoff and Streamflow in the Templeton Gap Watershed, Colorado, The Professional Geographer, 69:3, 372-382, DOI: 10.1080/00330124.2016.1252272

To link to this article: https://doi.org/10.1080/00330124.2016.1252272

Published online: 15 Dec 2016.

Assessing the Potential of Low-Impact Development Techniques on Runoff and Streamflow in the Templeton Gap Watershed, Colorado

Jeremy C. Tredway and David G. Havlick
University of Colorado, Colorado Springs

This study examines how the impact of impervious surface in the Templeton Gap watershed (Colorado) could be reduced through the use of low-impact development (LID) strategies. LID is a sustainable stormwater approach to land management that retains runoff close to the source by preserving natural landscape features and limiting imperviousness. Our research indicates that LID techniques could reduce peak flows generated by stormwater runoff, allow city engineers to restore the stream channel to a more natural state, and improve the safety of residents and the security of property below the levee. This study developed a model of the Templeton Gap watershed and its associated stormwater infrastructure using the Stormwater Management Model (SWMM) developed by the U.S. Environmental Protection Agency (EPA). Specifically designed for small urban watersheds, SWMM allows users to accurately represent stormwater runoff dynamics and project the impact of hypothetical LID features such as porous pavement, rain gardens, and infiltration trenches on runoff and streamflow. **Key Words: geographic information system, low-impact development, stormwater management, Stormwater Management Model, urban development.**

本研究检视邓普顿鸿沟流域 (科罗拉多) 的不透水表面之影响, 如何能够透过使用低冲击发展 (LID) 策略进行减少。 LID 是土地管理的可持续暴雨方法, 该方法透过保存自然地景特徵和限制不透性, 将径流保留在其来源处附近。我们的研究显示, LID 技术能够减少暴雨径流产生的最大流量, 让城市工程师能够将河道回復至更自然的状态, 并促进低于堤岸的居民安全与财产保安。本研究运用由美国环境保护署 (EPA) 所发展的暴雨管理模型 (SWMM) , 建立邓普顿鸿沟流域及其相关暴雨基础设施的模型。 SWMM 特别为小型城市流域而设计, 让使用者能够精确地再现暴雨径流动态, 并推测诸如透水性铺面、雨水花园以及下渗沟的假设性 LID 特徵对径流与暴雨流的影响。 **关键词:地理信息系统, 低冲击发展, 暴雨管理, 暴雨管理模型, 城市发展。**

Este estudio examina cómo el impacto de una superficie impermeable en la cuenca de la Templeton Gap (Colorado) podría reducirse con el uso de estrategias de desarrollo de bajo impacto (LID). LID es un enfoque sustentable para el manejo del agua de tormenta en el suelo que retiene la escorrentía cerca de la fuente preservando los rasgos del paisaje natural y limitando la impermeabilidad. Nuestra investigación indica que las técnicas LID podrían reducir los picos de flujo generados por la escorrentía del agua de tormenta, permitiendo a los ingenieros de la ciudad restaurar el canal de la corriente a un estado más natural y mejorar la seguridad de los residentes y de la propiedad por debajo del dique o *levee*. Este estudio desarrolló un modelo de la cuenca de la Templeton Gap y su infraestructura asociada de agua de tormenta utilizando el Modelo para el Manejo de Aguas de Tormenta (SWMM) desarrollado por la Agencia de Protección Ambiental de los EE.UU. (EPA). Designado específicamente para pequeñas cuencas urbanas, el SWMM permite a los usuarios representar con exactitud la dinámica de escorrentía del agua de tormenta y proyectar el impacto de rasgos hipotéticos del LID, tales como pavimento poroso, lluvia en los jardines y zanjas de infiltración en la escorrentía y flujo de las corrientes. **Palabras clave: sistema de información geográfica, desarrollo de bajo impacto, manejo del agua de tormenta, Modelo del Manejo de Aguas de Tormenta, desarrollo urbano.**

Located in the precipitation shadow of Pikes Peak, the city of Colorado Springs averages forty-two centimeters of annual precipitation (Figure 1; U.S. Climate Data 2015). Since the late 1800s, the arid climate of Colorado Springs has attracted settlement, including tuberculosis sanitaria that lured clients from humid regions across the country. Despite this benign reputation, convective summer storms deliver intense rainfall and periodically cause serious flooding. One small watershed, Templeton Gap Wash, became notorious after a June 1921 rainstorm sent water surging into Fountain Creek, the main stream that flows through Colorado Springs; this was followed by a June 1922 event that inundated parts of the Templeton Gap watershed to a depth of 1.2 m. In May 1935, Templeton Gap flooded again, submerging 200 city blocks and pushing Fountain Creek to 1,415 cubic meters per second (CMS; base flow averages approximately 0.85 CMS). One summary identified nine major floods affecting Colorado Springs between 1864 and 1935 (Pikes Peak Regional Building Department n.d.), and many of these destroyed homes, damaged city infrastructure, and caused casualties in the Templeton Gap drainage area (U.S. Army Corps of Engineers 1948).

In response, the U.S. Army Corps of Engineers developed the Templeton Gap Flood Control Project to divert the stream and redirect it to Fountain Creek's largest tributary, Monument Creek. Begun in 1949, the levee at the heart of this project was designed to carry a peak flow of 396.44 CMS (based on estimates of peak

Initial submission, May 2016; revised submission, August 2016; final acceptance, August 2016.
Published by Taylor & Francis Group, LLC.

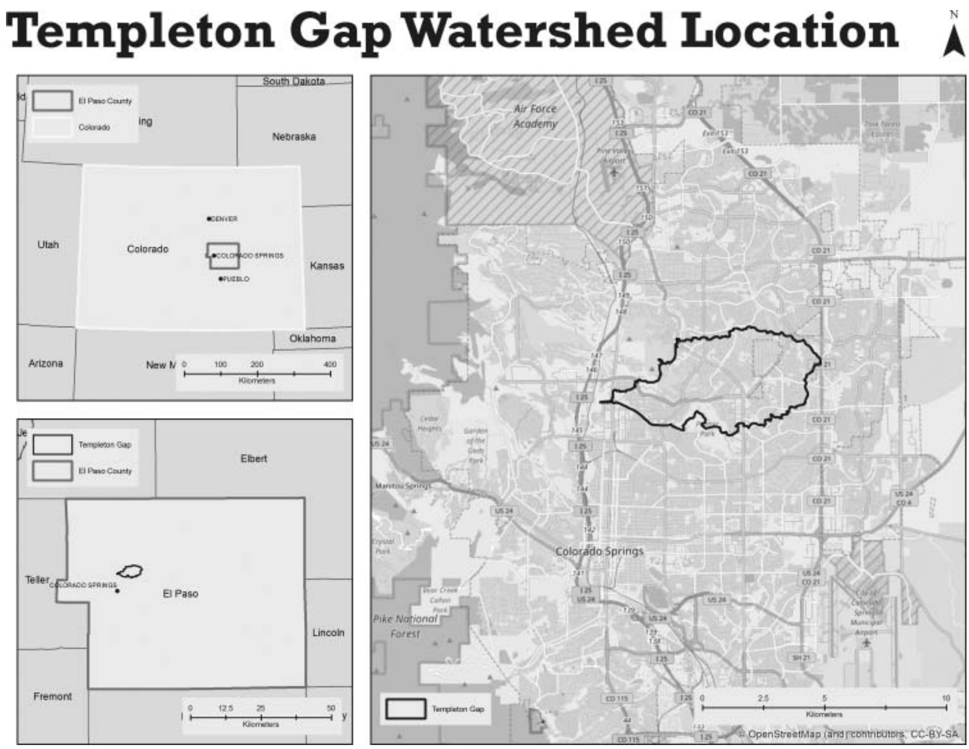


Figure 1 *The Templeton Gap Wash has undergone numerous changes as a result of urbanization.*

flow floods in Templeton Gap Wash and flow data from a nearby reference stream; see Anderson Consulting Engineers, Inc. and Lyman Henn, Inc. 2009). Since the levee's completion in 1952, related flood control projects have further channelized and hardened the stream.

Although there was little development in the Templeton Gap watershed when the levee was designed and constructed, the area has now become almost entirely urbanized. The corresponding increase in impervious surfaces has intensified the flashiness of the stream and amplified the strain on the levee. As a result, the Federal Emergency Management Agency declined to extend accreditation of the levee in 2009 as part of its Digital Flood Insurance Rate Map (DFIRM) initiative in the wake of Hurricane Katrina. To receive accreditation, the city must prove that the levee is capable of handling peak flows from a 100-year storm but, unfortunately, the levee accreditation plan commissioned by the City of Colorado Springs revealed that portions of the levee lacked the requisite freeboard for accreditation (Anderson Consulting Engineers, Inc. and Lyman Henn, Inc. 2009). Consequently, residents and business owners below the levee faced losing coverage under the National Flood Insurance Program (NFIP), potentially costing them about $3 million annually in insurance premiums.

This study examines how the effects of impervious surfaces could be reduced through the use of low-impact development (LID) strategies. LID is a sustainable stormwater approach to land management that retains runoff close to the source by preserving natural landscape features and limiting imperviousness (U.S. Environmental Protection Agency [EPA] 2015).

Urban streams, in general, are often more prone to unnaturally large and fast flows (Walsh et al. 2005). These and other characteristics of stream ecosystems in cities are captured under the umbrella term *urban stream syndrome* (Walsh et al. 2005; Wenger et al. 2009). As a common response to development and land use changes, urban streams frequently experience high levels of pollution, changes to the width and depth of their stream channels, and a decrease in the variety of species they can support. Stormwater runoff from impervious surfaces, deforestation, stream and floodplain encroachment, channel modifications, direct and indirect source pollution, and the heat island effect are drivers of urban stream syndrome (Walsh et al. 2005; Wenger et al. 2009; Everard and Moggridge 2012). Impervious surface cover, however, might be the most common contributor to and dominant determinant of hydrologic and geomorphic degradation.

Traditional engineering responses to flood and erosion—channelizing, culverting, riprapping, and clearing vegetation—often come in direct conflict with the environmental health of urban riparian areas (Riley 1998). Additionally, these remedies are typically expensive, fail to address the source of stream degradation, and instead displace symptoms farther downstream. A City of Colorado Springs Stormwater Needs Assessment Final Report completed in October 2013 identified Templeton Gap Floodway infrastructure replacement and levee reconstruction as a high priority for the city due to the risk to property and public health and safety. The study projected that the necessary upgrades for levee accreditation would cost more than $10 million (CH2MHILL 2013). Colorado Springs has already spent millions of dollars since completion of the levee channelizing, hardening, and diverting Templeton Gap Wash in the name of public safety. Hard engineering solutions, such as confining the wash to a trapezoidal channel, disrupt natural processes and have left the stream devoid of ecological, aesthetic, and recreational value, even as they have also failed to guarantee the safety of residents or protect property below the levee.

To date, city planners have primarily explored strategies such as raising the levee walls, excavating and regrading the channel floor, installing drop structures, and removing riparian vegetation that will further disrupt natural processes and require continual upgrades and maintenance without addressing the needs of the stream or the source of degradation. Not only do these alternatives fail to address the fundamental issues causing stream degradation but they are likely to propagate further imbalances downstream.

This study developed a model of the Templeton Gap watershed and its associated stormwater infrastructure using the Stormwater Management Model (SWMM) developed by the U.S. EPA. Specifically designed for small urban watersheds, SWMM allows users to accurately represent stormwater runoff dynamics and project the impact of hypothetical LID features such as porous pavement, rain gardens, and infiltration trenches on runoff and streamflow. The SWMM hydrologic model is a physics-based, distributed, deterministic rainfall-runoff simulator capable of modeling runoff quality and quantity from event-based or continuous precipitation (Rossman 2010). We chose SWMM for this study because the software is free, capable of modeling the potential effects of LID devices on water quantity, and meets the minimum requirements of the NFIP.

The EPA first designed SWMM in 1971 primarily to analyze sewer and stormwater systems in small, urban catchments, but the model has since been applied to nonurban areas as well (Gironas, Roesner, and Davis 2009). It is commonly used for drainage system design, flood control, flood plain mapping, nonpoint source pollutant investigations, and best management practice evaluations (Rossman 2010). Jia et al. (2012), Lee, Hyun, and Choi (2013), Doubleday et al. (2013), and Qin, Li, and Fu (2013) each applied SWMM specifically to analyze LID techniques.

Study Area

Located northeast of downtown Colorado Springs, Templeton Gap watershed runs southwest 10.5 km to its post-1950 confluence with Monument Creek. Templeton Gap Wash drains 13.7 km and drops 213.4 m from its highest point to its low point at Monument Creek. More than 80 percent of the area's precipitation typically occurs between April and September. Since data have been collected, the highest annual precipitation in the area was 70.1 cm in 1999; the lowest was 15.4 cm in 1939. The record one-day precipitation of 11.4 cm occurred on 14 September 2011 and resulted in an estimated peak flow of approximately 226.53 CMS. The highest twenty-four-hour precipitation event recorded in the area was 12.6 cm recorded from 11 to 12 September 2008. The Templeton Gap rain gauge operated by the U.S. Geological Survey (USGS), which began collecting data 6 March 2011, has recorded other intense rainfall events of 9.5 cm on 6 June 2012 and 13.8 cm over thirty-one hours from 12 to 13 September 2013.

Model Setup

To apply SWMM, the Templeton Gap watershed was divided into subcatchments and labeled in accordance with geographic data received from the City of Colorado Springs (Figure 2). SWMM can technically be applied with as little or as much information as the user wants to provide, but dividing the watershed into subcatchments allows for greater detail and accuracy. We then extracted the area for each subcatchment from the attributes table generated for each polygon in ArcGIS 10.2.1 (Desktop Release 10.2.1, Esri, Redlands, CA, USA). The subcatchment width parameter was determined by dividing the area by the length of the longest overland flow path or an average if there were multiple representative lengths. This study assumed 152.4 m to be the maximum overland flow path length for natural areas as recommended by the SWMM applications manual (Gironas, Roesner, and Davis 2009). For residential areas, the length was measured from the back of a representative lot to the center of the street. For urban features such as shopping centers, 15.2 m was assumed to be the maximum distance sheet flow could travel before being directed into open channels or pipes. The subcatchment slopes were calculated using a basic rise over run equation from the flow path's highest point to the outlet. The rise was calculated using elevation data from the Pikeview and Falcon NW Quadrangles produced by the USGS (2013a, 2013b); contour intervals are 6.1 m. The run was estimated using the ArcGIS measure tool.

To calculate imperviousness, we used GeoEye-1 and WorldView-2 images collected 17 June 2012 and a supervised maximum likelihood classification technique to create land cover maps depicting pervious and impervious surfaces (Figure 3; IDRISI Selva GIS, image processing software version 17.02, Clark Labs, Worcester, MA, USA). Neither of the available images covered the entirety of the study area and we did not have access to a complete image; however, Aguilar et al. (2014) showed that GeoEye-1 and WorldView-2 images are geometrically and radiometrically similar enough for use in the same study.

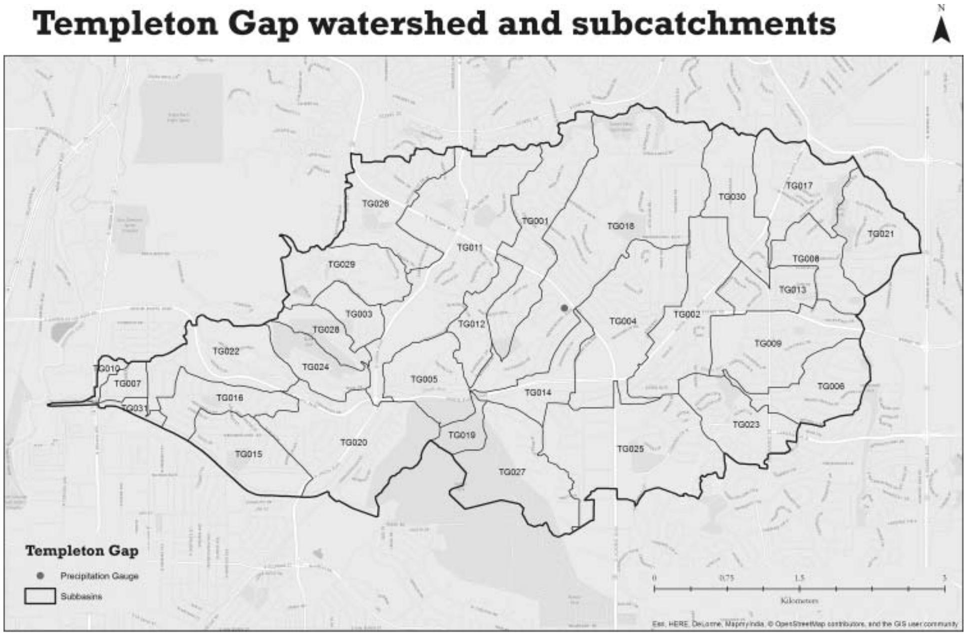


Figure 2 *Templeton Gap watershed and subcatchments.*

Multispectral classification of very high-resolution imagery has been shown elsewhere to be a useful tool for delineating land cover types in urbanized watersheds (e.g., Yuan and Bauer 2006; Chen, Ning, and Zhang 2012; Ribeiro and Fonseca 2012; Fernandez-Luque et al. 2013; Taherazedah and Shafri 2013).

To verify the accuracy of the classifications, 100 random points were generated within the watershed boundary using ArcMap (Figure 4) and verified for land cover type in the field using a Trimble GeoXT handheld Global Positioning System (GPS) receiver. The classification of the GeoEye-1 data resulted in an

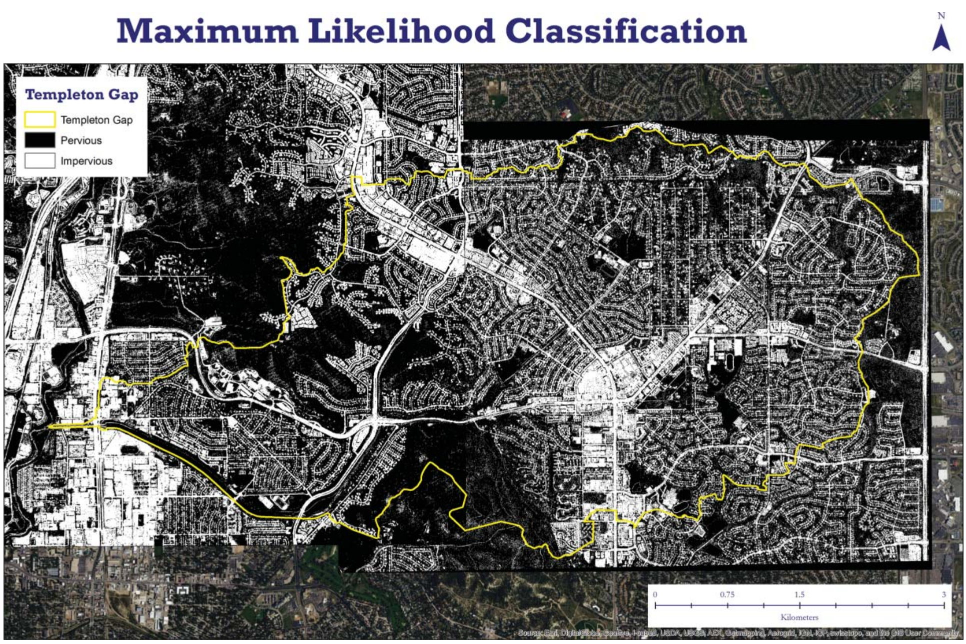


Figure 3 *A maximum likelihood classification of the western portion of the catchment was created using GeoEye-1 data collected 17 June 2012. The classification resulted in an overall accuracy of 87.5 percent. Additionally, a maximum likelihood classification of the eastern section of the watershed was created using WorldView-2 data collected 17 June 2012. The classification resulted in an overall accuracy of 79 percent. (Color figure available online.)*

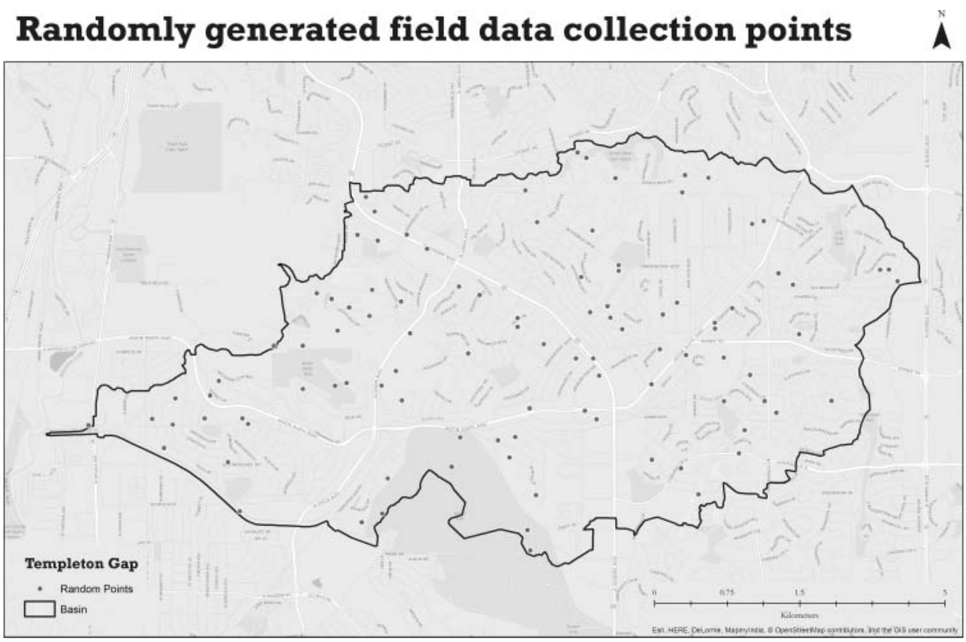


Figure 4 *To verify the accuracy of the classifications, 100 random points were generated within the watershed boundary using ArcMap and verified for land cover type in the field using a Trimble GeoXT handheld Global Positioning System receiver.*

overall accuracy of 87.5 percent with an 82.8 percent accuracy for pervious areas, a 100 percent accuracy for impervious areas, and a kappa score of 72.5. The classification of the WorldView-2 data resulted in an overall accuracy of 79.0 percent with 80.6 percent accuracy for pervious areas and 78.0 percent accuracy for impervious areas and a kappa score of 56.9. We imported the classified images into ArcGIS and then divided the number of impervious pixels by the total number of pixels for each subwatershed and multiplied by 100 to render a percentage imperviousness.

The subcatchment roughness coefficients for the amount of resistance encountered by overland flow were determined using field data and the roughness coefficients (Manning's *n*) for sheet flow table found in Urban Hydrology for Small Watersheds Technical Release-55 (Natural Resources Conservation Service 1986). The subcatchment depression storage was derived using field data and the Depression Storage chart found in Appendix A of the SWMM User's Manual (Rossman 2010). The percentage of impervious area without depression storage variable was set to 25 percent per the SWMM Applications Manual (Gironas, Roesner, and Davis 2009). Subarea routing was set to route stormwater from impervious surfaces to pervious surfaces. Because the watershed features residential buildings that are nearly surrounded by impervious surfaces, completely bordered by pervious surfaces, and just about every combination in between, this study assumed that approximately 50 percent of precipitation that falls on residential structures runs off onto pervious surface. Subsequently, the area of residential structures was calculated using ArcMap and 50 percent of that value was entered as the subarea routing value. The curve number method was selected as the infiltration model and values were assigned based on numbers derived for the Templeton Gap Hydrology Study (City of Colorado Springs 2008).

This study uses a single USGS-operated rain gauge to apply precipitation data to the watershed (Figure 2). The rain gauge rainfall data type was set to volume using input time series for 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, and 500-year storms with a five-minute recording time interval. Storm rainfall depths were provided by the City of Colorado Springs and design storms were constructed in accordance with the National Resource Conservation Service's (n.d.) Type II twenty-four-hour rainfall distribution curve.

Because this study is not concerned with the capability of the stormwater infrastructure to handle design storms, the conveyance system was purposely oversized so that all runoff is routed to the outfall. Conduits were configured as trapezoidal open channels using width, depth, and side slope data loosely based on the City of Colorado Springs (2008) Templeton Gap Hydrology Study. Subsequently, the smallest channels were built with a width of 10 feet, depth of 15 feet, and side slopes of 1 (ratio represents horizontal to vertical distance) and gradually increased in size to the largest channels, which were built with a width of 125 feet, depth of 25 feet, and side slopes of 2.

Initial Simulations

Using the dynamic wave routing model, this study modeled watershed response to 2-year, 5-year, 10-

Table 1 *Templeton Gap initial simulation results*

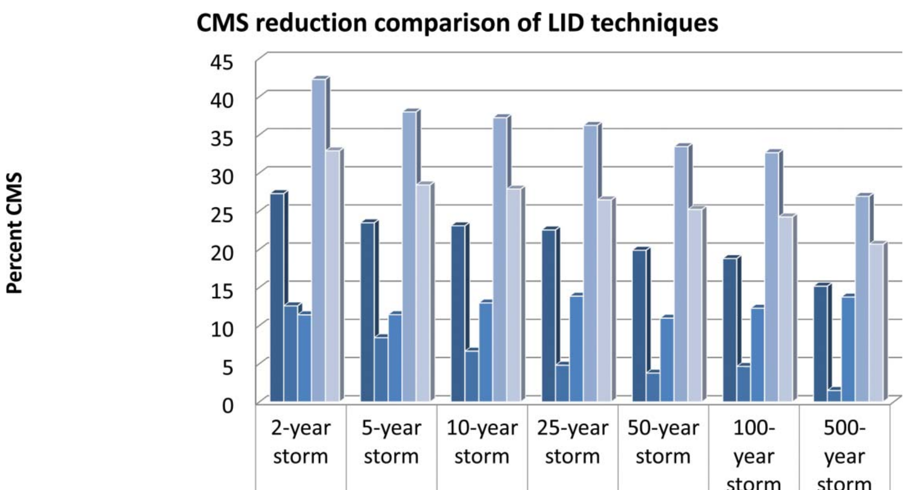
Design storm	Predicted (cm)	Modeled (cm)	Percentage difference
Austin Bluffs			
2-year	77.02	85.53	9.95
5-year	134.22	146.48	8.37
10-year	176.41	192.53	8.37
25-year	266.18	291.07	8.55
50-year	313.75	339.18	7.50
100-year	362.46	384.85	5.82
500-year	473.74	454.49	−4.24
Union Boulevard			
2-year	79.85	89.53	10.81
5-year	139.89	160.63	12.91
10-year	183.78	212.43	13.49
25-year	278.64	308.22	9.60
50-year	327.91	353.1	7.13
100-year	379.45	405.78	6.49
500-year	497.24	505.89	1.71
Monument Creek			
2-year	77.3	77.14	−0.21
5-year	137.05	137.57	0.38
10-year	181.79	185.8	2.16
25-year	279.2	288.86	3.34
50-year	330.17	333.82	1.09
100-year	381.99	381.2	−0.21
500-year	505.74	467.17	−8.26
	Continuity error percent		
Design storm	**Runoff**	**Routing**	
2-year	−2.06	−0.06	
5-year	−2.27	−0.03	
10-year	−2.36	−0.02	
25-year	−2.50	−0.02	
50-year	−2.55	−0.03	
100-year	−2.60	−0.04	
500-year	−2.67	−0.04	

year, 25-year, 50-year, 100-year, and 500-year storms and compared the results to the predicted peak discharge values calculated by the City of Colorado Springs (2008) Templeton Gap Hydrology Study, which used the Hydrologic Modeling System model (Table 1). The same simulations of storm events were run for each of the LID treatments considered, as well as combined LID techniques (Figure 5).

Low-Impact Development Simulations

Because there are limitless possible LID configurations within any particular watershed, one study cannot begin to consider all of them. At the time of the study, rainwater capture beyond seventy-two hours was prohibited in most cases under Colorado water law, so only infiltration and evapotranspiration options were considered. Although green roofs are permitted, the watershed is fully developed and many built structures might not support vegetated roofs. Therefore, they were eliminated from consideration.

In subwatersheds dominated by commercial and institutional uses, this study examined the potential for the use of pervious pavement in parking lots. Parking lots account for more than 8 percent of land cover in the Templeton Gap watershed and up to 54 percent of impervious surfaces in some subcatchments. Additionally, pervious pavement devices can be designed to infiltrate stormwater that falls directly onto their surface and that of neighboring buildings. If runoff from the stores, offices, and schools surrounding parking



	2-year storm	5-year storm	10-year storm	25-year storm	50-year storm	100-year storm	500-year storm
Pervious Pavement	27.3	23.48	23.08	22.54	19.88	18.79	15.17
Rain Gardens	12.59	8.42	6.65	4.81	3.78	4.65	1.5
Stream Naturalization	11.42	11.44	12.97	13.85	10.97	12.28	13.75
Combined LID	42.27	38	37.24	36.24	33.45	32.66	26.94
50% Combined LID	32.9	28.43	27.89	26.47	25.22	24.24	20.66

Figure 5 *Cubic meters per second reduction comparison of modeled low-impact development techniques. CMS = cubic meters per second; LID = low-impact development. (Color figure available online.)*

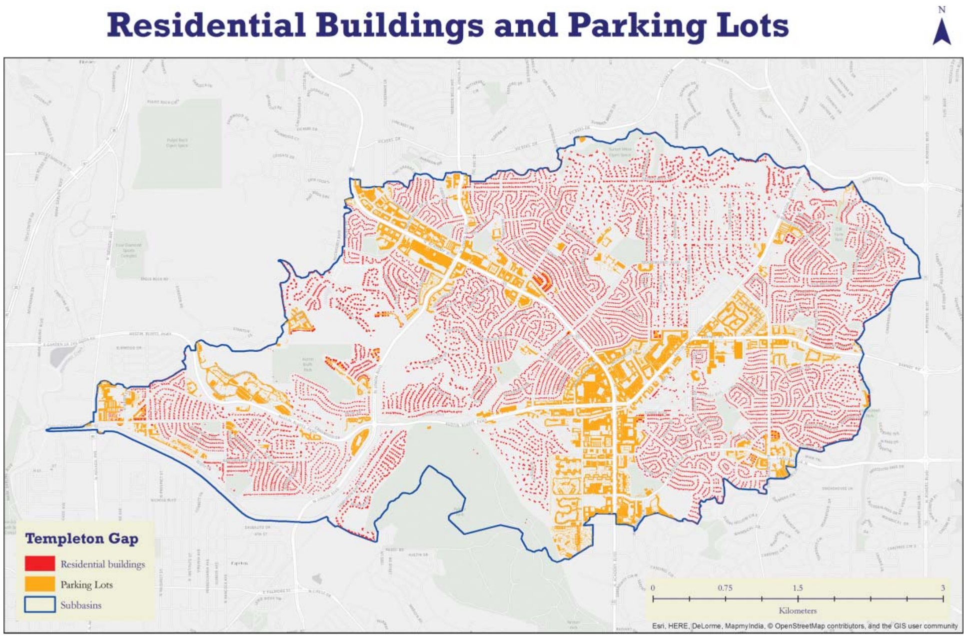


Figure 6 *Residential buildings and parking lots in the Templeton Gap watershed. (Color figure available online.)*

lots in the watershed is routed to infiltrate into the pervious pavement devices, up to 76 percent of impervious surfaces in some subwatersheds can be effectively treated.

In housing areas, this study looked at the potential impact of small, residential rain gardens. Houses, garages, and sheds occupy more than 8 percent of land cover in the Templeton Gap watershed and account for more than 45 percent of impervious surfaces in some subwatersheds. This study also converted hardened and straightened stream channels to natural stream channels to assess the impact of slowing the transport of water on peak discharge in Templeton Gap.

Pervious Pavement

To isolate parking lots in the watershed, we subtracted the Templeton Gap buildings layer provided by the City of Colorado Springs from the impervious surfaces layer using the clip feature in ArcMap. Then residential driveways and other remaining polygons that did not qualify as parking lots were manually edited out. Next, we used the resultant layer file and subwatershed layers to separate the parking lots into subcatchments using the intersect feature in ArcGIS. Finally, we used ArcGIS to calculate the sum area of parking lots in each subwatershed, manually counted parking lots, and divided the total area for each subwatershed into equal parts (Figure 6).

After determining the amount of parking lot area in each subwatershed, we composed a simple permeable pavement device to be used on all parking lot surfaces using the value ranges outlined in the SWMM user's manual (Rossman 2010). The device was built with a surface roughness of 0.1, typical of a parking lot, and a surface slope of 1.0 percent for appropriate infiltration. The pavement thickness was set to 10.2 cm with a void ratio of 0.15 and a permeability of 254 cm per hour. An underlying storage area was created with a thickness of 30.5 cm, a void ratio of 0.75, and a seepage rate of 25.4 cm per hour. An underdrain was not used for the device. This device was applied to all parking lot surfaces in each subwatershed and impervious surfaces were correspondingly decreased for the amount of area now occupied by pervious pavement. Finally, impervious surfaces from neighboring schools, offices, and commercial buildings were routed to be infiltrated by the pervious pavement devices.

Rain Gardens

To ascertain the potential impact of rain gardens, we assumed that each homeowner in the watershed would install a rain garden. Residential buildings were divided into subwatersheds using the intersect feature in ArcMap with the Templeton Gap buildings and subcatchment layers. Then we edited out schools, businesses, and other polygons that did not qualify as residential buildings. Apartment complexes and university dormitories were also edited out because pervious areas are typically inadequate and a reduction in impervious surfaces through pervious pavement would have a greater impact. Next, we calculated the sum area of residential buildings in each subwatershed using ArcGIS, counted the number of houses, and divided the total area for each subwatershed into equal parts (Figure 6).

After determining the area occupied by residential buildings in each subwatershed, we composed a basic rain garden device in SWMM for all residential units. The device was built with an area of 13.9 m^2 and a berm height of 20.3 cm. Using ArcGIS and U.S. Census Bureau new single-family housing data (n.d.), we estimated average home size in Colorado Springs to be approximately 185.8 m^2. We applied rain garden size calculations developed by the Colorado Stormwater Center (2013) and Wisconsin Department of Natural Resources (2003) to estimate the rain garden area necessary to capture runoff from the average roof. Finally, we used ArcGIS to ensure the average front lawn would accommodate a 13.9 m^2 rain garden. The thickness of the soil was set to 61 cm with a void ratio of 0.5 and a field capacity of 0.2. The wilting point was set to 0.1, conductivity was fixed to 5.1 cm per hour, conductivity slope was programmed to 10, and the suction head was established as 3.5. These numbers are representative of an average loam soil type (Rossman 2010). Although an amended soil could achieve a better infiltration rate, we did not assume that all homeowners would be willing to pay the added cost of excavation. Finally, impervious surfaces from residential buildings were routed to be infiltrated by the rain garden devices.

Stream Naturalization

To assess the impact of naturalizing stream channels in the Templeton Gap watershed, the surface roughness coefficient of open stream channels was adjusted to 0.45 to represent channels with tall grasses, brush, and trees (Rossman 2010). Stream channels downstream of Austin Bluffs Parkway were not considered in this simulation because they are part of the Templeton Gap levee and are required to be cleared of vegetation.

Combined and Combined 50 Percent LID Techniques

To assess the impact of using pervious pavement, rain gardens, and natural stream channels, the three preceding techniques were applied simultaneously. It is unlikely, however, that all businesses and institutions will replace their existing parking lots with pervious pavement or that all residents will install rain gardens. Therefore, we also reduced the amount of parking lot area converted to pervious pavement and residential rain gardens installed by half for a more realistic scenario. Although there is a substantial and growing amount of literature on stakeholder valuation of, support for, and participation in watershed conservation, restoration, and LID programs (Lichtenberg 2004; Shaw et al. 2011; Bowman et al. 2012; Kaplowitz and Lupi 2012; Larson, Caldwell, and Cloninger 2014), these questions are beyond the scope of this study. Stakeholder attitudes or motivations were not considered, nor did we determine the level of stakeholder participation that would be necessary to make pervious pavement or rain gardens successful LID alternatives. Fifty percent is simply an entry point to determining whether some participation could make a significant impact toward restoring the Templeton Gap hydrograph. These issues should be further explored in future research.

LID Results

According to our LID simulations, each of the treatment types resulted in substantial reductions in stormwater runoff. Of the five scenarios tested, stream naturalization by itself was the least effective for a 2-year event, with a peak flow reduction of 11.4 percent, but this increased to a 13.8 percent reduction for a 500-year storm. Rain gardens are projected to reduce peak runoff by just 1.5 percent for a 500-year event, but their effect increases to a 12.6 percent reduction for 2-year storms. Pervious pavement is more effective still, ranging from a 15.2 percent reduction for a 500-year event to a 27.3 percent reduction for 2-year storms. The combined LID treatment using all three of these techniques provided the most significant reduction in peak flows; these ranged from a 26.9 percent reduction for 500-year events to a 42.3 percent reduction for 2-year storms. The combined 50% simulation generated reductions ranging from 20.7 percent in 500-year storms to 32.9 percent reductions for 2-year events (see Table 2 and Figure 5).

Looking at the common planning standard of a 100-year storm, the simulations for pervious pavement (309.71 CMS), rain gardens (363.61 CMS), natural steam channels (334.52 CMS), combined LID techniques (256.79 CMS), and the 50 percent combined LID techniques (288.93 CMS) each produced peak discharge volumes below the 396.44 CMS levee design threshold. Additionally, the combined simulation produced a peak discharge below the 369.44 CMS threshold for a 500-year storm at 341.16 CMS, and the 50 percent combined LID simulation came in just above the threshold at 370.46 CMS. These are represented by percentage of reduction in Table 2.

Table 2 *Cubic meters per second reduction comparison of modeled low-impact development techniques for 100-year storm events*

Device	Pervious pavement	Rain gardens	Stream naturalization	Combined LID	Combined 50% LID
% reduction	18.8%	4.7%	12.3%	32.7%	24.2%

Note. LID = low-impact development.

Discussion

Unlike typical stormwater structures, which are designed to handle runoff generated by extreme storm events over large areas, LIDs mitigate runoff from a particular developed site for a range of storm events. As our results indicate, not all LID techniques function similarly across varying streamflow dynamics. Stream naturalization, for example, creates relatively minor reductions in flow for minor (2-year) precipitation events, but increases in efficacy for large 500-year storms. Conversely, rain gardens and pervious pavement can become fully saturated and less effective during extreme storm events but respond very well to lighter, more common storms conducive to infiltration or evapotranspiration.

LID structures feature one of three types of runoff reduction techniques: (1) infiltration, (2) evapotranspiration, or (3) capture and reuse. Infiltration measures include pervious pavements and pavers with underlying infiltration systems. Bioremediation structures (evapotranspiration) include rain gardens, swales, and vegetated roofs. Capture and reuse includes storage systems for collecting rainwater where it falls. In addition to structural measures, there are many nonstructural LID concepts that can be incorporated into watershed management plans. The basic concept of nonstructural LID measures is to prevent problems created by land development by reducing the amount of impervious surface required, limiting site disturbance, and using less space. Most of these techniques, though, need to be incorporated into plans prior to site development. Therefore, nonstructural LID measures have limited applicability in developed watersheds like Templeton Gap but should be integrated into future redevelopment projects. Nonetheless, the City of Colorado Springs and similar urban settings could achieve cost-effective, quantifiable benefits by disconnecting rooftops and impervious surfaces from the stormwater system, restoring compacted soils, and vegetating denuded areas.

To assess the accuracy of the model, we modeled discharge for three separate precipitation events recorded by the Templeton Gap Precipitation gauge and compared the results to stream discharge measurements we recorded in the field. The field-collected discharge data matched poorly with the SWMM-generated streamflow estimates, however. The results were on average 25 percent different. This could be due to a number of generalizations and assumptions made by this study and the software during the construction of the model. Because this study uses precipitation data from a single rain gauge, the model assumes that precipitation intensity and volume are spatially and temporally distributed evenly across the region when it is unlikely that this occurs, given the topographic heterogeneity of the region. Similarly, this study averaged and generalized slope, roughness, and permeability across topographically diverse regions and dissimilar land covers. Additionally, this study used impervious surface data from 2010 but took stream discharge measurements in 2013 and 2014. Therefore, the difference between predicted and measured discharge values might reflect changes in the watershed over that time. Finally, this study could have oversimplified the hydraulic infrastructure resulting in erroneous conveyance of runoff from subcatchment to downstream areas. The most likely reason for the discrepancy, however, is the fact that this study received most of its time lag data from the 2008 Templeton Gap Hydrology Study commissioned by the City of Colorado Springs. Subsequently, this study's model closely resembles the city's model but might not as directly represent the reality of the watershed. Because we envisioned City of Colorado Springs planners referencing this study in future policy decisions, it was important for our study to resemble the city's study.

Future studies should work to further develop the relationship between precipitation and discharge in the watershed by refining the model's variables. More accurate precipitation and streamflow data will enable calibration of future models. Furthermore, future studies should work to develop a relationship between the geographic distribution and placement of LID devices and the impact on overall discharge in the watershed. Despite these limitations and future research needs, results from this study indicate that the model is capable of making general predictions about the potential impact of using LID techniques in Templeton Gap. Similar techniques should be applicable in other urban drainages to assess the likely benefits of LID to reduce stormwater impacts.

There is a growing call from engineers, floodplain managers, and urban and downstream residents for cities to adopt a "no adverse impact" approach to development that challenges land owners to use their property in a manner that does not harm downstream property owners through increased flood risk and loss of development potential (DeLaria 2008; Urban Drainage and Flood Control District [UDFCD] 2008a). The effort shifts the focus of stormwater management from construction of drainage structures and stabilization projects in the right of way to requiring developers to mimic predevelopment hydrology through onsite runoff reduction and infiltration practices (DeLaria 2008; Rocky Mountain Land Use Institute 2009).

From a stormwater management perspective, small-scale, site-specific LID techniques spread across the watershed provide advantages over traditional "end-of-pipe" techniques that quickly route runoff to the nearest receiving waters. LID techniques reduce pollution and flooding without continuing to destabilize the receiving waterway, thereby avoiding the endless succession of drainageway projects to increase channel capacity and stability typically associated with traditional "hard engineering" solutions (DeLaria 2008; UDFCD 2008a).

For developers, LID techniques can represent a cost savings on the construction and maintenance of stormwater collection and conveyance infrastructure (DeLaria 2008; UDFCD 2008a). Developers might also benefit from stormwater fee discounts, open space credits, increased property values, greater marketability, and recognition within the community (UDFCD 2008a). Rain gardens, landscape islands, and permeable pavement systems can add character to gardens, plazas, rooftops, and parking lots, while mirroring community design goals and helping to create safe, pedestrian-oriented neighborhoods.

Additionally, the installation of LID techniques might qualify communities for flood insurance premium discounts through the NFIP in recognition of their flood damage reduction and water quality protection efforts (UDFCD 2008a). LID requires stormwater managers to modify their approach to land development design and to seek innovative methods for minimizing directly connected impervious surfaces, slowing the rate of runoff, decreasing runoff volumes, lessening peak flows, and promoting infiltration and filtering of precipitation (Rocky Mountain Land Use Institute 2009). Otherwise, local governments will find themselves trapped in a financially draining, positive feedback loop in which traditional drainage-based development necessitates continued capital improvement projects while further degrading water quality and riparian habitat.

Conclusions

The results of the SWMM simulations indicate that pervious pavement, rain gardens, and stream naturalization can be viable alternatives to further hardening, diversion, and channelization of the Templeton Gap watercourse. More broadly, our analysis suggests that site-specific, infiltration-based LID devices can be appropriate measures for offsetting the effects of urbanization on stormwater runoff in the Templeton Gap watershed. Although the watershed is fully developed, much of the infrastructure is aging and actively being replaced and modernized. City planners should encourage or require developers to consider LID devices as they redevelop the watershed. Although these measures do not directly address deficiencies in the performance of the levee system, implementing LID techniques in the catchment can reduce the severity of peak flows, reduce the likelihood of flooding, and satisfy Federal Emergency Management Agency accreditation requirements for requisite freeboard. The simulations performed in SWMM focused on water quantity, but installing LID devices will also improve stream function, aesthetics, and recreational value. Increasing the amount of stormwater infiltrated on site will reduce erosion, periods of abnormally low flow, and flooding downstream. ■

Notes

[1]Model parameters were calculated per the Storm Water Management Model User's Manual (Rossman 2010) and Applications Manual (Gironas, Roesner, and Davis 2009) using data provided by the City of Colorado Springs City Engineer Office unless otherwise stated.

[2]Dynamic wave routing theoretically produces the most accurate flow routing results. It solves the one-dimensional Saint Venant open-channel flow and surface runoff equations and can account for channel storage, backwater, entrance and exit losses, flow reversal, and pressurized flow (Gironas, Roesner, and Davis 2009).

[3]Suction head refers to a soil's ability to move water through capillary action without the aid of gravity.

Literature Cited

Aguilar, M. A., M. del Mar Saldana, F. J. Aguilar, and A. G. Lorca. 2014. Comparing geometric and radiometric information from GeoEye-1 and WorldView-2 multispectral imagery. *European Journal of Remote Sensing* 47:717–38.

Anderson Consulting Engineers, Inc. & Lyman Henn, Inc. 2009. *Templeton Gap flood control channel levee accreditation plan*. Colorado Springs, CO: Anderson & Lyman Henn.

Bowman, T., J. C. Tyndall, J. Thompson, J. Kliebenstein, and J. Colleti. 2012. Multiple approaches to valuation of conservation design and development features in residential subdivision. *Journal of Environmental Management* 104:101–13.

CH2MHILL. 2013. City of Colorado Springs stormwater needs assessment final report. http://www.springsgov.com/SIB/files/COS_Stormwater_Needs_Assessment_Report_10-11-13_FINAL.pdf (last accessed 21 November 2016).

Chen, Z., X. Ning, and J. Zhang. 2012. Urban land cover classification based on WorldView-2 image data. Paper presented at the 2012 International Symposium on Geomatics for Integrated Water Resources Management, Lanzhou, Gansu, China.

City of Colorado Springs. 2008. *Templeton Gap hydrology study*. Colorado Springs, CO: City of Colorado Springs.

Colorado Stormwater Center. 2013. Building a rain garden in Colorado. http://stormwatercenter.colostate.edu/wp-content/uploads/2013/05/Colorado-Rain-Garden-Guide1.pdf (last accessed 21 November 2016).

DeLaria, M. 2008. Low impact development as a stormwater management technique. http://www.law.du.edu/images/uploads/rmlui/rmlui-sustainable-RMLUILowImpactDevelopment.pdf (last accessed 21 November 2016).

Doubleday, G., A. Sebastian, T. Luttenschlager, and P. B. Bedient. 2013. Modeling hydrologic benefits of low impact development: A distributed hydrologic model of the Woodlands, Texas. *Journal of the American Water Resources Association* 49 (6): 1444–55.

Everard, M., and H. L. Moggridge. 2012. Rediscovering the value of urban rivers. *Urban Ecosystems* 15:293–313.

Fernandez-Luque, I., F. Aguilar-Torres, M. Aguilar-Torres, F. Alvarez-Taboada, and M. Saldana-Diaz. 2013. Impervious surface areas classification from GeoEye-1 and WorldView-2 Imagery through OBIA approach in a coastal area of Almeria (Spain). Paper presented at the 6th EARSeL Workshop on Remote Sensing of the Coastal Zone, Matera, Italy.

Gironas, J., L. A. Roesner, and J. Davis. 2009. *Storm Water Management Model applications manual*. Cincinnati, OH: U.S. Environmental Protection Agency National Risk Management Research Laboratory Office of Research and Development.

Jang, S., M. Cho, J. Yoon, Y. Yoon, S. Kim, G. Kim, L. Kim, and H. Aksoy. 2007. Using SWMM as a tool for hydrologic impact assessment. *Desalination* 212 (1–3): 344–56.

Jia, H., Y. Lu, S. L. Yu, and Y. Chen. 2012. Planning of LID-BMPs for urban runoff control: The case of Beijing Olympic Village. *Separation and Purification Technology* 84:112–19.

Kaplowitz, M. D., and F. Lupi. 2012. Stakeholder preferences for best management practices for non-point source pollution and stormwater control. *Landscape and Urban Planning* 104:364–72.

Larson, K. M., J. Caldwell, and A. Cloninger. 2014. Examining potential residential participation in financial incentives to mitigate impervious surface effects in Howard County, Maryland. *Suburban Sustainability* 2 (1): 2.

Lee, J., K. Hyun, and J. Choi. 2013. Analysis of the impact of low impact development on runoff from a new district in Korea. *Water Science & Technology* 68 (6): 1315–21.

Lichtenberg, E. 2004. Cost-responsiveness of conservation practice adoption: A revealed preference approach. *Journal of Agricultural and Resource Economics* 29 (3): 420–35.

Natural Resources Conservation Service. 1986. Urban hydrology for small watersheds. Technical Release 55, U.S. Department of Agriculture, NRCS, Washington, DC.

———. n.d. Transforming 24-hour SCS rainfall distributions to shorter durations. https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H%26H/rainDist/SCSrainfallDistTimeTransformations.xlsx (last accessed 22 November 2016).

Pikes Peak Regional Building Department. n.d. Significant flood events in the Pikes Peak region throughout the past century. http://www.pprbd.org/flood_files/History_of_Flooding_in_the_Pikes_Peak_Region.pdf (last accessed 8 May 2016).

Qin, H., Z. Li, and G. Fu. 2013. The effects of low impact development on urban flooding under different rainfall characteristics. *Journal of Environmental Management* 129:577–85.

Ribeiro, B. M. G., and L. M. G. Fonseca. 2012. Evaluation of WorldView-2 imagery for urban land cover mapping using the InterIMAGE system. Paper presented at the 4th GEOBIA, Rio de Janeiro, Brazil.

Riley, A. L. 1998. *Restoring streams in cities: A guide for planners, policymakers, and citizens*. Washington, DC: Island.

Rocky Mountain Land Use Institute. 2009. Low impact development and green infrastructure. In *sustainable community development code: A code for the 21st century*. http://www.law.du.edu/documents/rmlui/sustainable-development/LID-Green-Infrastructure.pdf (last accessed 22 November 2016).

Rossman, L. A. 2010. *Storm Water Management Model user's manual.* Version 5.0. Cincinnati, OH: U.S. Environmental Protection Agency National Risk Management Research Laboratory Office of Research and Development.

Shaw, B. R., B. T. Radler, R. Chenoweth, P. Heilberger, and P. Dearlove. 2011. Predicting intent to install a rain garden to protect a local lake: An application of the theory of planned behavior. *Journal of Extension* 49 (4): 4FEA6.

Taherzadeh, E., and H. Z. M. Shafri. 2013. Development of a generic model for the detection of roof materials based on an object-based approach using WorldView-2 satellite imagery. *Advances in Remote Sensing* 2:312–21.

U.S. Army Corps of Engineers. 1948. Appendix I: Hydrology. In *Arkansas River Basin definite project report on Templeton Gap Floodway, Colorado Springs, Colorado: Project on tributaries of Fountaine Que Bouille (Fountain) River, Colorado*. Albuquerque, NM: U.S. Army Corps of Engineers, Albuquerque District.

U.S. Census Bureau. n.d. Median and average square feet of floor area in new single-family houses completed by location. http://www.census.gov/construction/chars/pdf/medavgsqft.pdf (last accessed 22 November 2016).

U.S. Climate Data. 2015. Climate Colorado Springs - Colorado. http://www.usclimatedata.com/climate/colorado-springs/colorado/united-states/usco0078 (last accessed 3 June 2015).

U.S. Environmental Protection Agency. 2015. Low impact development (LID). http://water.epa.gov/polwaste/green/ (last accessed 22 November 2016).

U.S. Geological Survey (USGS). 2013a. Falcon NW Quadrangle, Colorado. 1:24,000. 7.5 Minute Series. Reston, VA: U.S. Department of the Interior.

———. 2013b. Pikeview Quadrangle, Colorado. 1:24,000. 7.5 Minute Series. Reston, VA: U.S. Department of the Interior.

Urban Drainage and Flood Control District (UDFCD). 2008. Floodplain preservation brochure. http://www.udfcd.org/downloads/pdf/other/good_examples_brochure.pdf (last accessed 22 November 2016).

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Margan. 2005. The urban stream syndrome: Current knowledge and the search for a cure. *Journal of the North American Benthological Society* 24 (3): 706–23.

Wenger, S. J., A. H. Roy, C. R. Jackson, E. S. Bernhardt, T. L. Carter, S. Filoso, C. A. Gibson, et al. 2009. Twenty-six key research questions in urban stream ecology: An assessment of the state of the science. *Journal of the North American Benthological Society* 28 (4): 1080–98.

Wisconsin Department of Natural Resources. 2003. Rain gardens: A how-to manual for homeowners. http://dnr.wi.gov/topic/shorelandzoning/documents/rgmanual.pdf (last accessed 22 November 2016).

Yuan, F., and M. Bauer. 2006. Mapping impervious surface area using high resolution imagery: A comparison of object-based and per pixel classification. Paper presented at the ASPRS 2006 Annual Conference, Reno, NV.

JEREMY C. TREDWAY recently graduated from the University of Colorado, Colorado Springs, with a master of arts degree in applied geography. E-mail: jeremyctredway@gmail.com. His research interests include ecological restoration in urban areas, water resources, and geographic information systems.

DAVID G. HAVLICK is an Associate Professor in the Department of Geography and Environmental Studies at the University of Colorado, Colorado Springs, Colorado Springs, CO 80918. E-mail: dhavlick@uccs.edu. His research interests include geographic perspectives on ecological restoration, critical examinations of militarized landscapes, and the relationship between infrastructure and conservation.