ADVANCING UNDERSTANDING AND PREDICTION OF REDEVELOPMENT IMPACTS ON STORMWATER RUNOFF IN SEMI-ARID URBAN AREAS

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Hydrology).

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ABSTRACT

As the global urban population grows, cities are densifying by redeveloping previously developed spaces. “Smart growth” through redevelopment is increasing the impervious coverage of urban areas and impacting the hydrologic regime in uncertain ways. Cities are looking to update current stormwater management criteria, which often exempt redevelopments, based on data-driven decisions informed by watershed-scale hydrologic modeling. Future stormwater management strategies must also consider climate changes and flood mitigation via low impact development (LID). Using the Berkeley neighborhood of Denver, Colorado, we investigated the impacts of redevelopment land use change, along with climate change and LID implementation, on stormwater quantity using a high-resolution, calibrated Stormwater Management Model for PC (PCSWMM). The model includes 170 subcatchments and parcel-scale predictions of impervious cover change for three scenarios of future redevelopment.

Simulations of design storms for multiple redevelopment scenarios predict that an increase of 1% in impervious area from redevelopment will increase surface runoff by 1.63% for the 2-yr, 24-hr design storm and by 0.91% for the 100-yr, 24-hr design storm resulting in greater relative flood risks for smaller storm events. When assessing the effectiveness of LID to mitigate increases in runoff from redevelopment, we found that model sensitivity to LID siting and routing parameters can impact the potential for meeting regulatory compliance. Relative sensitivity of runoff volume output to area treated and LID placement was found to be on average 3.0 and 11.2 times higher than the seven most sensitive physical LID and subcatchment parameters. Misunderstandings of model sensitivities can lead to costly decisions that are made based on modeling results. Finally, when assessing the combined impacts of redevelopment land use change and climate change on stormwater dual drainage system resilience, it was found that the system may be able to handle increases in runoff and flooding from redevelopment land use changes or climate changes alone, but likely not both. However, distributed LID implementation in conjunction with redevelopment provides a unique opportunity for increasing system resilience with a small LID footprint. All findings indicate a need to lower the current area threshold for requiring stormwater management with redevelopment within updated stormwater management criteria.

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CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Urbanization and Stormwater

Urbanization is increasing in the U.S. and around the world with projections predicting that 68% of the global population will live in urban areas by the year 2050 (United Nations, 2018). Currently, about half of the world's population lives in towns and cities, and the majority of the U.S. population lives in an urban environment (Grimm *et al.*, 2008). Many urban areas are experiencing population growth as more people move away from rural areas and towards population centers. The combination of a rapidly densifying urban population, changing land use patterns in urban areas, and climate change will have an important impact on the future of urban water management.

Urbanization converts pervious surfaces to impervious surfaces (Lee *et al.*, 2012; Grebel *et al.*, 2013; Liu *et al.*, 2015; Bloorchian *et al.*, 2016). Increases in impervious area alter the natural hydrologic response by increasing runoff quantity, increasing peak flows, and creating an overall "flashy" system (Lee *et al.*, 2012; Yang *et al.*, 2015; Bloorchian *et al.*, 2016). Stormwater runoff in urban areas is also a major source of surface water pollution (Sartor *et al.*, 1974; Lee *et al.*, 2012; Grebel *et al.*, 2013) and increased flood risk (NRC, 2009). These problems are expected to intensify as climate change alters precipitation regimes including the frequency, duration, and intensity of extreme precipitation events (Praskievicz and Chang, 2009; Forsee and Ahmad, 2011; Paerl *et al.*, 2016). Urban land use change and climate change are both drivers of hydrologic change in urban environments. Understanding the impacts of these drivers on urban hydrology, as well as solutions to address the impacts, is critical for the future of water resources.

1.1.2 Infill Development/Redevelopment

Many urban watershed studies compare pre-developed to developed conditions, but do not directly address stormwater runoff produced through urban *redevelopment*. As populations grow, cities must accommodate the new flux of people in housing without increasing the negative environmental, social, and economic impacts of urban sprawl (Goetz, 2013). Therefore, many cities are implementing solutions that result in growing inward (or upward) instead of outward. This type of growth manifests as *infill development*, where the sporadic, under-utilized parcels of the city are "filled" in with new developments. In this way, infill *re*develops a previously developed space instead of expanding into undeveloped land. Infill is a loosely defined term that can have several definitions and interpretations. In this research, *redevelopment* is synonymous to infill development, and is the main term used throughout the dissertation. Examples of redevelopment, as defined for this work, include a parking lot transformed into an apartment complex, or a single family home converted into a multi-family unit. An empty, or "vacant," parcel converted to any other use is also defined as redevelopment in this research. The main unifying feature of redevelopment is an increase in impervious, or hard, surfaces, such as roofs or driveways, relative to what previously existed (Thomas, 2009; EPA, 2016). Increases in impervious surfaces are expected to decrease infiltration, increase stormwater runoff, and increase pollutant conveyance to nearby streams and waterbodies. However, high-resolution, watershed-scale hydrologic analysis of redevelopment is lacking.

Previous studies on the impacts of redevelopment on stormwater have used more simplistic methods, such as the curve number (CN) approach, to determine how impervious cover change from redevelopment affects peak flows and runoff volumes (Pond and Kacvinsky, 2006; Hekl and Dymond, 2016). In addition, existing studies have typically been conducted on the scale of a few parcels or the smaller neighborhood scale. There is currently a lack of information regarding the cumulative impacts of redevelopment at the larger neighborhood, or watershed, scale using higher-resolution, calibrated modeling. Such modeling can also be used to identify the temporal and spatial distribution of impacts on stormwater runoff and flood volumes, and to determine if the existing storm sewer network has adequate capacity for increased stormwater flows.

1.1.3 Low Impact Development

Many studies have identified the benefits of implementing Best Management Practices (BMPs), Stormwater Control Measures (SCMs), Green Infrastructure (GI), or Low Impact Development (LID) in urban areas at site, local, or watershed scales to manage stormwater runoff. While all these terms refer to similar stormwater management practices (Fletcher *et al.*, 2015), the remainder of this dissertation uses the term LID. LID implementation is often assessed using hydrologic models such as HEC-HMS (Emerson *et al.*, 2005), SWMM or PCSWMM (Kabbani, 2015; Rosa *et al.*, 2015), and SUSTAIN (Lee *et al.*, 2012). These studies illustrate the positive impacts of LID - such as bioretention ponds, permeable pavements, and vegetative swales - on reducing peak flows, runoff volumes, and stormwater pollution through nature-mimicking mechanisms such as infiltration and chemical or biological reactions (Grebel *et al.*, 2013). While LID editors incorporated into hydrologic models are useful tools for testing an array of scenarios, there is great uncertainty associated with LID modeling, and the evaluation of model sensitivity to LID parameters is an ongoing investigation (Eckart *et al.*, 2017). In particular, the sensitivity of models to LID siting and routing parameters is under-studied as compared to physical LID parameters such as hydraulic conductivity or soil depths. Understanding model sensitivity to LID parameters is critical to accurately assess the viability of watershed-scale implementation plans, particularly in the context of urban redevelopment. It is unknown if current stormwater criteria regarding redevelopment is adequate, or if LID implementation can aid in the mitigation of redevelopment impacts on urban hydrology.

1.1.4 Stormwater Criteria and Urban Drainage Design

Redevelopment often takes place sporadically at compact scales on small land parcels (<0.1 ha, or <¼ acre) throughout a neighborhood. Thus, current regulations may or may not require stormwater management be implemented with redevelopment. For example, the City and County of Denver Storm Drainage Design and Technical Criteria Manual exempts flood control detention practices for redevelopment of a total area of 0.2 ha (½ acre) or less (DPW, 2013). In addition, the Environmental Protection Agency's (EPA) National Pollutant Discharge Elimination System (NPDES) program only requires permits for stormwater discharges from activities disturbing areas of 0.4 ha (1 acre) or larger (EPA, 2012). The consequences of such stormwater regulations when redevelopment occurs on many small, yet technically separate, land parcels are not yet clear. Existing storm sewer systems may become outdated and unable to handle increased runoff volumes from redevelopment, especially in areas that already experience sewer surcharges, or that expect large increases in rainfall due to climate change.

Many urban drainage networks in the US were originally sized to convey design storms up to the 5-yr and 10-yr, 24-hr storm (Moore *et al.*, 2016), while systems in Europe are designed to prevent floods from return periods ranging from the 10-yr to 50-yr storm (Salvadore *et al.*, 2015).

Problems arise when non-stationary factors such as increasing impervious area due to redevelopment, as well as changes to precipitation from climate change, violate the stationarity assumption of urban drainage design (Arisz and Burrell, 2006; Milly *et al.*, 2008).

1.1.5 Climate Change

In addition to impacts from land use change, the changing climate is affecting stormwater runoff in urban areas. A range of hydrologic modeling studies have evaluated the impacts of climate change on urban hydrology (Waters *et al.*, 2003; Zahmatkesh *et al.*, 2014; Moore *et al.*, 2016; Alamdari *et al.*, 2017). However, few studies have modeled the effects on stormwater of climate change alongside those of land use change, particularly in the context of redevelopment. There are challenges to studying climate change in urban watersheds including large uncertainties and variability in downscaled climate projections, which make adaptation approaches such as LID difficult to implement. In these situations, a resilience assessment may be better suited to assess at what rainfall thresholds an existing system fails current regulatory standards at varying levels of redevelopment under future climate change (Gersonius *et al.*, 2012). Then, LID modeling can be used to determine how different types of LID can improve system resilience.

Ultimately, changes in the runoff and flood volumes generated by storms that drainage systems were originally designed to handle are accompanied by threats to human safety and infrastructure integrity. According to Salvadore *et al.* (2015), many densifying urban areas are experiencing more frequent and devastating floods leading to the need for more assessments of urban water fluxes via distributed hydrologic modeling. The goal of this dissertation is to evaluate the combined impacts of redevelopment and climate change on stormwater runoff quantity using distributed hydrologic modeling. For this investigation, we use a case study of the Berkeley neighborhood in Denver, Colorado.

1.2 Research Objectives, Questions, and Hypotheses

This section summarizes the research objectives, and associated research questions and hypotheses for each chapter of this dissertation.

1.2.1 Objective 1: Quantify Stormwater Runoff in a Redeveloping Neighborhood

The objectives of the research performed for Chapter 2 were to 1) Quantify the impacts of increasing redevelopment on local flood volumes and the storm sewer network capacity for varying redevelopment scenarios including a range of design storm simulations, and 2) Quantify the volume, peak flow timing, and spatial distribution of stormwater runoff caused by redevelopment using parcel-scale predictions of redevelopment. To achieve these objectives, the following research questions were addressed, and hypotheses were evaluated:

Question 1: At what level of increase in impervious area from redevelopment and for what size storm event will an existing storm sewer network flood due to increases in runoff volume?

> ***Hypothesis 1*** – The existing storm sewer network in the Berkeley neighborhood will reach capacity and flood due to increased runoff volume from a moderate redevelopment scenario (increase in impervious area of 4.7%) during mid-sized storm events (e.g., 10-yr, 24-hr).

Question 2: How are changes to stormwater runoff volume and peak flow due to redevelopment spatially and temporally distributed for a range of design storms at the neighborhood scale?

> ***Hypothesis 2*** – Increases in stormwater runoff volume from baseline will be highest in subcatchments experiencing the most redevelopment and lowest in subcatchments with existing LID infrastructure. Redevelopment will impact all design storms similarly.

1.2.2 Objective 2: Evaluate Model Sensitivity to LID Siting and Routing Parameters

The objectives of the research performed for Chapter 3 were to 1) Evaluate the sensitivity of SWMM to LID siting and routing parameters, 2) Compare this sensitivity to that of other LID and subcatchment parameters, and 3) Discuss the potential implications for regulatory compliance. To achieve these objectives, the following research questions were addressed, and hypotheses were evaluated:

Question 3: How sensitive is SWMM to LID siting and routing parameters including LID placement in the model, outflow routing from LID units, and area treated by LID units?

> ***Hypothesis 3*** – All three siting and routing parameters will be sensitive and affect model runoff volume and flood volume outputs, but area treated will most affect model output followed by LID placement.

Question 4: How does the sensitivity of SWMM to LID siting and routing parameters compare to other physical LID and subcatchment parameters such as soil conductivity, soil thickness, depression storage, and infiltration rates?

Hypothesis 4 – Adjusting LID siting and routing parameters has a greater impact on SWMM runoff and flood volume outputs than physical LID parameters (such as soil conductivity and soil thickness), but subcatchment parameters (such as depression storage and infiltration rates) have a greater impact on SWMM runoff and flood volume outputs than any LID parameter.

1.2.3 Objective 3: Assess Resilience to Land Use and Climate Changes

The objectives of the research performed for Chapter 4 were to 1) Assess the resilience of a dual drainage system to redevelopment land use change and climate change, and 2) Evaluate how distributed and regional LID implementation impacts system resilience. To achieve these objectives, the following research questions were addressed, and hypotheses were evaluated:

Question 5: How do levels of redevelopment impact the tipping point of an urban neighborhood's stormwater system? *Tipping point* is defined as the level of climate change, or change in rainfall from historical, to exceed regulatory requirements for flood protection.

Hypothesis 5 – The stormwater system of the Berkeley neighborhood will reach a tipping point at a 20% and 30% increase in rainfall, for the minor and major storm event regulatory requirements, respectively, at baseline conditions. Redevelopment will decrease/worsen these tipping points with greater impact on the minor storm event than the major storm event.

Question 6: How do distributed and regional LID options impact the minor and major storm event tipping points at varying levels of redevelopment?

Hypothesis 6 –While both distributed and regional LID options will increase/improve tipping points, distributed LID will provide greater improvements than regional LID, and the minor storm event tipping point will be impacted more than the major storm event tipping point.

1.3 References

Alamdari, N., D. J. Sample, P. Steinberg, A. C. Ross, and Z. M. Easton. 2017. “Assessing the Effects of Climate Change on Water Quantity and Quality in an Urban Watershed Using a Calibrated Stormwater Model.” *Water*. 9(7). doi.org/10.3390/w9070464

Arisz, H., and B. C. Burrell. 2006. “Urban drainage infrastructure planning and design considering climate change.” Published in IEEE EIC Climate Change Conference. doi.org/10.1109/EICCCC.2006.277251

Bloorchian, A. A., L. Ahiablame, A. Osouli, and J. Zhou. 2016. “Modeling BMP and Vegetative Cover Performance for Highway Stormwater Runoff Reduction.” *Procedia Eng.* 145: 274-280. doi.org/10.1016/j.proeng.2016.04.074

Denver Department of Public Works (DPW), Wastewater Management Division, Engineering Division. 2013. “City and County of Denver Storm Drainage Design & Technical Criteria Manual.” denvergov.org

Eckart, K., Z. McPhee, and T. Bolisetti. 2017. “Performance and implementation of low impact development – A review.” *Sci. Total Environ*. 607-608: 413-432. doi.org/10.1016/j.scitotenv.2017.06.254

Emerson, C. H., C. Welty, and R. G. Traver. 2005. “Watershed-Scale Evaluation of a System of Storm Water Detention Basins.” *J. Hydrol. Eng*. 10(3). doi.org/10.1061/(ASCE)1084-0699

Environmental Protection Agency (EPA). 2012. “2012 Construction General Permit (CGP) – Fact Sheet.” <https://www3.epa.gov/npdes/pubs/cgp2012_finalfactsheet.pdf> (Accessed November 9, 2017).

Fletcher, T. D., W. Shuster, W. F. Hun, R. Ashley, D. Butler, S. Arthur, S. Trowsdale, S. Barraud, A. Semadeni-Davies, J. Bertrand-Krajewski, P. S. Mikkelson, G. Rivard, D. Dagenais, and M. Viklander. 2015. “SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage.” *Urban Water J.* 12(7): 525-542. doi.org/10.1080/1573062X.2014.916314

Forsee, W. J., and S. Ahmad. 2011. “Evaluating urban storm-water infrastructure design in response to projected climate change.” *J. Hydrol. Eng*. 16(11). doi.org/10.1061/(ASCE)HE.1943-5584.0000383

Gersonius, B., F. Nasruddin, R. Ashley, A. Jeuken, A. Pathirana, and C. Zevenbergen. 2012. “Developing the evidence bae for mainstreaming adaptation of stormwater systems to climate change.” *Water Res*. 46: 6824-6835. doi.org/10.1016/j.watres.2012.03.060

Goetz, A. 2013. “Suburban Sprawl or Urban Centres: Tensions and Contradictions of Smart Growth Approaches in Denver, Colorado.” *Urban Studies*. 50: 2178-2195. doi.org/10.1177/0042098013478238

Grebel, J. E., S. K. Mohanty, A. A. Torkelson, A. B. Boehm, C. P. Higgins, R. M. Maxwell, K. L. Nelson, and D. L. Sedlak. 2013. “Engineered Infiltration Systems for Urban Stormwater Reclamation.” *Environ. Eng. Sci*. 30(8): 437-454. doi.org/10.1089/ees.2012.0312

Grimm, N. B, S. H. Faeth, N. E. Bolubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2008. “Global Change and the Ecology of Cities.” *Science*. 319(5864): 756-760. doi.org/10.1126/science.1150195

Hekl, J. A. and R. L. Dymond. 2016. “Runoff Impacts and LID Techniques for Mansionization-Based Stormwater Effects in Fairfax County, Virginia.” *J. Sustainable Water in the Built Environ.* doi.org/10.1061/JSWBAY.0000815

Kabbani, M. S. 2015. “Using PCSWMM to simulate first flush and assess performance of extended dry detention ponds as structural stormwater BMPs in a large polluted urban watershed.” Ph.D. (Doctor of Philosophy) thesis, University of Iowa, <http://ir.uiowa.edu/etd/1653> (Accessed March 16, 2016).

Lee, J. G., A. Selvakumar, K. Alvi, J. Riverson, J. X. Zhen, L. Shoemaker, and F. Lai. 2012. “A watershed-scale design optimization model for stormwater best management practices.” *Environ. Modell. Softw*. 37: 6-18. doi.org/10.1016/j.envsoft.2012.04.011

Liu, Y., L. M. Ahiablame, V. F. Bralts, and B. A. Engel. 2015. “Enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff.” *J. Environ. Manage*. 147: 12-23. doi.org/10.1016/j.jenvman.2014.09.005

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity Is Dead: Whither Water Management? *Science.* 319(573): LP-574. doi.org/10.1126/science.1151915

Moore, T. L., J. S. Gulliver, L. Stack, and M. H. Simpson. 2016. “Stormwater management And climate change: Vulnerability and capacity for adaptation in urban and suburban contexts.” *Clim. Change*. 138: 491-504. doi.org/10.1007/s10584-016-1766-2

National Research Council (NRC). 2009. *Urban Stormwater Management in the United States*. Washington, DC: The National Academies Press. doi.org/10.17226/12465

Paerl, H. W., W. S. Gardner, K. E. Havens, A. R. Joyner, M. J. McCarthy, S. E. Newell, B. Qin, and J. T. Scott. 2016. “Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients.” *Harmful Algae*. 54: 213-222. doi.org/10.1016/j.hal.2015.09.009

Pond, M. C. and G. Kacvinsky. 2006. “Tear-downs - controlling stormwater impacts.” <http://waterbucket.ca/gi/files/2013/03/Teardowns-controlling-stormwater-impacts.pdf> (Accessed June 19, 2017).

Praskievicz, S., and H. Chang. 2009. “A review of hydrological modelling of basin-scale climate change and urban development impacts.” *Progress in Physical Geography: Earth and Environment*. 33(5): 650-671. doi.org/10.1177/0309133309348098

Rosa, D. J., J. C. Clausen, and M. E. Dietz. 2015. “Calibration and Verification of SWMM for Low Impact Development.” *J. Am. Water Resour. Assoc*., 51(3): 746-757. doi.org/10.1111/jawr.12272

Salvadore, E., J. Bronders, & O. Batelaan. 2015. “Hydrological modelling of urbanized catchments: A review and future directions.” *J. Hydrol.* 529: 62-81. doi.org/10.1016/j.jhydrol.2015.06.028

Sartor, J. D. *et al.* 1974. “Water pollution aspects of street surface contaminants.” *J. Water Pollut. Control Fed.* 46(3): 458-467.

Thomas, J. V. 2009. *Residential Construction Trends in America’s Metropolitan Regions*. U.S. Environmental Protection Agency: Development, Community, and Environment Division.

United Nations, Department of Economic and Social Affairs, Population Division. 2018. *World Urbanization Prospects: The 2018 Revision*. New York: United Nations.

Waters, D., W. E. Watt, J. Marsalek, and B. C. Anderson. 2003. “Adaptation of a storm drainage system to accommodate increased rainfall resulting from climate change.” *J. Environ. Plann. Man.* 46(5). doi.org/10.1080/0964056032000138472

Yang, Y., T.A. Endreny, and D.J. Nowak. 2015. “Simulating the effect of flow path roughness to examine how green infrastructure restores urban runoff timing and magnitude.” *Urban Forestry & Urban Greening*. 14(2): 361-367. doi.org/10.1016/j.ufug.2015.03.004

Zahmatkesh, Z., S. J. Burian, M. Karamouz, H. Tavakol-Davani, and E. Goharian. 2014. “Low-Impact Development Practices to Mitigate Climate Change Effects on Urban Stormwater Runoff: Case Study of New York City. *J. Irrig. Drain Eng.* 141(1): 04014043. doi.org/10.1061/(ASCE)IR.1943-4774.0000770.

CHAPTER 2

HIGH-RESOLUTION MODELING OF INFILL DEVELOPMENT IMPACT ON STORMWATER DYNAMICS IN DENVER, COLORADO

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2.1 Abstract

Growing cities require accurate knowledge of current and future hydrologic conditions to make effective stormwater management decisions. Yet, this information is lacking because cities are undergoing infill development/redevelopment, for which the hydrologic impacts are not adequately quantified. The current research studies the impacts of infill development on urban runoff in Denver, Colorado. A calibrated, high-resolution PCSWMM (Stormwater Management Model for PC) model was used to simulate design storms and summer rainfall periods for multiple future redevelopment scenarios. Results predict that an increase of 1% in impervious area due to redevelopment will increase surface runoff volume by 1.63% for the 2-yr, 24-hr design storm and by 0.91% for the 100-yr, 24-hr design storm resulting in greater relative flood risks for smaller storm events. Flooding volumes will increase from 30,000 m^3 to 36,000 m^3 for the 10-yr, 24-hr storm, which is 12% of the total storm rainfall volume. Results show the limitations of the existing storm sewer network, future flood potential, and the possibilities for stormwater beneficial use. Results will help inform current and future stormwater regulations regarding redevelopment.

2.2 Introduction

In the past century, the percentage of the global population living in urban areas has grown from 10% to over 50%, with continued growth expected over the next 50 years (Grimm *et al.*,

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2008). The combination of a rapidly densifying urban population and climate change will have an important impact on the future of urban water management. Stormwater runoff in urban areas is a major source of surface water pollution (Sartor *et al.*, 1974; Lee *et al.*, 2012; Grebel *et al.*, 2013) and increased flood risk (NRC, 2009), but it is also regarded as an opportunity to augment local water supply and recharge aquifers (Steffen *et al.*, 2013), particularly in water-stressed, semi-arid areas.

It is well known that urban growth increases the conversion from undeveloped, natural lands to non-rural land uses, thus converting pervious surfaces to impervious surfaces (Lee *et al.*, 2012; Grebel *et al.*, 2013; Liu *et al.*, 2015; Bloorchian *et al.*, 2016). This conversion changes an area's natural hydrologic runoff response by lowering the watershed's capacity for flood mitigation and water quality compliance as surface runoff increases and water quality degrades (Lee *et al.*, 2012; Yang *et al.*, 2015; Bloorchian *et al.*, 2016). Many studies have identified the benefits of implementing Best Management Practices (BMPs), or Green Infrastructure (GI), in urban areas at both local and watershed scales using models such as HEC-HMS (Emerson *et al.*, 2005), SWMM or PCSWMM (Kabbani, 2015; Rosa *et al.*, 2015), and SUSTAIN (Lee *et al.*, 2012). These studies illustrate the positive impacts of BMPs - such as vegetative swales, dry ponds, porous pavement, and filter strips - on reducing peak flows, runoff volumes, and stormwater pollution through nature-mimicking mechanisms such as infiltration and chemical or biological reactions (Grebel *et al.*, 2013). Yet, these studies focus on changes in the hydrologic regime due to a transformation of undeveloped to developed land, or the extension of development into suburban areas, but do not directly address stormwater runoff produced through urban *redevelopment*.

Redevelopment, which is defined as "infill development" in this study, is the increasingly popular practice of adding new development within existing urban areas on vacant or under-utilized parcels of land, typically resulting in an increase in impervious surfaces such as roofs, driveways, and parking lots (McConnell and Wiley, 2010). One example of redevelopment is replacing a low density, older single family home including a front lawn with a new, high density multi-family complex that covers the full parcel area (Figure 2.1). Through this conversion, the percentage of impervious coverage within a parcel can double, thereby decreasing rainwater infiltration, increasing stormwater runoff, and likely increasing pollutant conveyance to nearby streams and waterbodies. As cities worldwide reach their urban growth boundaries (UGBs), redevelopment is becoming the new face of urbanization (Johnson, 2001). Communities across the United States are recognizing the economic, social, environmental, and sustainability benefits of dense, urban centers versus the historical urban sprawl progression of growth (Goetz, 2013; Arvola and Pennanen, 2014). Infill development has been hailed as a solution to the problem of urban sprawl as well as an opportunity to economically revitalize existing neighborhoods and encourage public transportation, and is therefore encouraged through anti-sprawl, "smart growth" policies (Cooper, 2004; Downs, 2005; McConnell and Wiley, 2010).

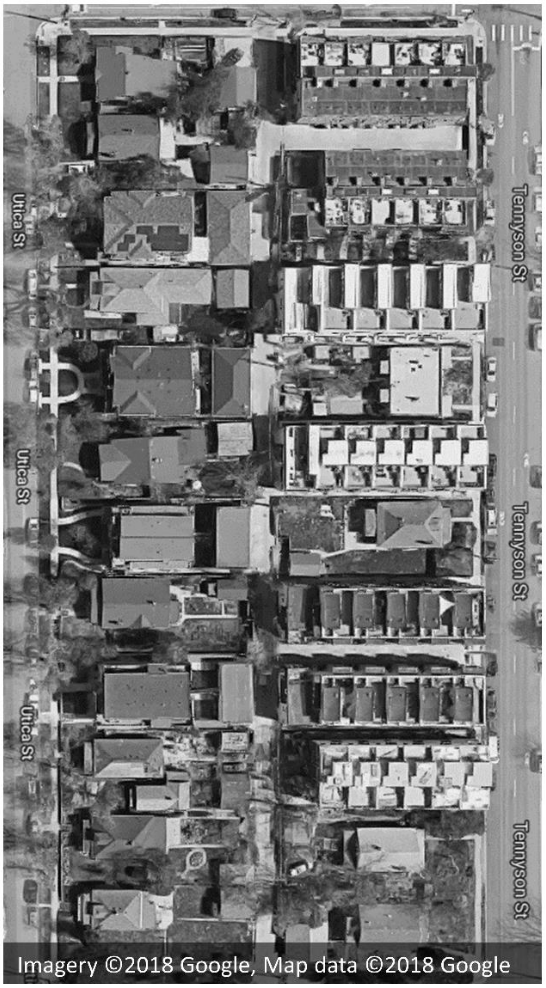


Figure 2.1 Example aerial image of infill development occurring along Tennyson Street in the Berkeley neighborhood of Denver, CO. The left side of the image shows single family homes with lawns, while the right side illustrates the increase in impervious area of redeveloped multi-family units. (Source: Google Maps)

Although there are many benefits to infill development, there is a paucity of research on its adverse impacts, especially in the context of urban water cycling and stormwater runoff (McConnell and Wiley, 2010). A study by Pond and Kacvinsky (2006) used the HEC-HMS model and curve number (CN) method to determine that average peak flows (from a range of design storms) at the outlet of a 136-ha residential redevelopment increased by 7% for an average impervious area increase of 6.7%. A more recent study by Hekl and Dymond (2016) analyzed 10 redeveloped parcels in Fairfax County, Virginia, also using the CN method in TR-55, and found that a total 7% increase in impervious area resulted in a 5.6% increase in runoff volume for the 10-yr, 24-hr storm. However, neither study investigated the cumulative effects of infill development on stormwater runoff at the larger neighborhood or watershed scale, or utilized a fully integrated, calibrated hydrologic model such as SWMM. In addition, prior studies have not addressed water quality or the possibility of harnessing potential increases in runoff volumes for water supply. Ultimately, cities once growing outwards (“sprawled growth”) are now growing inwards/upwards (“smart growth”), and understanding the resulting, and largely unknown, consequences on urban water cycling and water supply is increasingly relevant for water managers and residents in water-stressed cities across the globe (Burchell *et al.*, 2000).

Ideally, infill occurs in the context of broader urban planning with the goal of achieving neighborhoods that complement the existing urban form. Yet, infill often takes place sporadically at compact scales on small land parcels (0.1 ha or less) throughout a neighborhood. Thus, regulations may or may not require stormwater management after redevelopment. For example, the City and County of Denver Storm Drainage Design and Technical Criteria Manual exempts flood control detention practices for redevelopment of a total area of 0.2 ha or less (DPW, 2013). In addition, the Environmental Protection Agency’s (EPA) National Pollutant Discharge Elimination System (NPDES) program only requires permits for stormwater discharges from activities disturbing areas of 0.4 ha or larger (EPA, 2012). The consequences of such stormwater regulations when redevelopment occurs on many small, yet technically separate land parcels are not yet clear. Existing storm sewer systems may become outdated and unable to handle increased runoff volumes from infill, especially in areas that already experience sewer surcharges, flooding, and erosion. In addition, the contribution of increased impervious areas to stormwater pollutants such as nutrients and metals from nonpoint sources such as fertilizers, pesticides, and automobiles is not well-studied.

Denver has a population density that has tripled since 1910 and is expected to grow by nearly 100,000 people (about 14%) in the next fifteen years (Metro Denver, 2017). Consequently, the City is facing a cycle of increasing population and infill development. A result of the observed population growth is a rise in domestic water demand, a large part of which could be creatively mitigated through stormwater capture and management, particularly for non-potable uses. The novelty of the current study lies in utilizing a fully calibrated, high-resolution hydrologic model to conduct a holistic watershed system analysis of the alterations to urban stormwater dynamics due to infill in a Denver, Colorado neighborhood. Our work is part of larger effort to analyze the technical, legal, and economic feasibility of using the additional stormwater produced from ongoing redevelopment as a solution to reinvent stormwater management strategies and relieve pressure on regional water supplies. Specifically, our objectives are to:

1. Quantify the volume and spatial distribution of stormwater runoff caused by infill development using parcel-scale predictions of redevelopment.
2. Quantify the impacts of increasing infill development on local flooding potential and the storm sewer network capacity for varying redevelopment scenarios.

2.3 Methods

2.3.1 Study Site and Data Sources

The study area includes the Berkeley neighborhood in northwest Denver, Colorado (Figure 2.2), which has experienced significant infill development over the past fifteen years (Cherry, 2016). Denver's regional RainVieux Gauge-adjusted Radar Rainfall (GARR) tool (Vieux, Inc., 2017) provided observed five-minute rainfall data. This rainfall tool uses both gauge (Figure 2.3) and radar inputs to provide rainfall values by user-specified catchments, basins, or 1-km grids in the Denver area (Vieux, Inc., 2017). Thus, the RainVieux tool outputs data that has already been inverse-distance weighted in a model-ready format which was applied to the full study area. The RainVieux precipitation gauge network is shown in Figure 2.3. Rainfall data characteristics are summarized in Table 2.1, where simulations for the West and East Basins utilize the same period of rainfall data based on the installation dates of corresponding flow data sensors as described below.

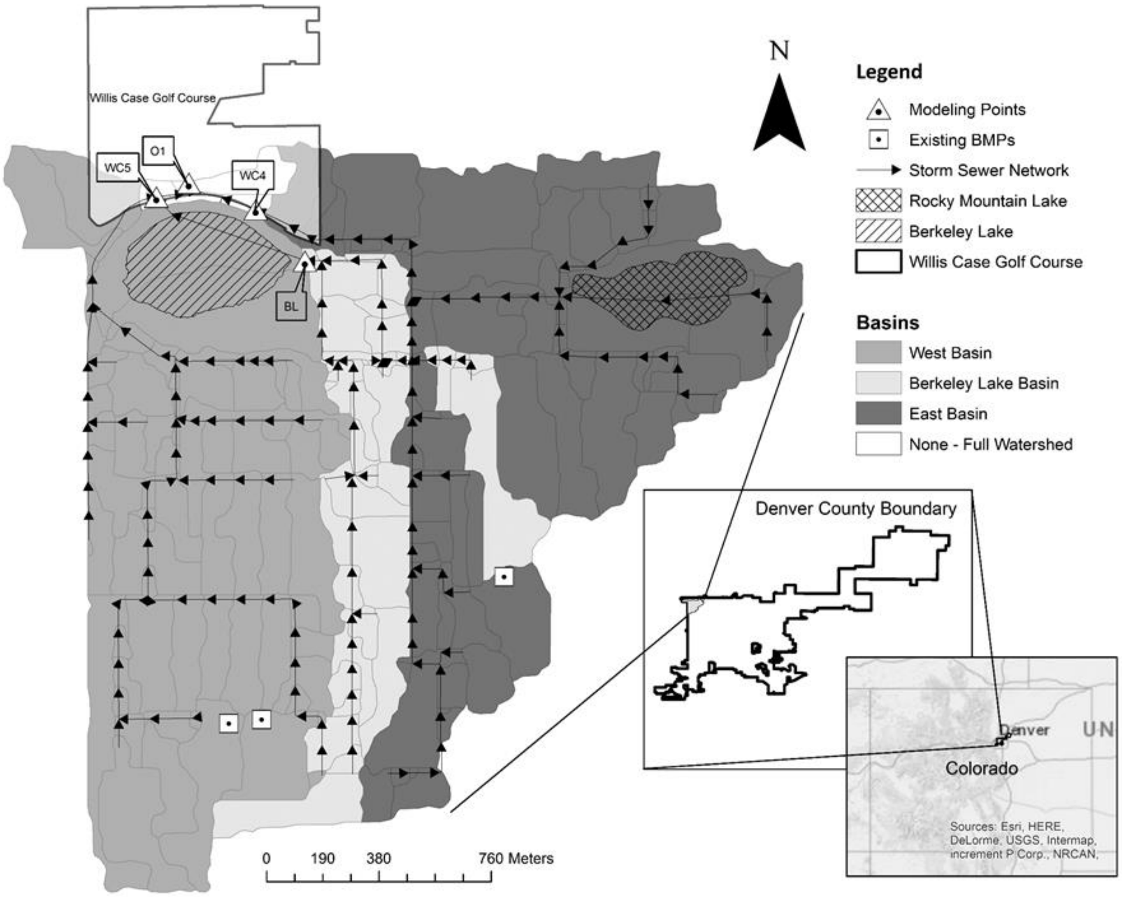


Figure 2.2 Berkeley neighborhood catchment study area including the existing storm sewer network, existing BMPs, modeling points, and modeled major basins. Smaller subcatchments are outlined in each basin.

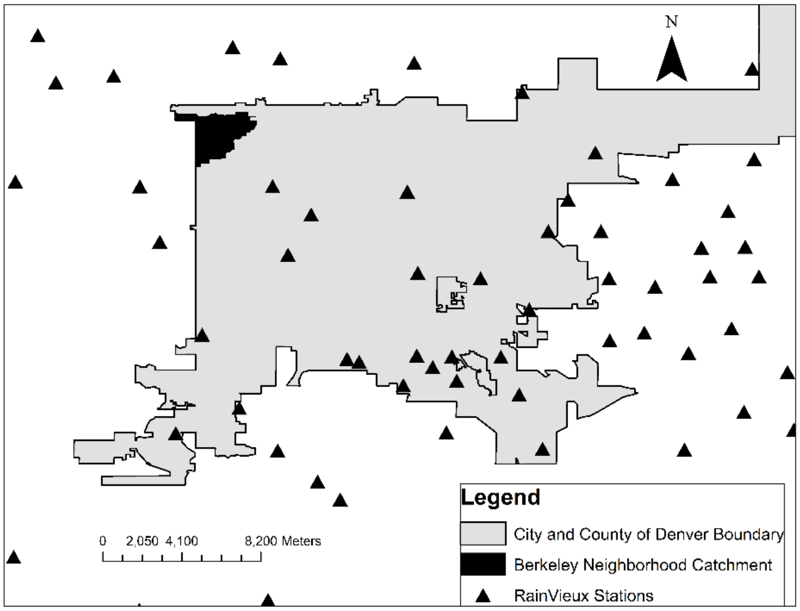


Figure 2.3 Map of Denver's regional RainVieux tool precipitation gauge network.

Table 2.1 Calibration and validation rainfall data details for each basin.

	Calibration					
Basin	Start Date	End Date	Total Rainfall (mm)	# Events > 2.54 mm	Largest Event Size (mm)	Median Event Size (mm)
West	04/17/2017	06/03/2017	106	11	25.5	0.483
East	04/17/2017	06/03/2017	106	11	25.5	0.483
Berkeley Lake	07/14/2016	09/05/2016	36	5	5.61	0.686

	Validation					
Basin	Start Date	End Date	Total Rainfall (mm)	# Events > 2.54 mm	Largest Event Size (mm)	Median Event Size (mm)
West	06/04/2017	07/27/2017	27	4	6.63	0.305
East	06/04/2017	07/27/2017	27	4	6.63	0.305
Berkeley Lake	09/02/2015	10/15/2015	14	2	4.04	0.737

Meteorological data, including monthly evaporation and wind speed estimates, were obtained from the Denver Water Administration Building gaging station operated by Denver Water. Storm sewer discharge (or flow) data was continuously monitored at three locations within the watershed (annotated WC5, WC4, and BL – see Figure 2.2) using two ISCO 2100 Ultrasonic Level Sensors mounted above the flow stream within the storm pipes (Isco, Inc.) for locations WC5 and WC4, and one HOBO pressure transducer (Onset Computer Corporation) within a PVC pipe stilling well at point BL. The ultrasonic sensors were installed in April 2017 and record stage height by calculating the elapsed time between transmitted sound pulses reflected off the water surface. The HOBO pressure transducer was installed in September 2015 and records stage height by measuring the pressure of water above the transducer. Stage height was converted to discharge via Manning's equations and developed rating curves, which is known to be an accurate method for partially filled sewer pipes (Saatci, 1990).

The Berkeley neighborhood is 419 ha and home to 11,000 people. The neighborhood has an average impervious area of 53% (in 2014) and an average slope of 5.5%. As of 2014, the main land use was single family residential (54%) with a modest portion of parks and recreation land use (18%) and multi-family units (10%). Land use was determined by the City and County of

Denver's Community Planning and Development (CPD) department using parcel-scale data compiled from the Assessor's parcel records from April to December 2014. Both single-family residential and parks and recreation land uses consist of properties with relatively high precipitation infiltration capacity. The highest density of development in the neighborhood resides along Tennyson Street, a north-south business corridor located in the center of the basin. Cherry (2016) estimated that future land covered by redevelopment in the study area would increase by 15% of total neighborhood parcels by the year 2024 resulting in an increase in impervious area of 1%. The Berkeley watershed utilizes a curb-and-gutter stormwater collection system and has 18.9 km of storm sewer pipes, 15.2 km of which were modeled for this study (Figure 2.2). All storm pipes within the basin drain from south to north, and stormwater discharges untreated into Clear Creek, a tributary of the South Platte River, the main drinking water source for Denver (Denver Water, 2016a). The basin contains no open water channels or streams, but does contain a historic drainage ditch, the Rocky Mountain Ditch, and two manmade lakes, Berkeley Lake to the west and Rocky Mountain Lake to the east (Figure 2.2).

2.3.2 Model Application

The EPA's SWMM, version 5.1.011, was used as part of the PCSWMM software (CHI Water) to model stormwater runoff and conveyance. City-provided GIS delineated shapefiles of the storm sewer network, as well as a 9-m resolution Digital Elevation Model (DEM), were imported into PCSWMM. Because storm pipe networks often cross topographic boundaries, the assumption that all stormwater runoff flows downhill is inaccurate in the studied watershed. Therefore, following the approach developed by Shamead *et al.* (2014), the storm sewer shapefile was "burned" into the DEM by artificially lowering elevation values by 3 meters in locations where a pipe exists to mimic surface channels in the locations of storm pipes for the purpose of subcatchment delineation. The full Berkeley watershed was modeled using a distributed sub-basin approach with the delineation of 170 subcatchments grouped into three larger basins in PCSWMM – West Basin, East Basin, and Berkeley Lake Basin (Figure 2.2). The subcatchments range in size from 0.016 ha to 16 ha, with a mean area of 2.4 ha. Digitization of the numerous subcatchments allowed for high-resolution modeling of the impacts of infill across the neighborhood.

2.3.3 Initial Parameter Estimates

Initial parameters for PCSWMM were estimated via GIS, field observations, literature review, and model defaults (Table 2.2). GIS was utilized to calculate slopes, widths, areas, and percent imperviousness area-weighted by fourteen different land use types. Recommended values of depression storage depths from the Urban Drainage and Flood Control District (UDFCD) proved to be sensitive parameters and were thus adjusted during calibration. With an absence of observed soils data in the studied basin, uncalibrated Horton infiltration parameters were based on the soil type C classification of an adjacent neighborhood in the EPA's National Stormwater Calculator (EPA, 2017). The DC parameter (directly connected impervious area) and routing for each sub-basin was calculated using the Denver-specific equation developed by Alley and Veenhuis (1983) (Equation 2.1) where the percent of runoff routed to impervious areas is equal to the DC value. The City of Denver provided information on pipe network parameters such as invert elevations, pipe diameters, and roughness coefficients.

$$DC = 0.15 * impervious\ area^{1.41} \tag{2.1}$$

2.3.4 Storage Nodes

The two lakes located within the basin were modeled as storage nodes within PCSWMM. Berkeley Lake has a surface area and volume of approximately 14 ha and 427,000 m^3 when full at a maximum depth of 3.05 m. Rocky Mountain Lake has a smaller surface area of approximately 9.7 ha, but has a maximum depth of 12.2 m for a full volume of 1,183,400 m^3. The lakes were not built for storage purposes, but ultimately offer a combined volume of over 1.6 million m^3. For simplicity, the lakes were assumed to be rectangular boxes due to the small depth relative to surface area of both lakes. Stage-area relationships were developed for both systems and entered into PCSWMM. To account for rain falling on the lakes, they were simulated as subcatchments classified as 100 percent impervious with no depression storage and wide overland flow widths, resulting in all rainfall converting to runoff routed directly to the storage nodes. In addition to the lakes, existing BMPs were modeled as aggregate bio-retention cells in three of the subcatchments (locations shown in Figure 2.2) using available dimensions data and estimated media parameters (DPW, 2014).

Table 2.2 Initial and calibrated PCSWMM parameters.

Parameter	Initial Value(s)	Calibrated Value(s)	Data Source
Subwatershed Area (ha)	0.016 – 16.6	No change	GIS
Subwatershed Slope (%)	0.61 – 19	1.4 – 43	DEM
Subwatershed Width (m)	26.5 – 9,390	60.3 – 51,500	GIS
N-Impervious	0.01	0.001 - 0.01	Default
N-Pervious	0.1	0.1 - 0.163	Default
Depression Storage - Impervious (mm)	2.54	3.20 – 25.4	UDFCD
Depression Storage - Pervious (mm)	8.89	8.89 – 14.8	UDFCD
% Impervious	20 – 81	No change	City and County of Denver's Community Planning and Development Department
% Zero Impervious	25	14 – 82	Default
% Routed to Impervious	10 – 74	No change	Alley and Veenhuis (1983)
Max Infiltration Rate (mm/hr)	5.08	2.54 – 25.4	SSURGO web soil survey (NRCS)
Min Infiltration Rate (mm/hr)	1.52	1.52 – 7.37	SSURGO web soil survey (NRCS)
Decay Constant (1/hr)	4	0.83 – 4	Default
Drying Time (days)	7	3.5 – 7	Default

2.3.5 Calibration and Validation

The full watershed was calibrated and validated to three locations in the storm sewer network based on the placement of the ultrasonic level and HOBO pressure transducer sensors; designated as WC5, BL, and WC4, corresponding to the West Basin, Berkeley Lake Basin, and East Basin, respectively (Figure 2.2). Model calibration and validation was performed using a split-sample evaluation with continuous 5-minute RainVieux rainfall data for the time periods listed in

Table 2.1. Different simulation periods were used for different study basins based on flow data availability, but all data periods include between two and eleven rainfall events larger than 2.54 mm, which is the threshold found to produce runoff by the UDFCD (UDFCD, 2015). Total rainfall for the calibration and validation time series ranges from 14 to 106 mm with a typical median event size from 0.305 to 0.737 mm.

Summer months were modeled based on data availability and to avoid the impacts of snowmelt. All simulations utilized one month of observed rainfall data to "spin-up" the model and equilibrate soil moisture and storage node conditions. In addition, anthropogenic inflows contributing to the storm sewers in the form of lawn or landscape irrigation runoff between storm events (particularly in the modeled summer months) was separated from observed flows via the USGS's hydrograph separation program, HYSEP (USGS, 2016), and added to the model as continuous time series files at the three modeling calibration locations.

A sensitivity analysis following methods presented by Rosa *et al.* (2015) was performed to quantitatively determine which parameters most impacted model output. Model parameters were adjusted over ranges of physically feasible values while keeping all other parameters unchanged. The model was run using rainfall data from April to June 2017. Then, the percent change in peak flow at the study area outlet (point O1, Figure 2.2) and total runoff volume were recorded. These percent changes were then normalized to the percent change in the parameter to produce relative sensitivity results showing percent changes in model output per 1% change in model parameters. The model parameters exhibiting the highest sensitivity were emphasized during calibration. Manual calibration was performed and assisted by PCSWMM's SRTC (sensitivity-based radio tuning calibration) tool, which runs simulations for maximum and minimum parameter scenarios based on user-defined parameter tolerances (Finney and Gharabaghi, 2011). Validation utilized the calibrated parameters from all three basins without additional modifications.

We assessed model performance using a combination of standard regression, error index, and dimensionless statistics in addition to graphical techniques. Statistics included those recommended by Moriasi *et al.* (2007) such as Root Mean Square Error Standard Deviation Ratio (RSR) in Equation 2.2, Nash-Sutcliffe Efficiency (NSE) in Equation 2.3, coefficient of determination (R^2) in Equation 2.4, and Percent Bias (%BIAS) in Equation 2.5, where recommended values for "good" model performance are RSR between 0 and 0.6, NSE and R^2 between 0.65 and 1.00, and %BIAS less than 15%, and recommended values for "satisfactory" model performance are RSR between 0.6 and 0.7, NSE and R^2 between 0.50 and 0.65, and %BIAS less than 25% (Moriasi *et al.*, 2007).

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\frac{1}{n}\sum(M-O)^2}}{\sqrt{\sum(O-O_{avg})^2}} \tag{2.2}$$

$$NSE = 1 - \frac{\sum(O-M)^2}{\sum(O-O_{avg})^2} \tag{2.3}$$

$$R^2 = 1 - \frac{\sum(M-O)^2}{\sum(M-O_{avg})^2} \tag{2.4}$$

$$\%BIAS = \frac{\sum(M-O)}{\sum O} \tag{2.5}$$

$Where$:

O = observations

O_{avg} = average of observations

M = model simulations

n = number of data points

2.3.6 Development Scenarios

To evaluate the impacts of land cover change due to infill development, we modeled and analyzed existing and future impervious surface scenarios including: a baseline simulation using land cover and percent impervious data from 2014; Scenario 1) 1.2% impervious increase from baseline (as predicted in Cherry, 2016); Scenario 2) 4.7% impervious increase from baseline; and Scenario 3) 8.1% impervious increase from baseline. In other words, the baseline scenario has a percent impervious value of 53.5% based on 2014 data. Scenario 1 simulates a percent impervious change of 1.2%, increasing the total basin impervious area to 54.7%. Scenario 2 simulates a percent impervious change of 4.7%, increasing the total basin impervious area to 58.2%. Scenario 3 simulates a percent impervious change of 8.1%, increasing the total basin impervious area to 62.7%. Parcels predicted for redevelopment in all three scenarios utilized probabilities of redevelopment from Cherry (2016) at various thresholds, where the first probability of 30% (Scenario 1) was determined by Cherry (2016) using statistical models to determine the threshold associated with redevelopment in the Berkeley study area through 2024. Scenarios 2 and 3 represent incremental thresholds of increasing infill development above Scenario 1. Scenario 1 predicts that parcels with probabilities over 30% that are theorized to redevelop will be redeveloped between 2014 and 2024, Scenario 2 predicts that parcels with probabilities over 20% will redevelop and Scenario 3 predicts that parcels with probabilities over 10% will redevelop from 2014 to an undetermined or hypothetical time period.

A key assumption is that only land uses defined as “Single Family,” “Multi-Family Low Rise,” and “Vacant” in 2014 would be redeveloped. It was assumed that Single Family parcels would redevelop to Multi-Family Mid Rise parcels, Multi-Family Low Rise parcels would redevelop to Multi-Family Mid Rise parcels, and Vacant parcels would redevelop to Single Family parcels with the corresponding changes in percent impervious area of those parcels (Table 2.3). Impervious value changes were then distributed to the 170 model subcatchments via area-weighting (larger areas are weighted more heavily) for each of the three scenarios, resulting in overall increases in watershed imperviousness spatially consistent with the scenarios described above. Figure 2.4 illustrates the area of land use types for the three scenarios, where 251 ha are classified as “other” for all scenarios, meaning 251 ha of the catchment do not undergo redevelopment for any of the future scenarios. The Single Family and Multi-Family Low Rise land uses decrease significantly from baseline through Scenario 3 as they are converted to Multi-Family Mid Rise (which increases from 1.3 ha at baseline to 175 ha in Scenario 3; Figure 2.4). Vacant area decreases slightly between baseline and Scenario 3.

Table 2.3 Current (2014) land uses, redeveloped land uses, and changes in percent impervious values by land use.

Current Land Use	Redeveloped Land Use	Current %Impervious	Redeveloped %Impervious	% Impervious Change by Land Use
Single Family	Multi-Family Mid Rise	43	70	27
Multi-Family Low Rise	Multi-Family Mid Rise	52	70	18
Vacant	Single Family	21	43	22

After calibration and validation, runoff was simulated for all scenarios using synthetic rainfall events for the 2, 5, 10, 25, 50, and 100-year, 24-hour design storms using a Type-II National Resources Conservation Service (NRCS) rainfall distribution at 5-minute intervals (Akan and Houghtalen, 2003) as well as the 6-hour Water Quality Capture Volume (WQCV) event, as defined by the Urban Storm Drainage Criteria Manual, Volume 3. The WQCV event corresponds to the 80th percentile storm, or 17.5 mm in the study area (UDFCD, 2015). UDFCD has determined that capturing and treating the runoff volume produced by the WQCV storm event results in significant improvements to water quality (Urbonas *et al.*, 1989).

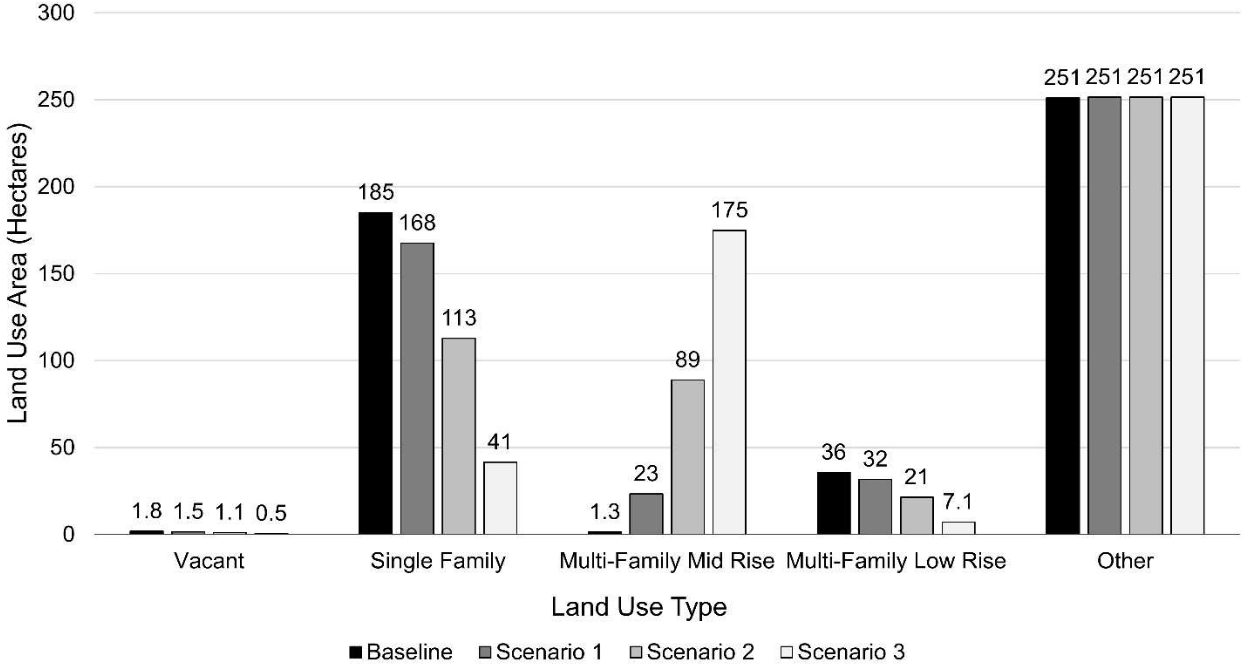


Figure 2.4 Land use area by redevelopment scenario. 251 hectares (60% of the full watershed) are not redeveloped and therefore stay constant.

Results for each design storm were analyzed at the full study area outlet (see point O1, Figure 2.2) for stormwater runoff volume, peak flow in the storm sewer network, runoff ratios (r), and flooding volume. Runoff ratios are defined by Equation 2.6 where Q is the stormflow in mm and P is the total precipitation in mm.

$$r = \frac{Q}{P} \tag{2.6}$$

In addition, long-term simulations were performed for each redevelopment scenario using 5-minute RainVieux precipitation data from May through September for 2013, 2014, 2015, 2016, and 2017 (note that RainVieux sensors are turned off in the winter as the study site receives the majority of its rainfall from May through September). The long-term simulations were analyzed at the full study area outlet (point O1) for total runoff volume, mean and maximum statistics, and the number of data points with discharge greater than the WQCV (defined above).

2.4 Results

2.4.1 Calibration and Validation

Results of the sensitivity analysis revealed that the most sensitive PCSWMM model parameters included impervious depression storage and impervious Manning's roughness coefficient with moderate sensitivity to pervious depression storage, overland flow width, and subcatchment slope, which agrees with results of previous SWMM studies (Niazi *et al.*, 2017; Rosa *et al.*, 2015). The model was insensitive to pervious Manning's roughness coefficient. Calibration resulted in "good" model performance statistics as defined by Moriasi *et al.* (2007) at the outlet of all three modeled basins (Table 2.4 and Figure 2.5) with a high average NSE value of 0.814 and a low average %BIAS of about 2% (absolute bias) at the 5-minute time step. The Berkeley Lake Basin resulted in the best model performance with a calibrated NSE value of 0.979 and calibrated %BIAS of -1.18%. For both calibration and validation, the Berkeley Lake Basin has a slight negative %BIAS (under-prediction of runoff) while the West and East Basins have a positive %BIAS (over-prediction of runoff). It is likely that the Berkeley Lake Basin under-predicts flow slightly due to the rapid rate of redevelopment occurring in the basin. Therefore, there are more discrepancies between the land cover data from 2014 and the runoff data from 2016 in this basin than in other areas of the neighborhood. Interestingly, the calibrated depression storage values increased significantly from uncalibrated values (Table 2.2), particularly for the East Basin, perhaps indicating an unknown existing BMP or other existing infrastructure is providing depression storage.

Several validation statistics improved for the East Basin (NSE, R^2, and RSR), but worsened for the West Basin (NSE, R^2, and %BIAS). Across all three modeled basins, validation yielded "satisfactory" overall model performance as defined by Moriasi *et al.* (2007) (Table 2.4) with an average NSE value of 0.724 and an average %BIAS of about 12% (absolute bias). The West Basin resulted in the poorest validation, but all are still within the "satisfactory" model performance range. Two storm events were under-predicted during the Berkeley Lake Basin validation (Figure 2.5), but these storms accounted for a small number of 12,175 total data points (Table 2.4) thus resulting in good overall validation statistics. Overall, the calibrated and validated model adequately simulates runoff volume and storm sewer flow peaks and timing at a 5-minute interval across the studied Berkeley neighborhood watershed.

Table 2.4 Performance statistics for PCSWMM model calibration and validation.

	Simulation Dates	Number of Data Points	Basin	NSE	R^2	RSR	Percent Bias (%)
Calibration	4/17/2017 – 6/3/2017	13,362	West Basin	0.748	0.794	0.50	4.13%
	7/14/2016 – 9/5/2016	15,205	Berkeley Lake Basin	0.979	0.979	0.15	-1.18%
	4/17/2017 – 6/3/2017	13,362	East Basin	0.716	0.726	0.53	1.14%
Validation	6/4/2017 – 7/27/2017	15,366	West Basin	0.500	0.615	0.70	19.63%
	9/2/2015 – 10/15/2015	12,175	Berkeley Lake Basin	0.921	0.923	0.28	-6.14%
	6/4/2017 – 7/27/2017	15,366	East Basin	0.751	0.868	0.50	9.71%

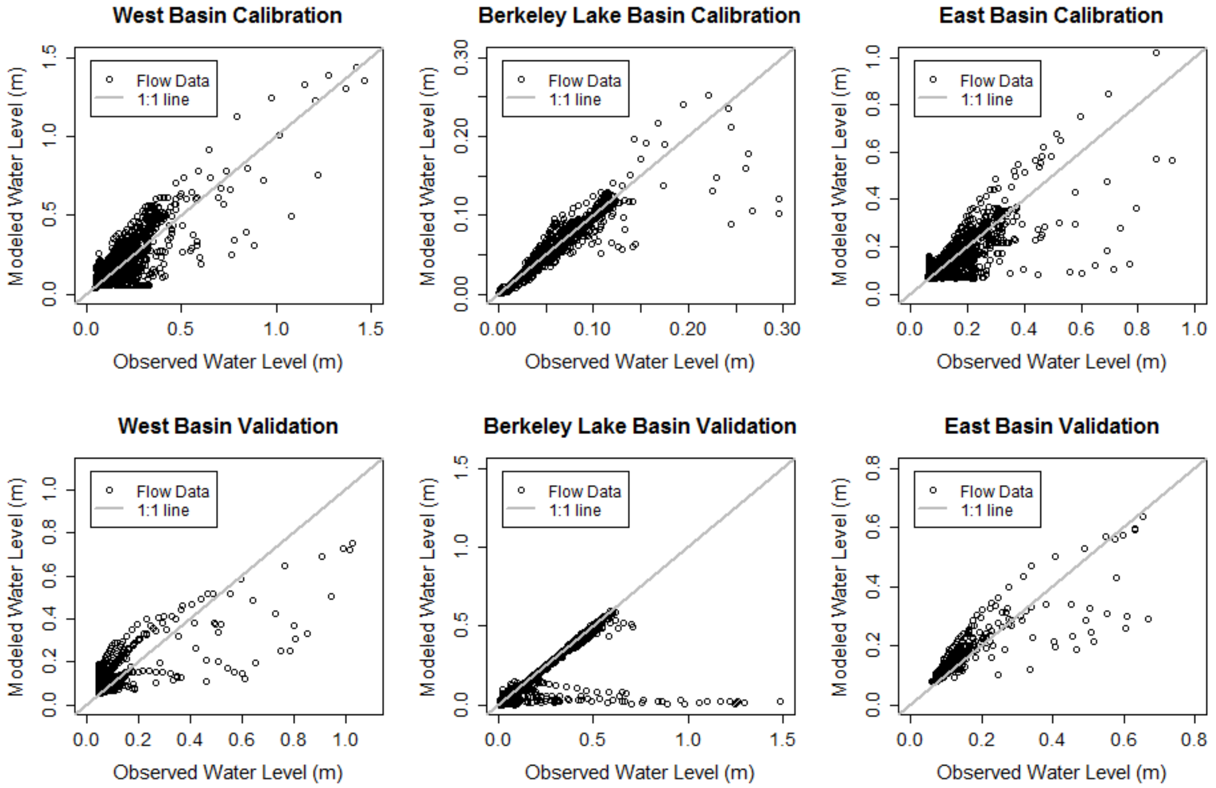


Figure 2.5 One-to-one plots of observed versus modeled outlet water level for the West, Berkeley Lake, and East Basins for calibration and validation. Points along the one-to-one line indicate a perfect model fit.

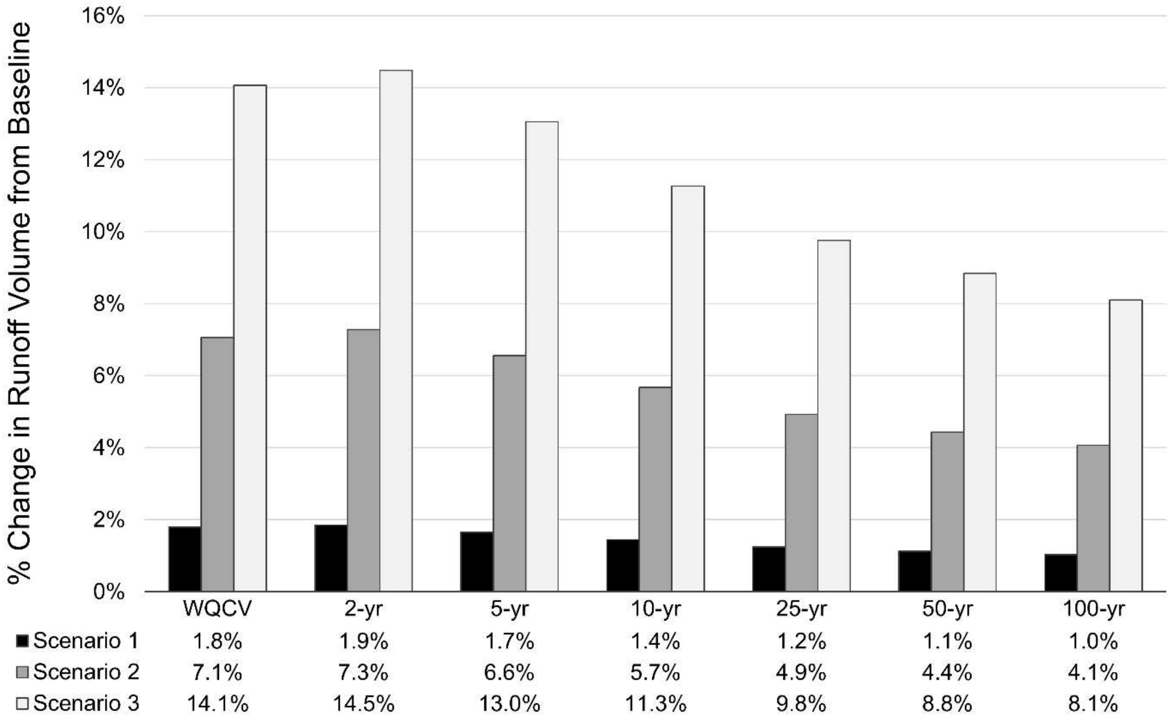
2.4.2 Development Scenarios

Simulations of increasing impervious cover due to infill in the Berkeley neighborhood show increases in total surface runoff volume compared to baseline for all evaluated storms (WQCV, 6-hr event to the 2-yr through 100-yr, 24-hr events). The percentage increase in runoff volumes are largest for the smaller storm events. In general, pervious areas become fully saturated during larger, intense storm events effectively acting as impervious areas and increasing runoff generation. Therefore, in the context of a larger storm, a change from pervious to impervious land cover is less impactful.

Table 2.5 shows the average increase in runoff volume per 1% increase in imperviousness for each storm event averaged across all three redevelopment scenarios. Increases in runoff volume are 1.9%, 7.3%, and 14.5% for the 2-yr, 24-hr storm for Scenarios 1, 2, and 3, respectively (Figure 2.6), as a result of the 1.2, 4.7, and 8.1 % increases in imperviousness, respectively. Again, increases in runoff volume per increase in impervious area are larger for smaller storm events (i.e., 1.63% increase for the 2-yr, 24-hr storm versus 0.91% for the 100-yr, 24-hr storm). The 1.27% increase in runoff volume predicted for the 10-yr, 24-hr storm is larger than the Hekl and Dymond (2016) prediction of a 0.8% runoff volume increase for the same design storm in a study area in Fairfax County, Virginia, although of the same magnitude (i.e., less than a few %). In addition, the average watershed runoff ratio (ratio of runoff depth to rainfall depth across all storm events) increases from 0.566 at baseline to 0.574, 0.598, and 0.629 for Scenarios 1, 2, and 3, respectively.

Table 2.5 Average percent increase in runoff volume per 1% increase in imperviousness by simulated storm event.

Storm Event	Average Percent Increase in Runoff Volume per 1% Increase in Imperviousness
WQCV, 6-hr	1.58%
2-yr, 24-hr	1.63%
5-yr, 24-hr	1.46%
10-yr, 24-hr	1.27%
25-yr, 24-hr	1.10%
50-yr, 24-hr	0.99%
100-yr, 24-hr	0.91%



	WQCV	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
■ Scenario 1	1.8%	1.9%	1.7%	1.4%	1.2%	1.1%	1.0%
▨ Scenario 2	7.1%	7.3%	6.6%	5.7%	4.9%	4.4%	4.1%
□ Scenario 3	14.1%	14.5%	13.0%	11.3%	9.8%	8.8%	8.1%

Figure 2.6 Percent increase in total surface runoff volume from baseline for each design storm event by scenario. Note that the WQCV is a 6-hr event, while all others are 24-hr.

The impact of infill development on small to large storm events is further illustrated in Figure 2.7, which depicts the full basin outlet (design point O1) hydrographs for the 2-yr, 10-yr, and 100-yr, 24-hr storms for the Baseline scenario and Scenario 3. Note that for clarity, this figure details only the middle/peak three hours of the full 24-hour storms, and only includes three of the seven modeled storms and two of the four modeled scenarios. For the 2-yr storm, there is an increase in outlet discharge for the full three hours of the hydrograph and a 0.85 m^3/s increase in peak flow between the Baseline scenario and Scenario 3. By contrast, the 100-yr storm shows difference in flow between the scenarios for the rising limb of the hydrograph, but nearly identical peak flows and receding limbs. Figure 2.7 illustrates that again, relative changes between scenarios are largest for small storm events, including changes in peak flow.

Results also show that the relationship between increased impervious area and stormwater runoff volume is linear across all storm events for the investigated scenarios (Figure 2.8). This relationship is helpful in determining the potential runoff volume for impervious cover changes not investigated in the three scenarios. For example, if a new prediction states that impervious cover in Berkeley will increase to 57% from its current 53%, stormwater managers can expect a 2-yr runoff volume of 9.87×10^4 m^3 based on this approximately linear relationship.

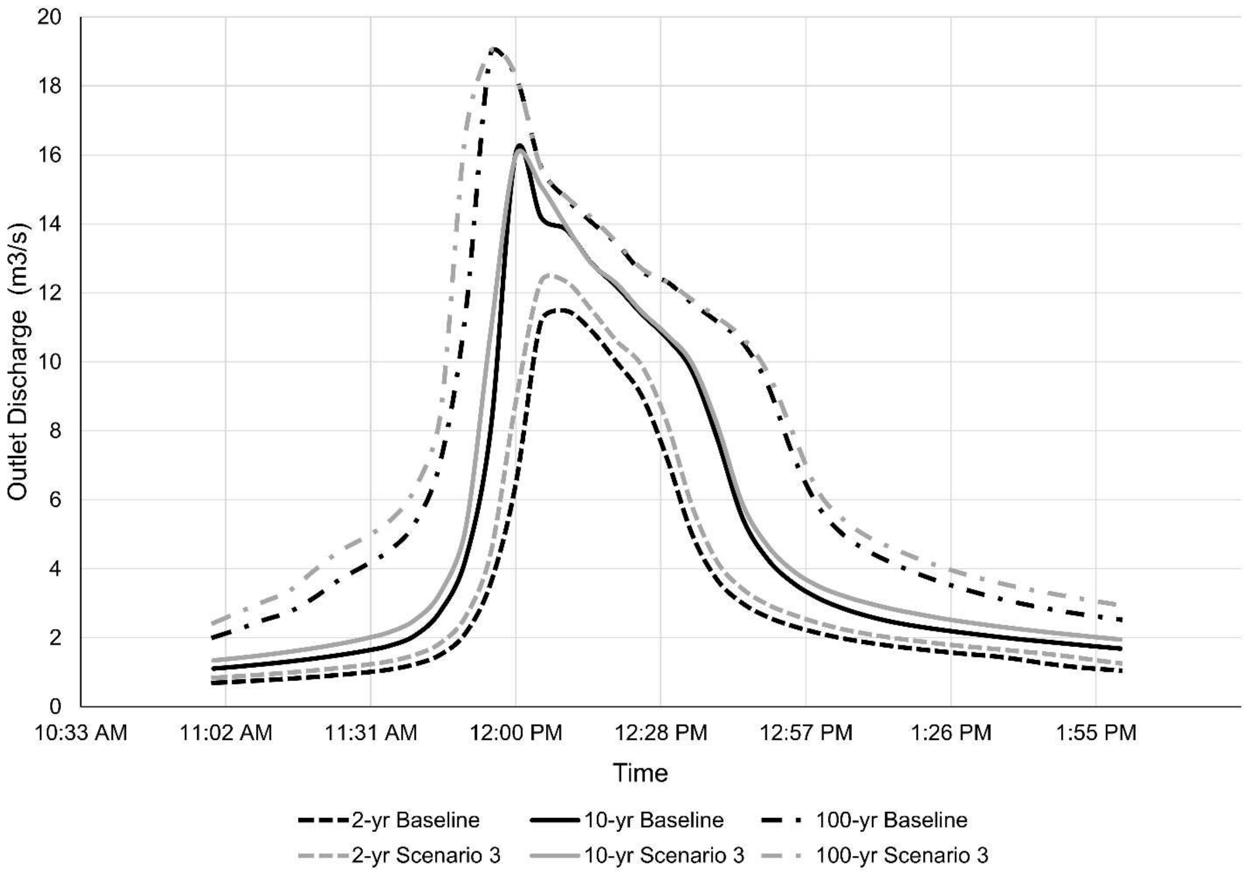


Figure 2.7 Discharge hydrographs for the peak three hours of the 2-yr, 10-yr, and 100-yr, 24-hr storms for the Baseline scenario and Scenario 3.

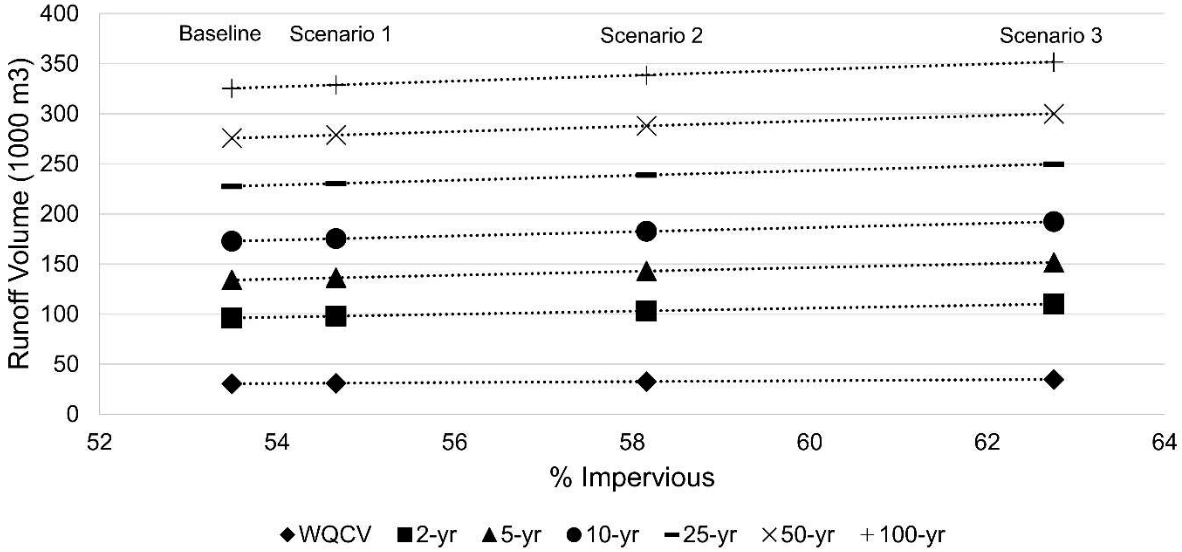


Figure 2.8 Relationship between increased impervious area and stormwater runoff volume.

As noted, peak flows also increase with increasing percent impervious area at various storm sewer locations throughout the catchment, but these increases are often to levels *above* storm sewer pipe capacities. At four modeling points within the catchment, storm sewer capacities are exceeded for storm sizes equal to or larger than the 5-yr, 24-hr storm for Scenario 1 (Figure 2.9). Other locations in the storm sewer network reach capacity at the 2-yr, 24-hr storm event. Similar results are observed for Scenarios 2 and 3. When pipe capacities are reached, the storm sewers fill, and surcharging and flooding occurs in the form of ponded water at the surface.

The simulated design storm scenarios predict that minimal to no flooding occurs during the 6-hr, WQCV event, and that the storm sewer network in the Berkeley catchment begins to flood at the 2-yr, 24-hr storm event. Similar to peak flows, flooding volumes also increase with increasing impervious area and larger storm sizes. The number of flooded locations within the catchment and the total flood hours also increase. Similar to runoff volume, there is a linear relationship between increased impervious area and flooding volume across all storm events, which again could be used to predict flooding volumes across the Berkeley catchment for different percent impervious values.

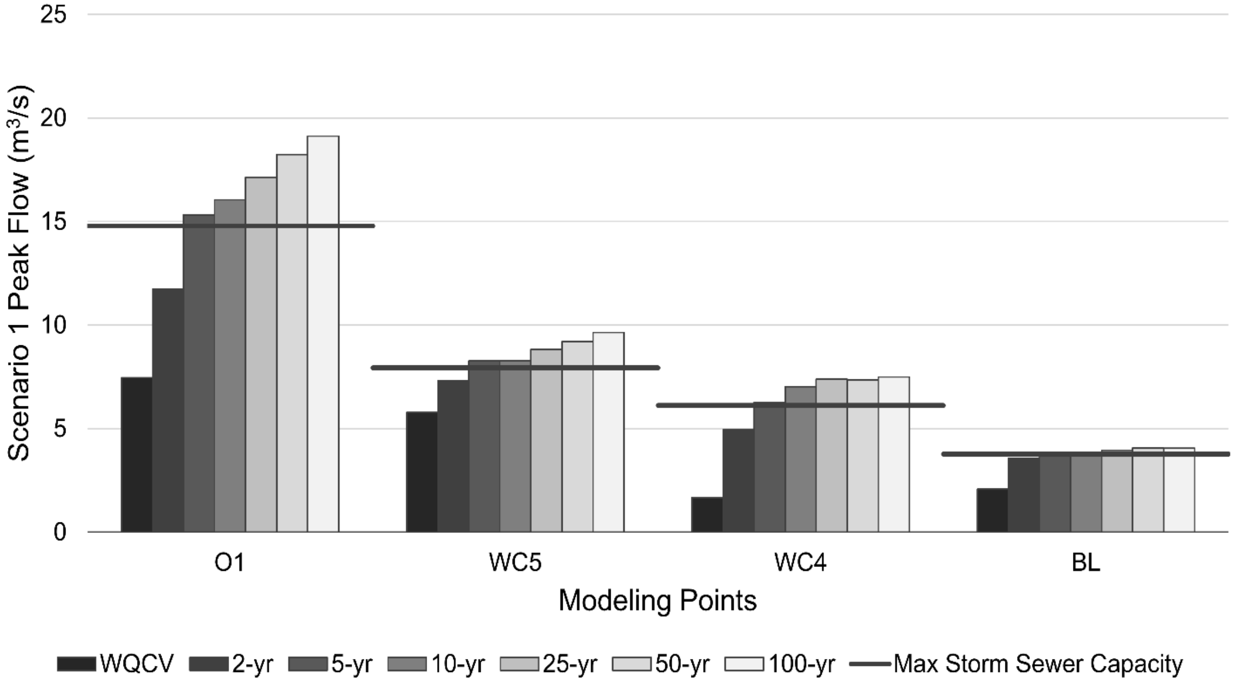


Figure 2.9 Scenario 1 peak flows at four modeling points for the simulated design storms. Maximum peak flows at each modeling point (based on storm pipe parameters and capacities) are shown by horizontal lines.

A spatial map of the Scenario 1 simulation (1.2% impervious increase by 2024) for the 2-yr, 24-hr storm event (Figure 2.10) shows runoff ratios by subcatchment that range from 0.131 to 0.807. Higher runoff ratios are concentrated around and east of Tennyson Street, a rapidly growing business corridor which is targeted for continued infill development. Subcatchments including the two existing lakes in the catchment show lower runoff ratios, demonstrating the storage and buffering capacities of the lake systems. Subcatchments including existing BMPs in the East and West basins also show a lower runoff response. The seventeen subcatchments (top 10%) with the largest increases in runoff volume (indicated with stars in Figure 2.10) are located throughout the basin in various proximity and connection to the lakes and existing BMPs, illustrating that the impacts of infill on runoff volume can occur regardless of existing management systems. A spatial map of the Scenario 1 simulation of the 2-yr, 24-hr storm event depicting total flood volume at each of the modeled storm sewer network nodes/manholes illustrates that storm sewer surcharging also occurs throughout the Berkeley catchment (Figure 2.11). In addition, results show increasing numbers of flooding/surcharging nodes with increasing storm size and each progressive infill scenario.

The average results of the long-term May through September simulations for the years 2013 through 2017 are summarized in Table 2.6. It was found that stormwater runoff volume increases 41,000 m^3 above the Baseline scenario to Scenario 3 for a total runoff volume of 362,000 m^3, which is nearly 85% of the full capacity of the neighborhood's Berkeley Lake. In addition, the mean discharge, maximum discharge, and discharge above the WQCV increase with each successive scenario.

Table 2.6 Average results for model simulations of May through September rainfall for 2013 through 2017.

	Baseline	Scenario 1	Scenario 2	Scenario 3
Total Runoff Volume (m^3)	321,000	326,500	342,000	362,000
Additional Runoff Volume from Baseline (m^3)	0	5,500	21,000	41,000
Mean Discharge (m^3/s)	0.0237	0.0241	0.0252	0.0268
Maximum Discharge (m^3/s)	9.56	9.70	10.10	10.56
# of data points > 7.32 m^3/s (WQCV)	4.6	5.2	5.8	7

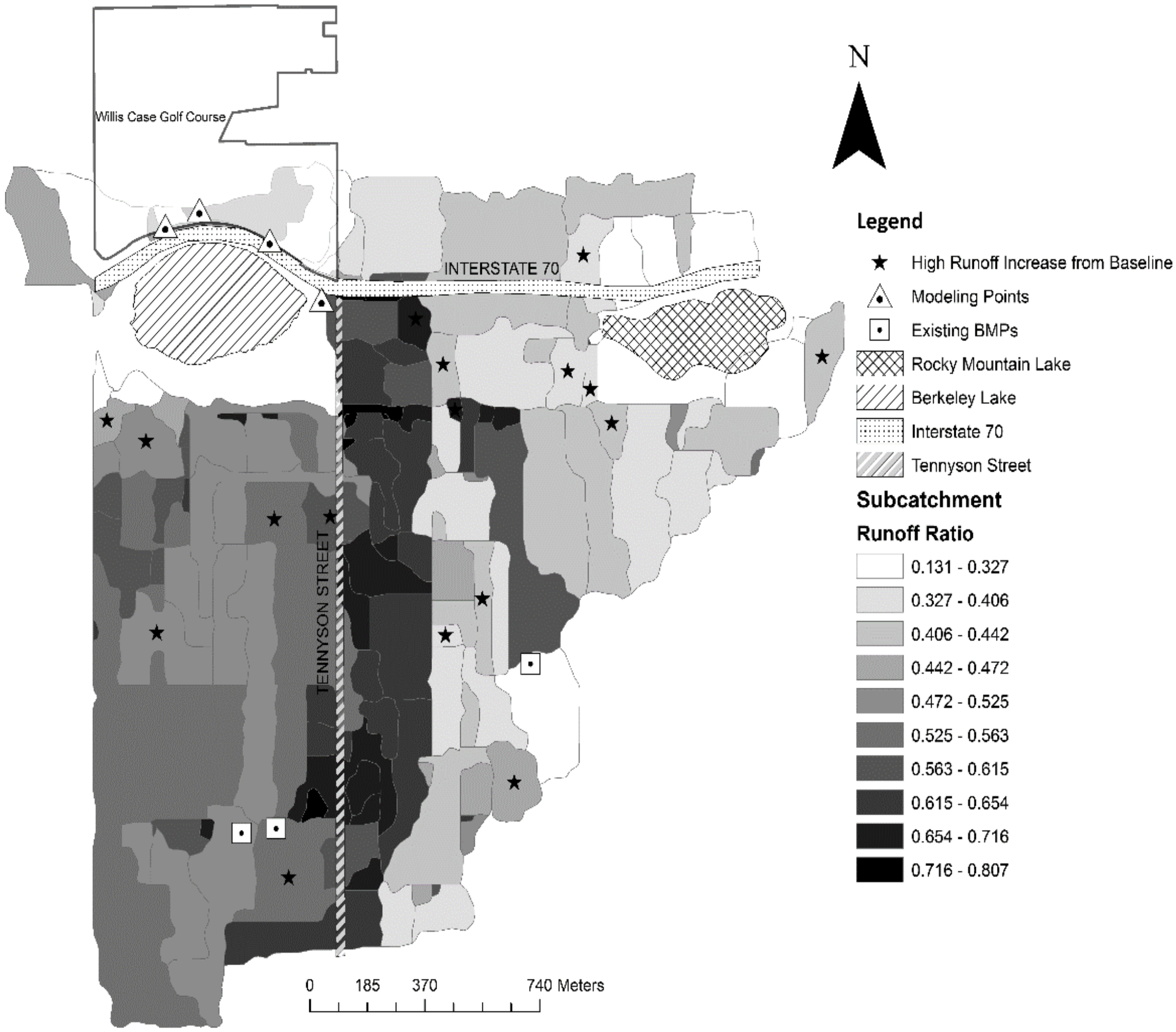


Figure 2.10 Spatial map of runoff ratios by subcatchment for the 2-yr, 24-hr storm event Scenario 1 simulation.

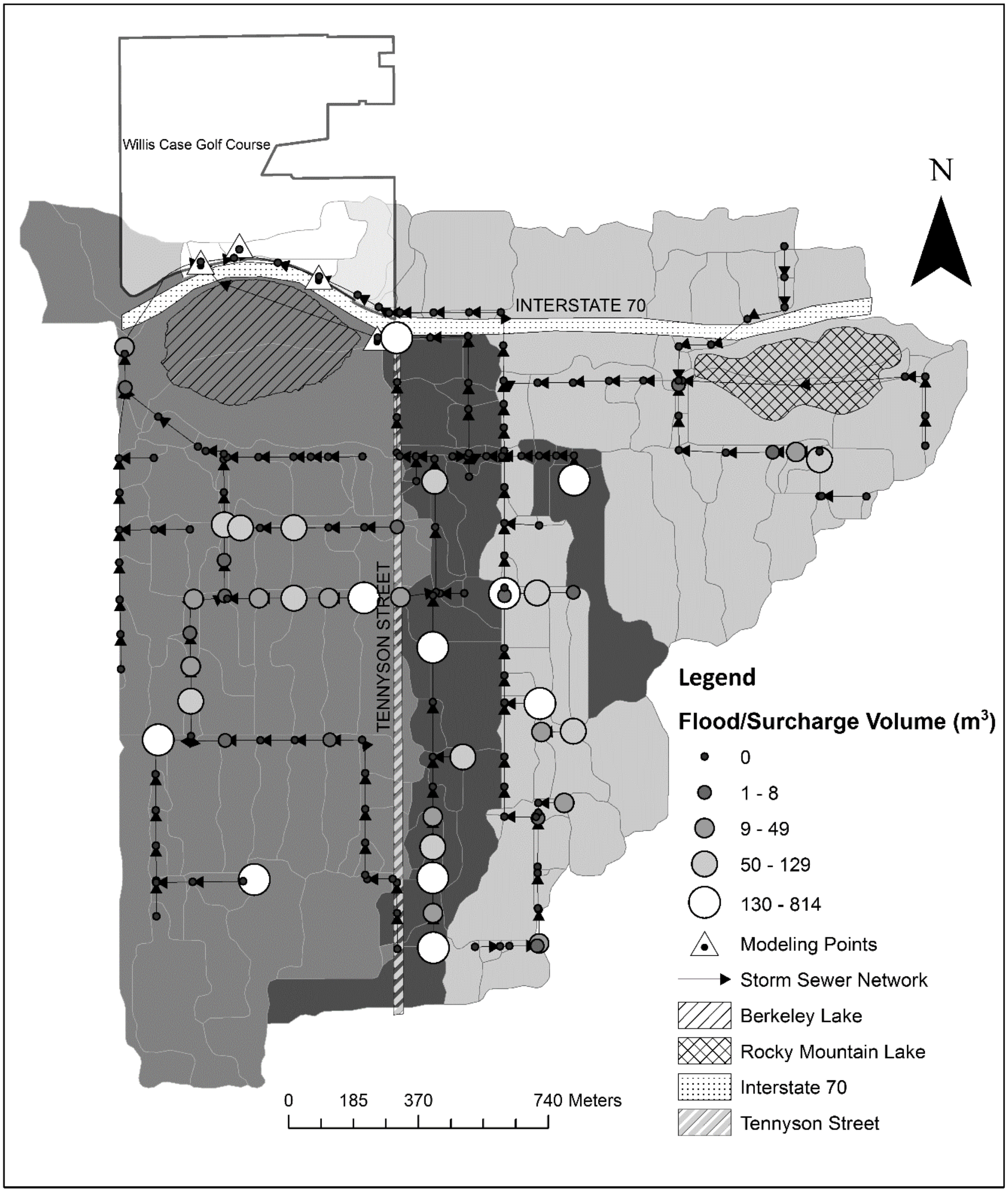


Figure 2.11 Spatial map of total flood volume (in m^3) by node (storm sewer manhole) for the 2-yr, 24-hr storm Scenario 1 simulation. Flooding occurs throughout the catchment and is calculated based on the amount of stormwater that exceeds the storm sewer capacity at the node.

2.5 Discussion

The current City and County of Denver Storm Drainage Design and Technical Criteria Manual (DPW, 2013) states that flood control detention practices are exempt for redevelopment of 0.2 ha or less. In the studied scenarios, over 99% of redeveloped parcels for all three future redevelopment scenarios were smaller than this threshold and would thus be exempt from flood control requirements under current policy. Results show flooding potentials up to $1.02\text{x}10^5$ m^3 for a single storm event (Scenario 3, 100-yr, 24-hr event) that could damage residential and non-residential buildings, the storm sewer system, power, water, and gas supplies, and roadways. It was found that flooding locations are not correlated to any one parameter (pipe size, invert depth, runoff ratios, etc.), but are instead influenced by a combination of these factors. This makes pinpointing flood locations, or remediating storm infrastructure, to account for flooding under future redevelopment scenarios difficult without the aid of hydrologic modeling such as that conducted in this study. Changes in policy that would require current flood control detention practices on properties less than 0.2 ha could result in capture of excess stormwater runoff before it becomes a flood risk.

The combination of increased flood volumes and increased stormwater runoff volume due to future infill development provides interesting possibilities for relieving increased water stress in the Denver area through beneficial use of stormwater. Simulations of runoff from May through September revealed that up to 362,000 m^3 of runoff volume is produced in Scenario 3. For perspective, this is theoretically enough water to supply the local Willis Case Golf Course (location shown in Figure 2.2) with irrigation water for over fourteen months based on a 308,000 m^3/year demand (R. Murtaugh, Willis Case Golf Course Superintendent, personal communication, 2016). As the last Denver golf course to use potable water for irrigation (D. Mollendor, City and County of Denver Wastewater Management, personal communication, 2016), the potential for stormwater re-use is compelling. If used for residential outdoor water use (which is ~50% of total residential water use in Denver), the stormwater runoff produced from Berkeley could meet the May through September outdoor water needs of over 4,700 Denver residents – based on 2015's 0.5 m^3/day per capita water use (Denver Water, 2016b) – which is 43% of the Berkeley neighborhood's current population. Similar water use implications for Scenarios 1 and 2 are shown in Figure 2.12.

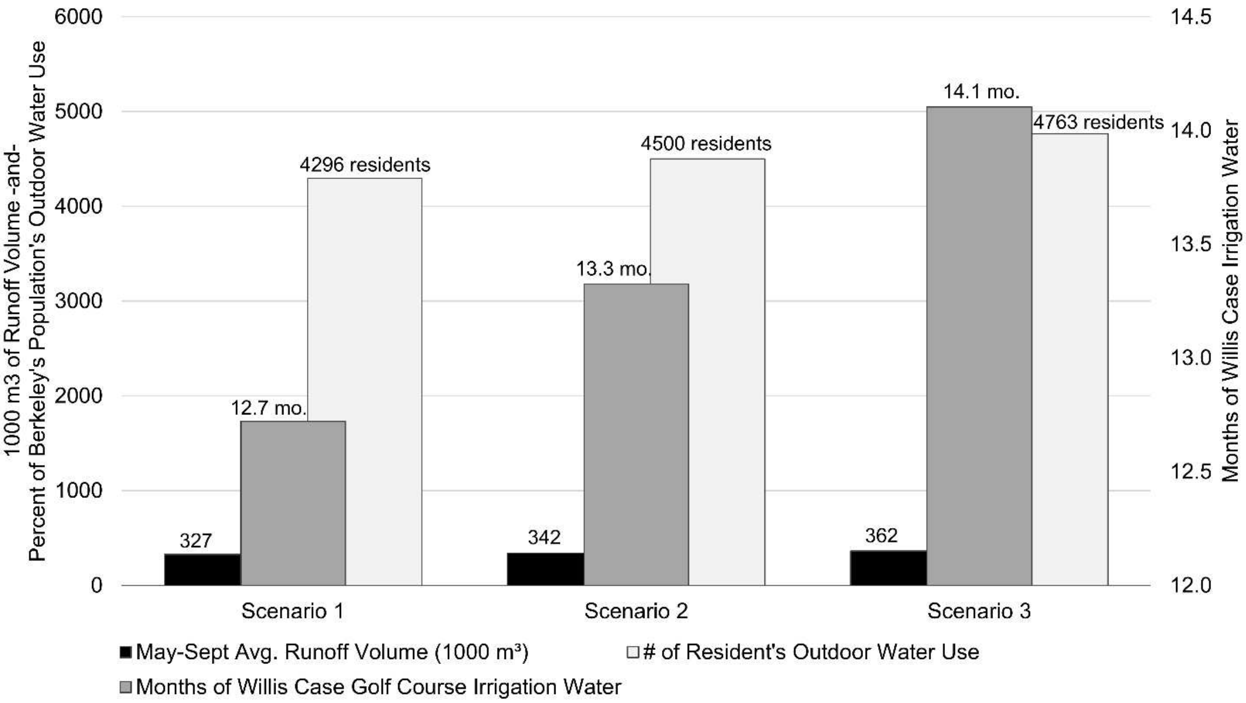


Figure 2.12 Implications of beneficial use of stormwater runoff on water supply needs including the potential months of Willis Case Golf Course irrigation water provided and number of Denver residents' outdoor water use (May through September) served.

While capturing all of the stormwater runoff from the Berkeley neighborhood and putting it to beneficial use invokes many water rights questions and issues within Colorado's prior appropriation doctrine as well as conversations about timing and storage, the idea merits further investigation and serious consideration. Plans to design a BMP treatment train for the Willis Case Golf Course or other nearby parks are underway to capture a portion of the additional stormwater runoff from infill development in the Berkeley neighborhood.

2.6 Conclusions

Previous urban studies have generally focused on the changes to stormwater dynamics caused by a direct conversion from undeveloped to developed land uses. Few studies have investigated redevelopment, or "infill" development, and there has been substantial debate on the impact of this type of growth on runoff behavior, peak flows, flood events, and water quality. Key conclusions and contributions from this research include:

- Infill development causes increases in impervious area that result in percent increases in surface runoff volumes that are largest for smaller storm events; the relationship between increased impervious area and stormwater runoff volume is approximately linear across all storm sizes.

- Peak flows increase with increasing impervious area due to infill development, and in the case of the Berkeley neighborhood, the existing storm sewer network reaches capacity (and begins to flood) for the 2-yr, 24-hr design storm event for all studied future redevelopment scenarios. Spatial maps of the catchment pinpoint areas of high runoff volume and flooding surrounding a rapidly growing business corridor and the local interstate.
- Flooding volumes, number of flooded locations, and total flooded hours increase approximately linearly with increasing impervious area and larger storm sizes.
- 99% of the parcels redeveloped in the study scenarios are exempt from flood control detention under current policy, demonstrating that current stormwater capture policies regarding infill development need to be revisited.
- If the stormwater runoff produced from redevelopment in an average "summer" (May through September) was captured and put to beneficial use, up to 4,700 Denver residents' May through September outdoor water use would be accounted for, or 14 months of golf course irrigation water that is currently potable.

2.7 Acknowledgements

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2.8 References

Akan, A. O. and R. J. Houghtalen. 2003. *Urban Hydrology, Hydraulics, and Stormwater Quality: Engineering Applications and Computer Modeling*, John Wiley and Sons, Hoboken, New Jersey.

Alley, W. M. and J. E. Veenhuis. 1983. "Effective Impervious Area in Urban Runoff Modeling." *J. Hydraul. Eng.* 109(2): 313-319. doi.org/10.1061/(ASCE)0733-9429(1983)109:2(313)

Arvola, A. and K. Pennanen. 2014. "Understanding residents' attitudes towards infill development at Finnish urban suburbs." In *Conference proceedings World Sustainable Building 2014, WSB14.* 3: 19-28.

Bloorchian, A. A., L. Ahiablame, A. Osouli, and J. Zhou. 2016. "Modeling BMP and Vegetative Cover Performance for Highway Stormwater Runoff Reduction." *Procedia Eng.* 145: 274-280. doi.org/10.1016/j.proeng.2016.04.074

Burchell, R. W., D. Listokin, and C. C. Galley. 2000. "Smart growth: More than a ghost of urban policy past, less than a bold new horizon." *Housing Policy Debate*. 11(4): 821-879. doi.org/10.1080/10511482.2000.9521390

Cherry, L. 2016. "Predicting Parcel Scale Redevelopment within the Berkeley Neighborhood in Denver Colorado Using Linear and Logistic Regression." M.S. thesis, Colorado School of Mines, <http://hdl.handle.net/11124/170658> (Accessed May 24, 2017).

Cooper, M. H. 2004. "Can Managed Growth Reduce Sprawl?" *Congressional Quarterly Researcher.* 14(20): 469-492.

Denver Department of Public Works (DPW), Wastewater Management Division, Engineering Division. 2013. "City and County of Denver Storm Drainage Design & Technical Criteria Manual." denvergov.org

Denver Department of Public Works (DPW). 2014. "City and County of Denver Storm Drainage Master Plan." denvergov.org

Denver Water. 2016a. "2016 Water Quality Report." denverwater.org

Denver Water. 2016b. "2016 Comprehensive Annual Financial Report." denverwater.org

Downs, A. 2005. "Smart Growth: Why We Discuss It More Than We Do It." *J. Am. Plan. Assoc.* 71(4): 367-378. doi.org/10.1080/01944360508976707

Emerson, C. H., C. Welty, and R. G. Traver. 2005. "Watershed-Scale Evaluation of a System of Storm Water Detention Basins." *J. Hydrol. Eng.* 10(3). doi.org/10.1061/(ASCE)1084-0699

Environmental Protection Agency (EPA). 2012. "2012 Construction General Permit (CGP) – Fact Sheet." <https://www3.epa.gov/npdes/pubs/cgp2012_finalfactsheet.pdf> (Accessed November 9, 2017).

Environmental Protection Agency (EPA). 2017. "National Stormwater Calculator." < https://www.epa.gov/water-research/national-stormwater-calculator> (Accessed October 20, 2017).

Finney, K., and B. Gharabeghi. 2011. “Using the PCSWMM 2010 SRTC Tool to Design a Compost Biofilter for Highway Stormwater Runoff Treatment.” *J. Water Manag. Model.* doi.org/10.14796/JWMM.R241-09

Goetz, A. 2013. “Suburban Sprawl or Urban Centres: Tensions and Contradictions of Smart Growth Approaches in Denver, Colorado.” *Urban Studies*. 50: 2178-2195. doi.org/10.1177/0042098013478238

Grebel, J. E., S. K. Mohanty, A. A. Torkelson, A. B. Boehm, C. P. Higgins, R. M. Maxwell, K. L. Nelson, and D. L. Sedlak. 2013. “Engineered Infiltration Systems for Urban Stormwater Reclamation.” *Environ. Eng. Sci*. 30(8): 437-454. doi.org/10.1089/ees.2012.0312

Grimm, N. B, S. H. Faeth, N. E. Bolubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2008. “Global Change and the Ecology of Cities.” *Science*. 319(5864): 756-760. doi.org/10.1126/science.1150195

Hekl, J. A. and R. L. Dymond. 2016. “Runoff Impacts and LID Techniques for Mansionization-Based Stormwater Effects in Fairfax County, Virginia.” *J. Sustainable Water in the Built Environ.* doi.org/10.1061/JSWBAY.0000815

Johnson, M. P. 2001. “Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda.” *Environment and Planning A.* 33 (4): 717-735. doi.org/10.1068/a3327

Kabbani, M. S. 2015. “Using PCSWMM to simulate first flush and assess performance of extended dry detention ponds as structural stormwater BMPs in a large polluted urban watershed.” Ph.D. (Doctor of Philosophy) thesis, University of Iowa, <http://ir.uiowa.edu/etd/1653> (Accessed March 16, 2016).

Lee, J. G., A. Selvakumar, K. Alvi, J. Riverson, J. X. Zhen, L. Shoemaker, and F. Lai. 2012. “A watershed-scale design optimization model for stormwater best management practices.” *Environ. Modell. Softw*. 37: 6-18. doi.org/10.1016/j.envsoft.2012.04.011

Liu, Y., L. M. Ahiablame, V. F. Bralts, and B. A. Engel. 2015. “Enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff.” *J. Environ. Manage*. 147: 12-23. doi.org/10.1016/j.jenvman.2014.09.005

McConnell, V. and K. Wiley. 2010. “Infill Development: Perspectives and Evidence from Economics and Planning,” working paper, Resources for the Future, Washington, DC.

Metro Denver. 2017. “Historic & Projected Population.” <http://www.metrodenver.org/do-business/demographics/population/> (Accessed July 14, 2016.)

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. “Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations.” *J. Am. Soc. Agric. Biol. Eng.* 50(3): 885-900. doi.org/10.13031/2013.23153

National Research Council (NRC). 2009. *Urban Stormwater Management in the United States*. Washington, DC: The National Academies Press. doi.org/10.17226/12465

Niazi, M., C. Nietch, M. Maghrebi, N. Jackson, B. R. Bennett, M. Tryby, A. Massoudieh. 2017.

"Storm Water Management Model: Performance Review and Gap Analysis." *J. Sustainable Water Built Environ*. 3 (2). doi.org/10.1061/JSWBAY.0000817

Pond, M. C. and G. Kacvinsky. 2006. "Tear-downs - controlling stormwater impacts." <http://waterbucket.ca/gi/files/2013/03/Teardowns-controlling-stormwater-impacts.pdf> (Accessed June 19, 2017).

Rosa, D. J., J. C. Clausen, and M. E. Dietz. 2015. "Calibration and Verification of SWMM for Low Impact Development." *J. Am. Water Resour. Assoc*., 51(3): 746-757. doi.org/10.1111/jawr.12272

Saatci, A. 1990. "Velocity and Depth of Flow Calculations in Partially Filled Pipes." *J. Environ. Eng*. 116(6): 1202-1208. doi.org/10.1061/(ASCE)0733-9372(1990)116:6(1202)

Sartor, J. D. *et al.* 1974. "Water pollution aspects of street surface contaminants." *J. Water Pollut. Control Fed*. 46(3): 458-467.

Shamead, S. M., C. Fan, W. Cao, D. Banting, D. Joksimovic, and J. Li. 2014. "A New Automated Approach to Sewershed Delineation for Urban Drainage Modelling Studies: A City of Toronto Case Study." 11th International Conference on Hydroinformatics. HIC 2014, New York City, USA.

Steffen, J., M. Jensen, C. A. Pomeroy, and S. J. Burian. 2013. "Water Supply and Stormwater Management Benefits of Residential Rainwater Harvesting in U.S. Cities." *J. Am. Water Resour. Assoc*. 49(4): 810-824. doi.org/10.1111/jawr.12038

Urban Drainage and Flood Control District (UDFCD). 2015. "Urban Storm Drainage Criteria Manual: Volume 3." Chapter 3 Calculating the WQCV and Volume Reduction. udfcd.org/volume-three

Urbonas, B., J.C.Y. Guo, and L.S. Tucker. 1989. "Sizing Capture Volume for Stormwater Quality Enhancement." *Flood Hazard News*. Urban Drainage and Flood Control District: Denver, CO.

United States Geological Survey (USGS). 2016. "HYSEP: Hydrograph Separation Program." < https://water.usgs.gov/software/HYSEP/> (Accessed May 22, 2017).

Vieux, Inc. 2017. "RainVieux." <http://vflo.vieuxinc.com/rainvieux.html> (Accessed June 1, 2015).

Yang, Y., T.A. Endreny, and D.J. Nowak. 2015. "Simulating the effect of flow path roughness to examine how green infrastructure restores urban runoff timing and magnitude." *Urban Forestry & Urban Greening*. 14(2): 361-367. doi.org/10.1016/j.ufug.2015.03.004

CHAPTER 3

SWMM SENSITIVITY TO LID SITING AND ROUTING PARAMETERS: IMPLICATIONS FOR STORMWATER REGULATORY COMPLIANCE

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Chelsea L. Panos, Jordyn M. Wolfand[5], Terri S. Hogue

3.1 Abstract

Many cities are experiencing new growth through infill development, or “redevelopment,” where lower density land uses are redeveloped to high density resulting in increased impervious surfaces. Cities need revised stormwater criteria to manage increases in stormwater runoff and flooding from redevelopment via low impact development (LID). Watershed-scale hydrologic modeling in the Stormwater Management Model (SWMM) can inform these criteria. Several studies recognize the sensitivity of LID modeling to LID scale and sizing, to rainfall event size, and to physical LID parameters such as hydraulic conductivity. However, the impacts of other parameterizations such as outflow routing from LID, LID placement, and area treated by LID are not well studied. Using a case study of a redeveloping neighborhood in Denver, Colorado, we tested 32 configurations of these parameters in a calibrated, watershed-scale PCSWMM model. We found some configurations lead to counter-acting model processes that result in similar runoff reduction across a variety of LID configurations, suggesting reduction targets may be met in a myriad of ways. Relative sensitivity of runoff volume output to area treated and LID placement was found to be on average 3.0 and 11.2 times higher than the seven most sensitive physical LID and subcatchment parameters. Given this sensitivity, these parameters should be key considerations to improve modeling efforts that inform regulations.

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3.2 Introduction

Population projections predict that by 2050, 68% of the world's population will live in urban areas (United Nations, 2018). As populations grow, cities must accommodate the new influx of people in housing without increasing the recognized negative impacts of urban sprawl (Goetz, 2013). Therefore, many cities are implementing solutions that result in growing inward (or upward) instead of outward. This type of growth manifests as infill development, where the sporadic, under-utilized parcels of a city are "filled in" with new development. In this way, infill *re*develops a previously developed space instead of expanding into undeveloped land. Infill development is a loosely defined term and is referenced in several previous studies and criteria manuals (Johnson, 2001; Pond and Kacvinsky, 2006; Burchell *et al.*, 2010). The terms *infill*, *infill development*, and *redevelopment* are often used to describe the same phenomenon, and the remainder of this study solely uses *redevelopment*. Examples of redevelopment, as defined for this work, include a parking lot transformed into an apartment complex, or a single-family home converted into a multi-family unit. The main unifying feature of redevelopment is an increase in impervious surfaces relative to what previously existed (EPA, 2016). While redevelopment may address the housing needs of a growing city, the effects of this type of development on stormwater runoff are not well studied. Many studies focus on changes in hydrologic regime due to increases in imperviousness from undeveloped to developed land, but do not directly address stormwater runoff produced through urban redevelopment.

Panos *et al.* (2018) investigated the impacts of redevelopment on stormwater runoff for the 419-ha Berkeley neighborhood of northwest Denver, CO using future predictions of parcel-scale impervious cover change (Cherry *et al.*, 2019). A calibrated Storm Water Management Model for PC (PCSWMM) was used to quantify the runoff produced from a range of 24-hr design storms and predicted increases of 0.91% to 1.63% in stormwater runoff volume per 1% increase in impervious area due to redevelopment (Panos *et al.*, 2018). In addition, it was found that the existing storm sewer network is undersized to handle increases in flow, leading to increased flooding volumes and potential flood risk to urban infrastructure and neighborhood residents (Panos *et al.*, 2018). It is possible that the implementation of low impact development (LID) could reduce runoff volumes enough to counter increases in runoff due to redevelopment.

Implementation of LID, also sometimes referred to as Green Infrastructure (GI), Stormwater Control Measures (SCMs), or Best Management Practices (BMPs) (Fletcher *et al.*, 2015), within urban areas has been found to achieve an array of environmental benefits including decreased peak flows and runoff volumes, and increased water quality (Dietz, 2007; Bedan and Clausen, 2009; Ahiablame *et al.*, 2012), as well as social co-benefits such as increased aesthetics and green space (Apostolaki *et al.*, 2006; Baptiste *et al.*, 2015; Brown *et al.*, 2016). However, in many cities, current stormwater criteria exempt smaller (less than 0.4 ha, or 1 ac) redeveloped parcels from the installation of LID during redevelopment (Denver DPW, 2013; EPA, 2016). The City of Denver is in the process of revising criteria to include smaller redeveloped parcels. Many stormwater criteria and regulations are written with the goal of returning runoff volumes to below pre-development volumes (Rosa *et al.*, 2015; Jefferson *et al.*, 2017). However, it is not known to what extent or under what assumptions LID can and need to be implemented in a redeveloping urban neighborhood to return storm sewer flows to pre-*re*development conditions.

While site-scale LID modeling is common to address site-specific goals and needs, as urbanization increases and cities aim to improve stormwater management strategies through large-scale adoption of LID practices, watershed-scale analyses are needed and informative (Lee *et al.*, 2012; Ahiablame and Shakya, 2016; Hu *et al.*, 2017). Municipalities and practitioners conduct watershed-scale modeling studies using hydrologic models such as SWMM, the System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN), the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), or the Source Loading and Management Model for Windows (WinSLAMM) to inform policy and regulations. Many models have been updated to include LID, and while LID editors are useful tools for testing an array of scenarios, LID parameterization and integration into existing watershed models requires further study (Eckart *et al.*, 2017). Many assumptions are made when parameterizing LID hydrologic models, particularly when implementing LID at the watershed-scale when site-scale parameters may be unknown. These assumptions are coupled with unknown sensitivities to certain parameterizations. Watershed-scale modeling of LID implementation to inform data-driven decisions regarding stormwater criteria includes a variety of modeling assumptions with potential impacts on runoff and flood volume reductions and the ability to meet regulatory compliance.

Watershed-scale LID modeling studies typically focus on the scale of LID implementation, the impacts of rainfall event size, and the parameterization of physical LID and subcatchment parameters. Several studies recognize the sensitivity of LID modeling to LID scale and distribution (Wolfand *et al.*, 2018; Wang *et al.*, 2019), to rainfall event size and duration (Qin *et al.*, 2013; Fry and Maxwell, 2017; Mao *et al.*, 2017), and to physical LID parameters such as hydraulic conductivity or soil thickness (Gülbaz and Kazezyılmaz-Alhan, 2017; Gao *et al.*, 2018). However, model sensitivity to other siting and routing parameters such as outflow routed from LID, LID placement with adjusted imperviousness, and the percent of impervious area runoff treated by LID is not well studied.

1. **Outflow Routing.** Outflow is one of the computed components of an LID water balance along with storage, infiltration, and evaporation. The subsequent routing of outflow volume to either pervious areas or a subcatchment outlet is a model parameter that can be overlooked. Gao *et al.* (2018) found that changes in bioretention design parameters, such as hydraulic conductivity, most significantly influence the proportion of flow that is outflow compared to infiltration, overflow, and evaporation. This indicates that outflow is a sensitive parameter to bioretention design, and the amount of outflow has the potential to fluctuate. However, Gao *et al.* (2018) do not discuss subsequent routing of bioretention outflow in the model.
2. **LID Placement.** Kaykhosravi *et al.* (2018) reviewed eleven LID models and note the advantages and disadvantages of modeling LID as either new subcatchments or by placing LID within a parent subcatchment, but do not comment on the impacts of placement location or model adjustments that must be made with LID placement. Fry and Maxwell (2017) studied the effects of converting pervious areas to LID and concluded LID placement is more important for runoff reduction than storage capacity/sizing, indicating LID placement is an important consideration in LID modeling. Palla and Gnecco (2015) modeled the effect of reducing the effective impervious area (EIA) of a watershed and identified a threshold of 5% EIA reduction required for noticeable hydrologic benefits. However, EIA reduction is often used as an independent LID strategy, and the change in impervious areas with the implementation of other LID strategies is often overlooked.
3. **Area Treated.** In a study of bacteria load reduction in the Ballona Creek watershed, Wolfand *et al.* (2018) found the percent of watershed area treated by LID to be the most sensitive factor for achieving water quality compliance. Given the link between water quality and quantity (Jefferson *et al.*, 2017), this suggests area treated as an important factor for runoff and flood reduction as well. This hypothesis is supported by studies that

have investigated a response in runoff reduction to area treated (Walsh *et al.*, 2014; Wright *et al.*, 2016), but is still uncertain under a context of redevelopment.

Ultimately, the effectiveness of proposed revised LID criteria in redeveloping cities based on watershed-scale modeling studies depends on sensitivity to LID siting and routing parameters. This study elucidates how various LID modeling parameterizations impact runoff and flood volumes, the limitations of considering only sizing or physical parameters of LID, and the potential implications for regulatory compliance.

3.3 Methods

3.3.1 Study Area

The study area includes the Berkeley neighborhood in northwest Denver, Colorado (39.776110, -105.039245) as investigated in Panos *et al.* (2018) (Figure 3.1). The Berkeley neighborhood catchment is 419 ha (1.62 mi^2). The neighborhood had an average total impervious area of 53.5% in 2014 that has been steadily increasing due to redevelopment. The Berkeley catchment utilizes a curb-and-gutter stormwater collection system and has 18.9 km of storm sewer pipes, 15.2 km of which were modeled for this study. The basin contains no open water channels or streams, but does contain a historic drainage ditch, the Rocky Mountain Ditch, and two manmade lakes, Berkeley Lake to the west and Rocky Mountain Lake to the east (Figure 3.1).

Given findings of higher redevelopment impacts for smaller storm events (Panos *et al.*, 2018), runoff was simulated for the neighborhood using synthetic rainfall events for the 2, 5, and 10-yr, 24-hour design storms corresponding to 46, 59, and 71 mm (1.80, 2.33, and 2.79 in) rainfall depths, respectively. Storms were developed using a Type-II National Resources Conservation Service (NRCS) rainfall distribution at 5-minute intervals (Akan and Houghtalen, 2003). All model simulations were run with dynamic wave routing, Horton infiltration, and five antecedent dry days. We did not test varying initial soil moisture conditions. However, given that initial soil moisture conditions can impact LID performance, we recognize this as a limitation of this study. Results for each design storm were analyzed at the full study area outlet (see point O1, Figure 3.1) for stormwater runoff volume and flood volume. For this study, *runoff volume* is defined as a combination of the runoff routed directly to the outlet and the runoff produced on the subcatchment. *Flood volume* refers to the volume of stormwater that exceeds the rim elevations of all model nodes.

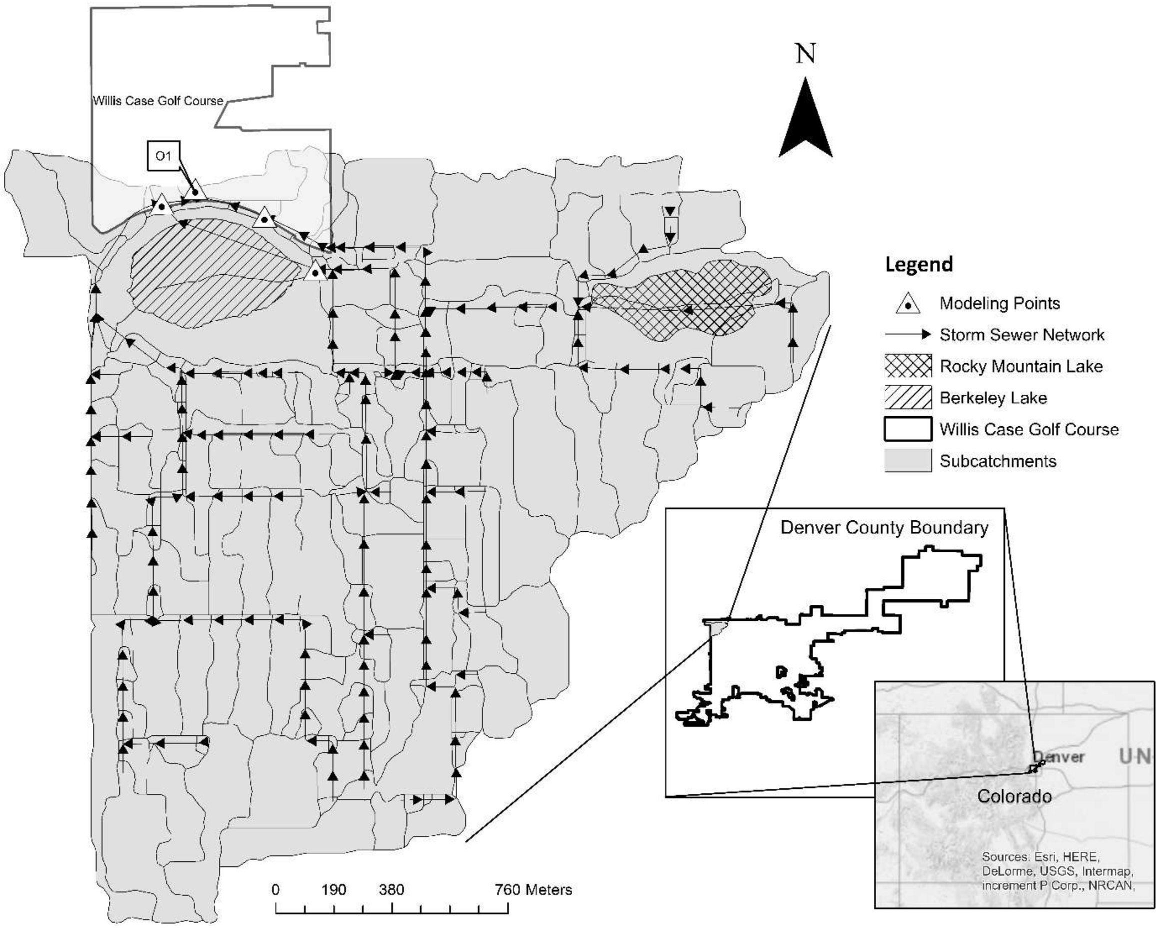


Figure 3.1 Berkeley neighborhood catchment study area including the existing storm sewer network, catchment outlet (modeling point O1), lakes, and delineated subcatchments.

3.3.2 Model Development

The high-resolution PCSWMM hydrologic model of Panos *et al.* (2018) was used to model LID implementation in this study. The model was updated with new subarea runoff routing and re-calibrated by adjusting parameters such as depression storage and infiltration parameters. The model was calibrated and validated to observed flow and water level data collected at several modeling points in the catchment (indicated by triangles in Figure 3.1). Table 3.1 summarizes performance statistics for model calibration and validation. Calibration and validation resulted in good to very good model performance on average as defined by Moriasi *et al.* (2007) with high average NSE values of 0.745 and 0.786, and low average percent bias values of 6.65% and 6.66% (absolute bias) at the 5-min time step, for calibration and validation, respectively. Simulations reported in this study were run with this re-calibrated model using SWMM Version 5.1.012.

Table 3.1 Performance statistics for PCSWMM model calibration and validation.

	Simulation Dates	Number of Observed Data Points	Basin	NSE	R^2	Percent Bias (%)
Calibration	4/17/2017 – 6/3/2017	13,362	West Basin	0.732	0.809	15.80%
	7/14/2016 – 9/5/2016	15,205	Berkeley Lake Basin	0.957	0.958	-0.99%
	4/17/2017 – 6/3/2017	13,362	East Basin	0.545	0.736	3.16%
Validation	6/4/2017 – 7/27/2017	15,366	West Basin	0.553	0.630	16.06%
	9/2/2015 – 10/15/2015	12,175	Berkeley Lake Basin	0.971	0.972	-3.22%
	6/4/2017 – 7/27/2017	15,366	East Basin	0.835	0.837	-0.69%

To evaluate distributed, watershed-scale LID implementation, a bioretention (BR) unit was added to each parcel predicted for redevelopment under a moderate case of redevelopment (Scenario 2 as defined in Panos *et al.*, 2018). This forecasted case of redevelopment consists of an associated 4.7% increase in overall neighborhood total imperviousness from the 2014 baseline value of 53.5% to 58.2%. Bioretention units are commonly implemented by current developers in the Denver area (personal communication, Brian Wethington, Water Quality Project Manager, Green Infrastructure Group, May 25, 2018). A total of 1,507 BR units were placed on a total of 1,507 redeveloped parcels; however, BR units were modeled as one aggregate unit per subcatchment for a total of 170 aggregate units. The spatial distribution of redeveloped parcels is shown in Figure 3.2.

Bioretention reduces stormwater runoff by retaining water on-site, infiltrating runoff through soil media, evapotranspiring, and discharging water into an underdrain and surrounding soils (Figure 3.3). Through these mechanisms, bioretention provides both water quality and hydromodification benefits. BR units were placed on all redeveloped parcels regardless of pre- and post-redevelopment land use. BR units were added to each delineated subcatchment via the LID Control Editor within PCSWMM. Redeveloped parcels that cross subcatchment boundaries were counted only within the subcatchment containing the majority of that parcel. The modeled BR units include physical input parameters (Figure 3.3) derived from a variety of sources including SWMM manuals and the Urban Drainage and Flood Control District's (UDFCD) Volume III Manual (UDFCD, 2018) (see Table B.1).

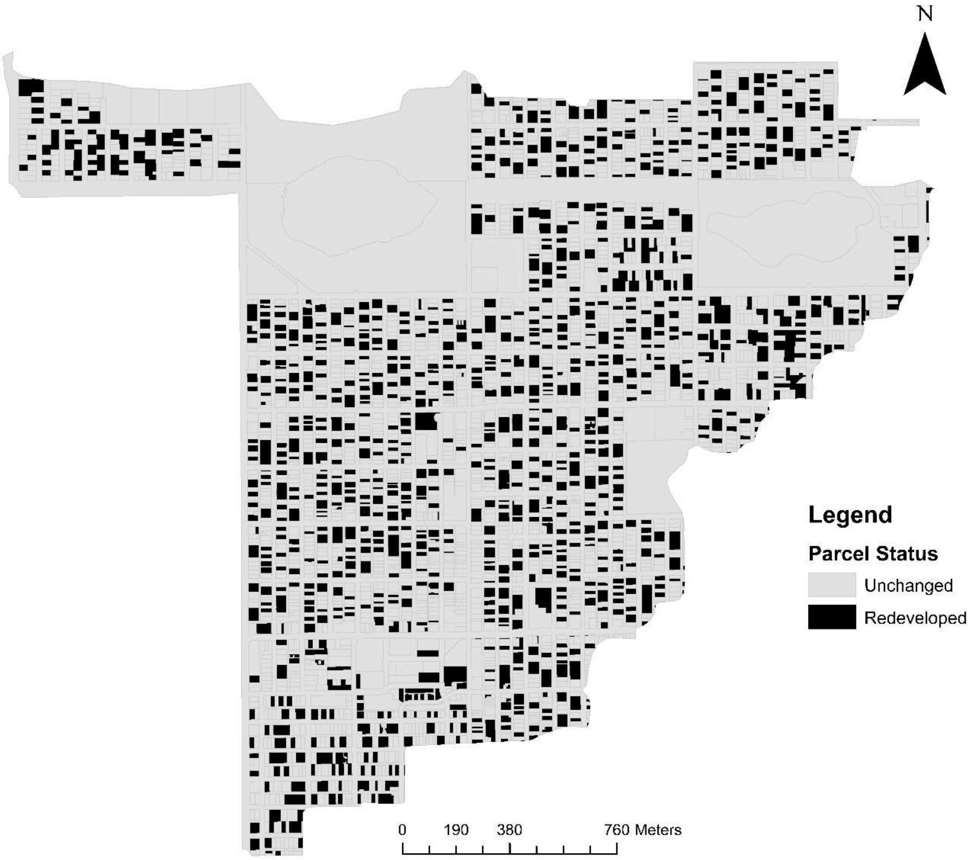


Figure 3.2 Spatial distribution of redeveloped and unchanged parcels for the redeveloped condition of the Berkeley neighborhood catchment. One bioretention (BR) unit was placed on each of the 1,507 redeveloped parcels for all low impact development (LID) configurations.

Given the location of the study site in Colorado, physical bioretention parameters (such as soil thickness, porosity, field capacity, and conductivity) were also adjusted to attain adequate draining times to protect downstream water rights holders under the prior appropriation doctrine; specifically, parameters were adjusted to ensure full release or infiltration of the BR units of the 5-yr storm within 72-hrs and the 100-yr storm within 120-hrs of the end of the precipitation event to comply with Colorado Revised Statute 37-92-602(8) (UDFCD, 2015). Further parameter adjustment was performed to ensure full release or infiltration of the Denver-defined Water Quality Capture Volume (WQCV) within 12-hrs of the end of the precipitation event (UDFCD, 2011). During this adjustment, BR parameters were constrained to realistic values based on literature; however, BR parameters were not calibrated to observed data given the limited data availability of the observed performance of these systems.

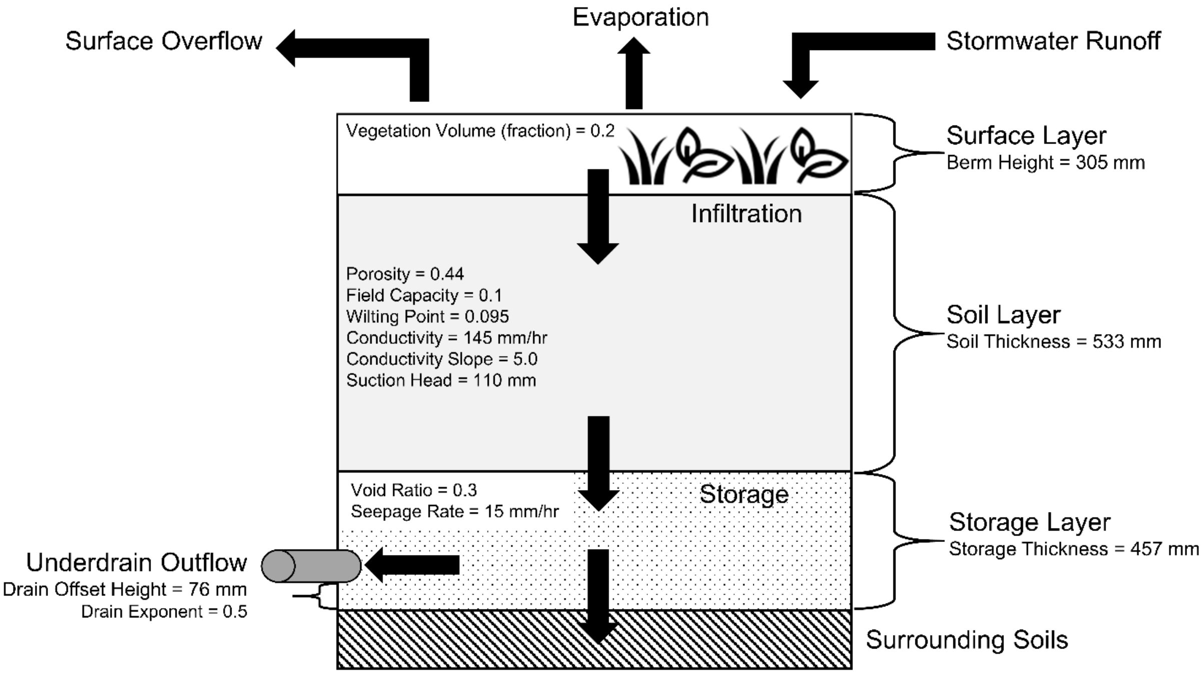


Figure 3.3 Schematic of a bioretention (BR) unit as modeled in this study.

Due to the limited infiltrating capacity of the soil types in Denver and the study area, underdrains were added to each BR unit and modeled via Equation 3.1:

$$q = Ch^n \tag{3.1}$$

where q is the outflow from the underdrain (mm/hr), C is a drain coefficient, h is the height of saturated media above the drain (mm), and n is the drain exponent (unitless) (Rossman, 2015). All underdrains were modeled as orifices, and n was assigned a value of 0.5 (Rossman, 2015).

Given previous literature indicating the sensitivity of model output to the characterization of impervious areas (Alley and Veenhuis, 1983; Booth and Jackson, 1997; Lee and Heaney, 2003; Han and Burian, 2009), impervious areas were separated into directly connected impervious areas (DCIA) and unconnected impervious areas (UIA) to better represent runoff generation. UIA represents impervious areas in the catchment that drain onto pervious surfaces such as a roof gutter draining onto a lawn. DCIA are areas that are directly connected to the storm sewer network such as driveways and parking lots.

DCIA was expressed as a percent of the total impervious area (TIA) and calculated using the Denver-specific equation developed by Alley and Veenhuis (1983) (Equation 3.2). It was assumed that all impervious areas that were not DCIA were UIA (Equation 3.3).

$$DCIA\,\% = \frac{EIA}{TIA} = \frac{0.15\,TIA^{1.41}}{TIA} = 0.15\,TIA^{0.41} * 100\% \tag{3.2}$$

$$UIA\,\% = (100 - DCIA\,\%) \tag{3.3}$$

The *Subarea Routing* option was used in PCSWMM to route runoff from DCIA and UIA to the subcatchment outlet and pervious areas, respectively. Runoff from pervious areas was routed to the subcatchment outlet. Figure 3.4a illustrates a conceptual model of runoff routing without LID implementation. Runoff routing with LID implementation is shown in Figure 3.4b.

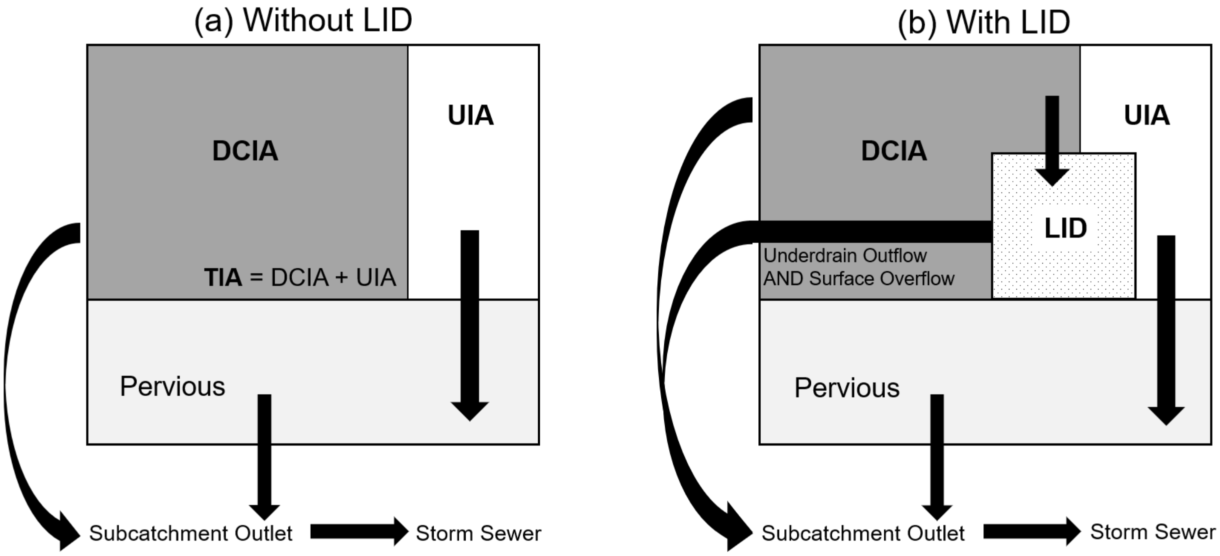


Figure 3.4 Conceptual schematic of runoff routing in PCSWMM (a) without and (b) with LID implementation for LID placement on impervious area and outflow routed to outlet configurations. DCIA = directly connected impervious area; UIA = unconnected impervious area; TIA = total impervious area; LID = low impact development.

3.3.3 LID Siting and Routing Parameter Sensitivity

A total of 32 parameter configurations (Figure 3.5) were run to test SWMM sensitivity to three LID sizing and routing parameters in a redevelopment context: (1) outflow routing from LID, (2) LID placement, and (3) area treated by LID:

1. **Outflow Routing.** Depending on LID sizing, and storm size and duration, LID may reach capacity and flow may exit the LID unit through the underdrain or as surface overflow. Together, this *outflow* may be directed towards a pervious surface such as nearby grass, or it may be routed directly back into the storm sewer network via an outlet. Both assumptions were tested in our modeling. We did not test configurations in which the outflow of underdrains and surface overflow were routed to two different places, although this is possible within SWMM (Rossman, 2015).

2. **LID Placement.** LID can be modeled two different ways within SWMM: 1) LID as its own subcatchment, which allows series routing of LID; or 2) by placing LID within a parent subcatchment, which allows parallel routing of LID (Rossman, 2015; Kaykhosravi *et al.*, 2018). This study investigated the second option, which means that the model parameter impacted by LID placement is the subcatchment percent imperviousness. Model adjustments to subcatchment imperviousness with LID implementation is described further below. Simulations were run to evaluate the impact of placing LID on existing impervious versus pervious areas in the parent subcatchment. For the redevelopment context, in current practice in Denver, typical redeveloped parcels have a high impervious area percentage. Therefore, it is likely with new criteria that distributed LID would take the place of impervious areas in the model of redeveloped conditions. However, it is also possible that what little pervious area remains on redeveloped lots (grasses and small plantings) would simply be replaced with stormwater control instead. This study investigates the impacts of both options. We did not consider configurations in which LID replaced a portion of both pervious and impervious surfaces.
3. **Area Treated.** For area treated, or the amount of impervious area runoff routed to/captured by LID, configurations tested the impact of treating runoff from *all* redeveloped impervious areas with bioretention versus treating runoff from impervious areas *added* during redevelopment. In other words, in the latter configuration, developers would only be responsible for treating runoff generated from the additional impervious areas added by redevelopment and not runoff generated from the impervious areas that existed before redevelopment took place.

A conceptual parcel for each of the LID placement and area treated model configurations based on a hypothetical parcel with baseline (pre-redevelopment) and redeveloped conditions is illustrated in Figure 3.6. Runoff from un-redeveloped parcels (grey “unchanged” parcels in Figure 3.2) was not routed to LID in any configuration.

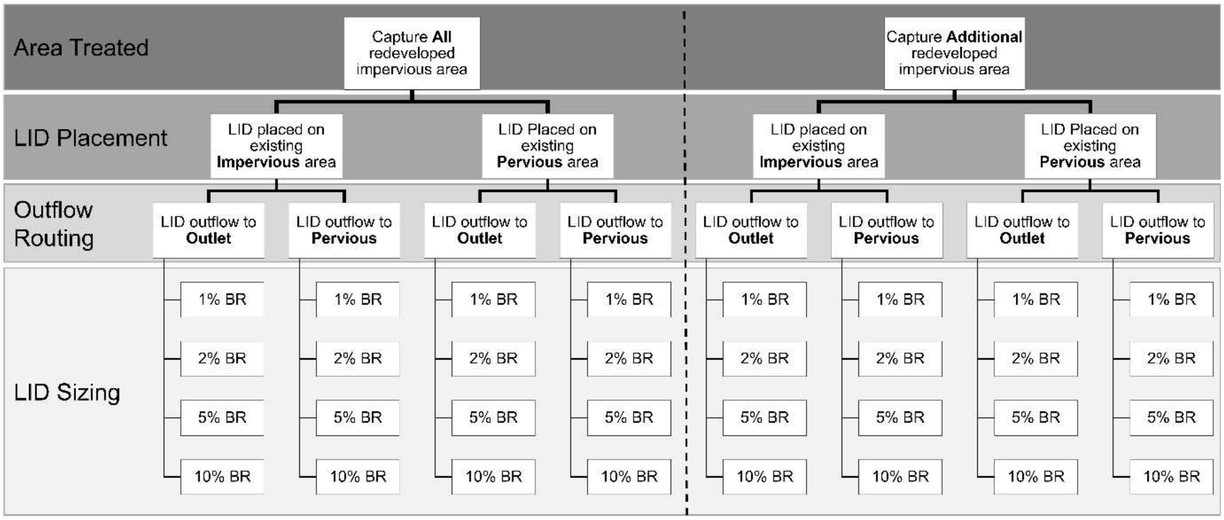
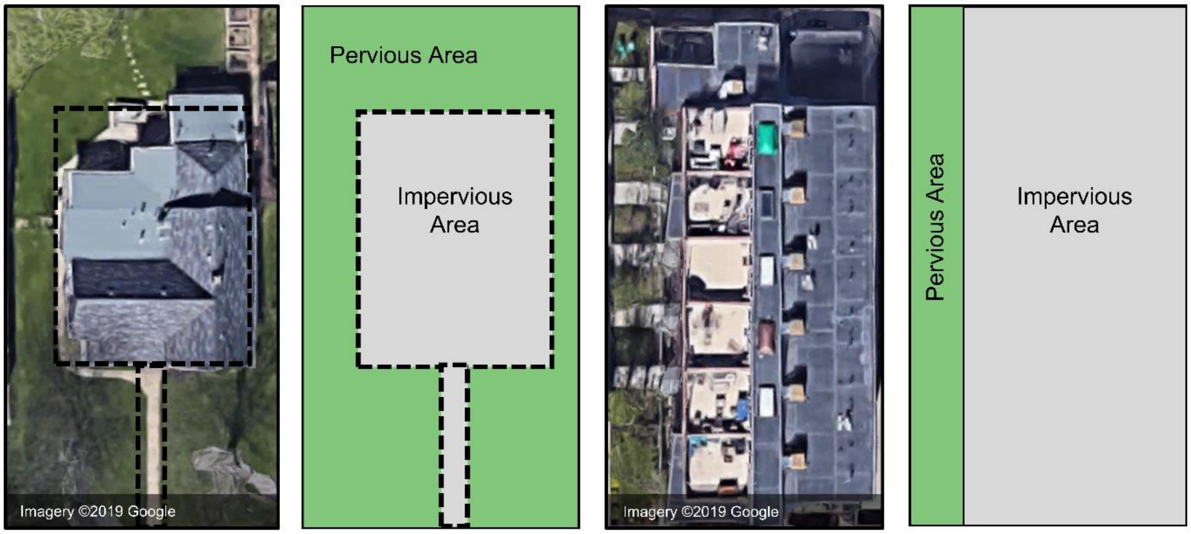


Figure 3.5 Depiction of combinations of LID siting and routing parameterizations into 32 possible configurations under four different LID sizing scenarios. Each branch of the "tree" represents one configuration (e.g., capture *all* area, LID placed on *pervious*, outflow routed to *outlet*) tested for each LID sizing scenario. LID sizing refers to the implementation of bioretention (BR) on redeveloped parcels in which the surface area of the BR units was sized to 1%, 2%, 5%, and 10% of the redeveloped parcel area.

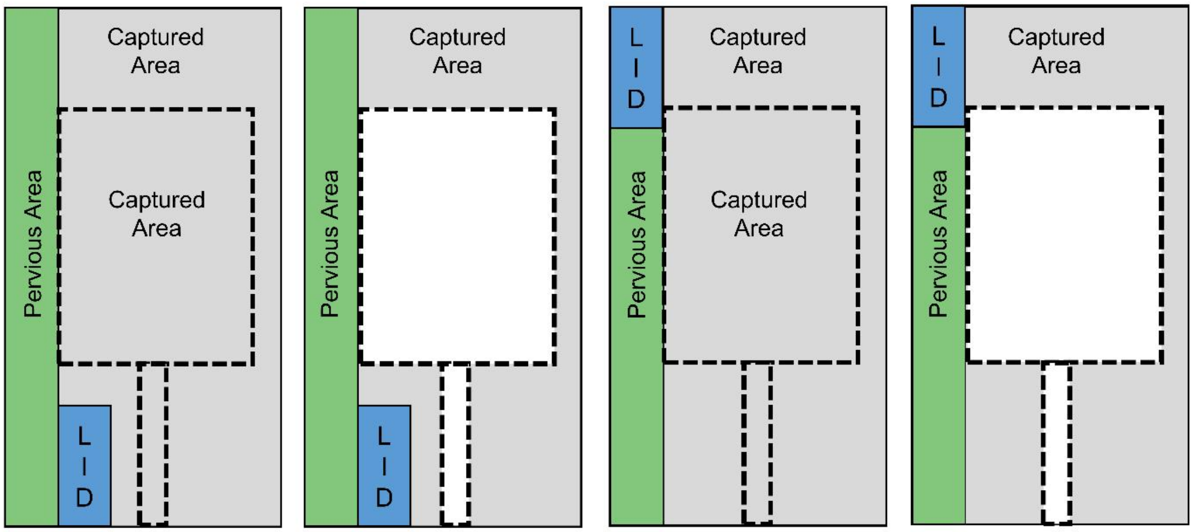
3.3.4 LID Sizing Scenarios

LID sizing is typically a key focus of LID implementation as they are often sized to capture a certain volume of water, such as a Water Quality Capture Volume (WQCV) (UDFCD, 2011). Similar to running simulations across a range of design storms, to test how model sensitivity to LID siting and routing parameters may also be impacted by LID sizing, all LID siting and routing parameter configurations were tested across a range of LID sizing scenarios. One common practice of bioretention design is to size a BR unit as a percentage of the drainage area with percentages typically ranging from 3–10% (LA DPW, 2010; Beyerlein, D. Producer, 2018. Bioretention Modeling Done Right [Video webinar] foresteruniversity.com). Given the small average redeveloped parcel size of this study (0.053 ha, 53 m^2, or 0.013 ac) and the objective of capturing runoff from each redeveloped parcel, the surface area of the BR units was sized to 1%, 2%, 5%, and 10% of the redeveloped parcel area to test a range of potential sizing schemes (Figure 3.5). For example, on a 0.202-ha (2,023 m^2 or 0.5 ac) parcel, the BR unit placed on that parcel was sized to 20.2 m^2, 40.5 m^2, 101 m^2, and 202 m^2, for the 1%, 2%, 5%, and 10% scenarios, respectively. The total associated bioretention storage volume for each scenario is listed in Table 3.2 along with other watershed and LID metrics.



(a) Baseline Parcel

(b) Redeveloped Parcel



(c) Capture All; LID on Impervious

(d) Capture Additional; LID on Impervious

(e) Capture All; LID on Pervious

(f) Capture Additional; LID on Pervious

Figure 3.6 Aerial imagery and simplified representation of the pervious and impervious areas of (a) a baseline condition parcel and (b) a redeveloped condition parcel. Panels (c) through (f) illustrate a conceptual redeveloped parcel for each of the area treated/captured and LID placement configurations. Dotted lines show the pre-redevelopment building outline. Runoff from gray areas are captured and treated by LID. (Imagery © 2019 Google)

Table 3.2 Watershed and LID metrics by bioretention (BR) sizing scenario.

	1% BR	2% BR	5% BR	10% BR
Percent of Redeveloped Surface Area that is Bioretention (%)	1%	2%	5%	10%
Percent of Total Catchment Surface Area that is Bioretention (%)	0.18%	0.36%	0.91%	1.81%
Total Bioretention Surface Area (km^2)	0.008	0.015	0.039	0.077
Total Bioretention Storage Volume (m^3)	8,233	16,500	41,100	82,300
Bioretention Density (#/km^2)	360	360	360	360
Adjusted Watershed Imperviousness (%) when BR placed on existing Impervious area	58.09%	58.02%	57.80%	57.43%
Adjusted Watershed Imperviousness (%) when BR placed on existing Pervious area	58.27%	58.38%	58.72%	59.29%

3.3.5 Impervious Area Adjustments with LID Placement

After LID implementation, SWMM models subcatchments as a non-LID and LID fraction, and although not often addressed in the literature, but often a source of confusion amongst modelers and practitioners, percent impervious parameters must be adjusted accordingly based on LID placement (Rossman, 2015). Assuming LID placement on impervious areas, the total percent imperviousness (TIA in Figure 3.4) of each subcatchment was adjusted as detailed by the SWMM User's Manual (Version 5.1 in Section 3.3.14) by subtracting the surface area of bioretention from existing impervious areas and from the total subcatchment area (Rossman, 2015). When assuming LID placement on pervious areas, TIA was adjusted by subtracting the surface area of bioretention from the total subcatchment area, but not from the existing impervious areas. Adjusted watershed imperviousness by scenario is reported in Table 3.2. Subcatchment width was not adjusted. Directly connected and unconnected impervious areas were then revised based on the adjusted total impervious area of each subcatchment for each scenario (recalculated using Equations 3.2 and 3.3). Table 3.3 shows the percent of impervious and total area, on average, treated by bioretention for all scenarios based on LID placement.

Table 3.3 Percent of impervious and total area treated by bioretention (BR) by scenario on average.

	Area Treated	LID Placement	1% BR	2% BR	5% BR	10% BR
Percent of Impervious Area Treated by BR (%)	Capture *additional* redeveloped impervious areas	BR placed on:				
		Impervious	7.51	7.24	6.40	4.96
		Pervious	7.78	7.78	7.78	7.78
	Capture *all* redeveloped impervious areas	BR placed on:				
		Impervious	21.14	20.92	20.25	19.10
		Pervious	21.36	21.36	21.36	21.36
Percent of Total Watershed Area Treated by BR (%)	Capture *additional* redeveloped impervious areas	BR placed on:				
		Impervious	12.93	12.47	11.07	8.63
		Pervious	13.35	13.33	13.25	13.13
	Capture *all* redeveloped impervious areas	BR placed on:				
		Impervious	36.40	36.06	35.04	33.27
		Pervious	36.65	36.59	36.38	36.03

3.3.6 Comparisons to Physical LID and Subcatchment Parameter Sensitivity

In order to assess model sensitivity to LID siting and routing parameters, as compared to other physical LID and subcatchment parameters, a sensitivity analysis was performed to quantitatively determine which parameters most impact model output (Jewell *et al.*, 1978; James and Burges, 1982; Rosa *et al.*, 2015). A total of 28 parameters were investigated, including 16 physical LID parameters such as soil conductivity and storage thickness; nine subcatchment parameters such as slope and depression storage; and the three siting and routing parameters that are the focus of this study, including outflow routing, area treated, and LID placement. All parameters were set to initial values (as described below), then individually adjusted while keeping all other parameters unchanged. The corresponding differences in original and new runoff volume and flood volume were recorded for the 2-yr, 24-hr design storm event (46 mm rainfall depth), and relative sensitivity was calculated from Equation 3.4 as reported in Rosa *et al.* (2015):

$$Sensitivity = \left(\frac{dR}{dP}\right)\left(\frac{P}{R}\right) \tag{4}$$

where *dR* is the difference between original and new model output, *dP* is the difference between original and adjusted parameter values, *R* is the original model output, and *P* is the original parameter value. If multiplied by 100%, this equation can also be conceptualized as the percent change in output per 1% change in the parameter value.

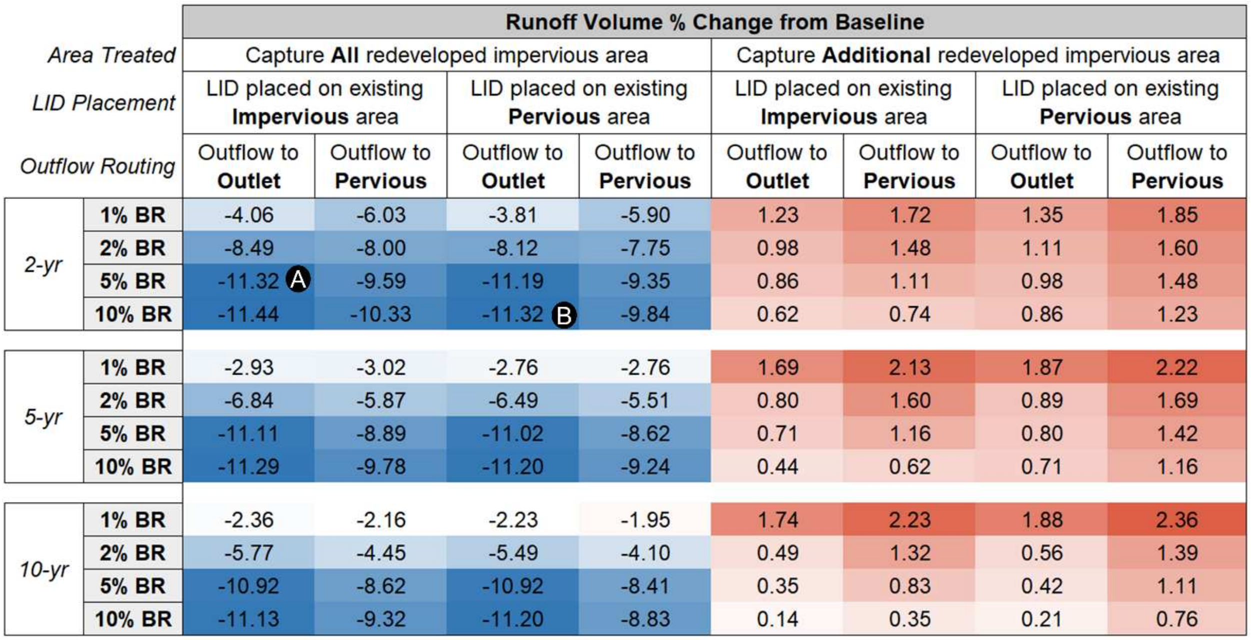
Physical LID parameters were adjusted over ranges of physically feasible values. Parameter ranges were informed by the SWMM 5 manual and other LID modeling studies (Rossman, 2015; Rossman and Huber, 2016; Gülbaz and Kazezyılmaz-Alhan, 2017). Initial physical LID parameters were set to the averages of the possible ranges. Initial subcatchment parameters were set to previously calibrated parameters. Subcatchment parameters were adjusted by $\pm 50\%$ of initial values (Rosa *et al.*, 2015). Initial siting and routing parameters were set to outflow routed to the *outlet*, *all* redeveloped impervious area treated, and LID placed on *impervious* areas (with associated subcatchment imperviousness values). "Adjusted" values tested the opposite conditions (outflow to *pervious*, *additional* redeveloped impervious area treated, and LID placed on *pervious* areas). Finally, LID sizing was also investigated as a physical LID parameter. Initial sizing was set to the 5% BR scenario, then 2% BR and 10% BR sizing values were also tested.

3.4 Results

3.4.1 Runoff Volume Results

Results of implementing bioretention units on redeveloping parcels in the Berkeley neighborhood to test model sensitivity to LID siting and routing parameters show varying degrees of runoff and flood volume reduction. Figure 3.7 shows the percent change in total watershed runoff volume between each LID scenario and the baseline scenario (no redevelopment or BR implementation) for all 32 LID configurations for the 2-yr, 5-yr, and 10-yr, 24-hr design storms. Negative percentages indicate configurations that successfully lower runoff to below baseline conditions (as typically desired by regulatory standards), while positive percentages indicate configurations that do not meet baseline conditions (even though they do reduce runoff from redeveloped conditions). Results are investigated by each parameter:

1. **Outflow Routing.** Assuming outflow is routed to the *outlet* results in higher runoff reduction than assuming outflow is routed to *pervious* areas. When outflow is routed to *pervious* areas, it has the potential to become runoff, particularly for larger storm sizes when pervious soils become saturated. When outflow is routed to the *outlet*, the water becomes a part of the storm sewer flow and does not contribute to runoff but may contribute to flooding of the storm sewer network. Outflow routing is more important for larger storm sizes as BR units are more likely to reach capacity and overflow during large storm events. Assuming that outflow is routed to *pervious* areas versus the *outlet* increases the watershed runoff volume up to 1,605 m^3 on average (across all 32 configurations) for the 10-yr storm (Figure 3.8).



		Runoff Volume % Change from Baseline							
Area Treated		Capture **All** redeveloped impervious area				Capture **Additional** redeveloped impervious area			
LID Placement		LID placed on existing **Impervious** area		LID placed on existing **Pervious** area		LID placed on existing **Impervious** area		LID placed on existing **Pervious** area	
Outflow Routing		Outflow to **Outlet**	Outflow to **Pervious**	Outflow to **Outlet**	Outflow to **Pervious**	Outflow to **Outlet**	Outflow to **Pervious**	Outflow to **Outlet**	Outflow to **Pervious**
2-yr	**1% BR**	-4.06	-6.03	-3.81	-5.90	1.23	1.72	1.35	1.85
	2% BR	-8.49	-8.00	-8.12	-7.75	0.98	1.48	1.11	1.60
	5% BR	-11.32 Ⓐ	-9.59	-11.19	-9.35	0.86	1.11	0.98	1.48
	10% BR	-11.44	-10.33	-11.32 Ⓑ	-9.84	0.62	0.74	0.86	1.23
5-yr	**1% BR**	-2.93	-3.02	-2.76	-2.76	1.69	2.13	1.87	2.22
	2% BR	-6.84	-5.87	-6.49	-5.51	0.80	1.60	0.89	1.69
	5% BR	-11.11	-8.89	-11.02	-8.62	0.71	1.16	0.80	1.42
	10% BR	-11.29	-9.78	-11.20	-9.24	0.44	0.62	0.71	1.16
10-yr	**1% BR**	-2.36	-2.16	-2.23	-1.95	1.74	2.23	1.88	2.36
	2% BR	-5.77	-4.45	-5.49	-4.10	0.49	1.32	0.56	1.39
	5% BR	-10.92	-8.62	-10.92	-8.41	0.35	0.83	0.42	1.11
	10% BR	-11.13	-9.32	-11.20	-8.83	0.14	0.35	0.21	0.76

Figure 3.7 Percent change in total watershed runoff volume between each LID configuration and the baseline scenario (no redevelopment or BR implementation). Negative percentages shown in blue shading meet baseline conditions; positive percentages shown in red shading do not meet baseline conditions. Darker blue and red shading indicates values that are further away from baseline conditions (0% change). The “A” and “B” labels indicate an example of two configurations that achieve the same runoff volume reduction with two different sizing scenarios.

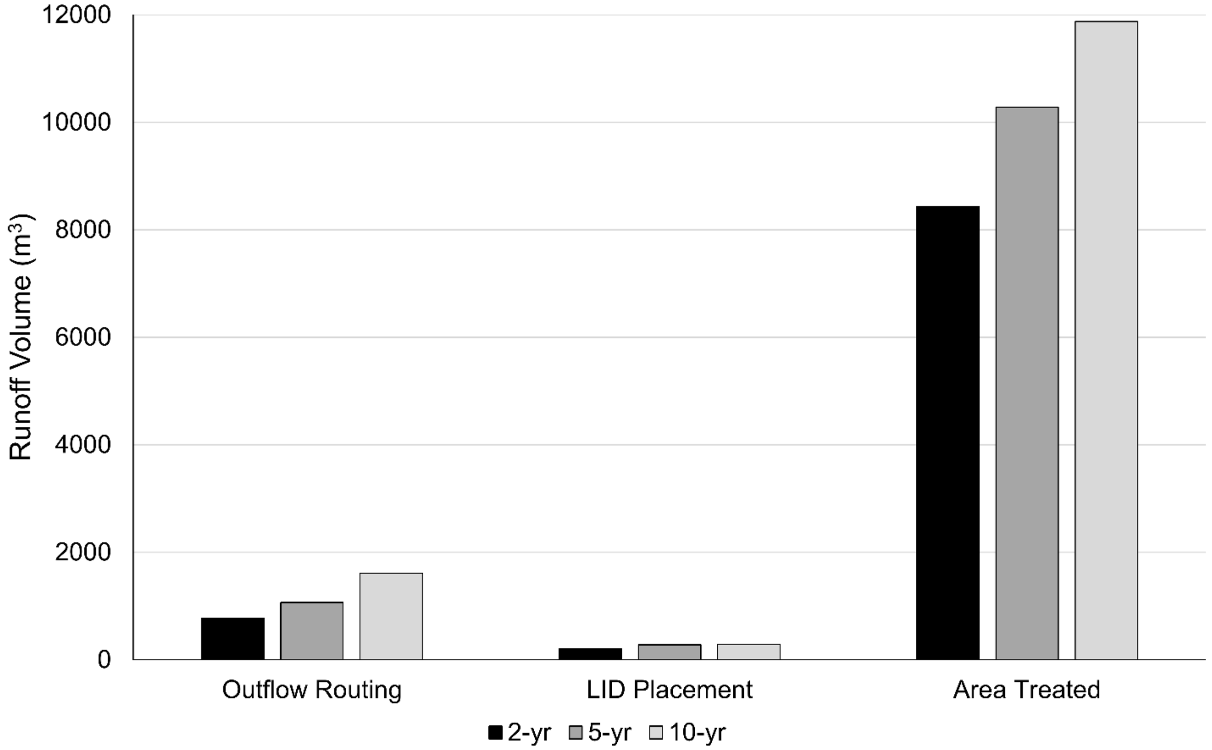


Figure 3.8 Average absolute difference in runoff volume (m^3) by storm event between configurations where one parameterization is different, and all others are the same (e.g., for the first set of bars labeled “Outflow Routing,” LID placement, area treated, and LID sizing are the same between configurations, but outflow routing is different).

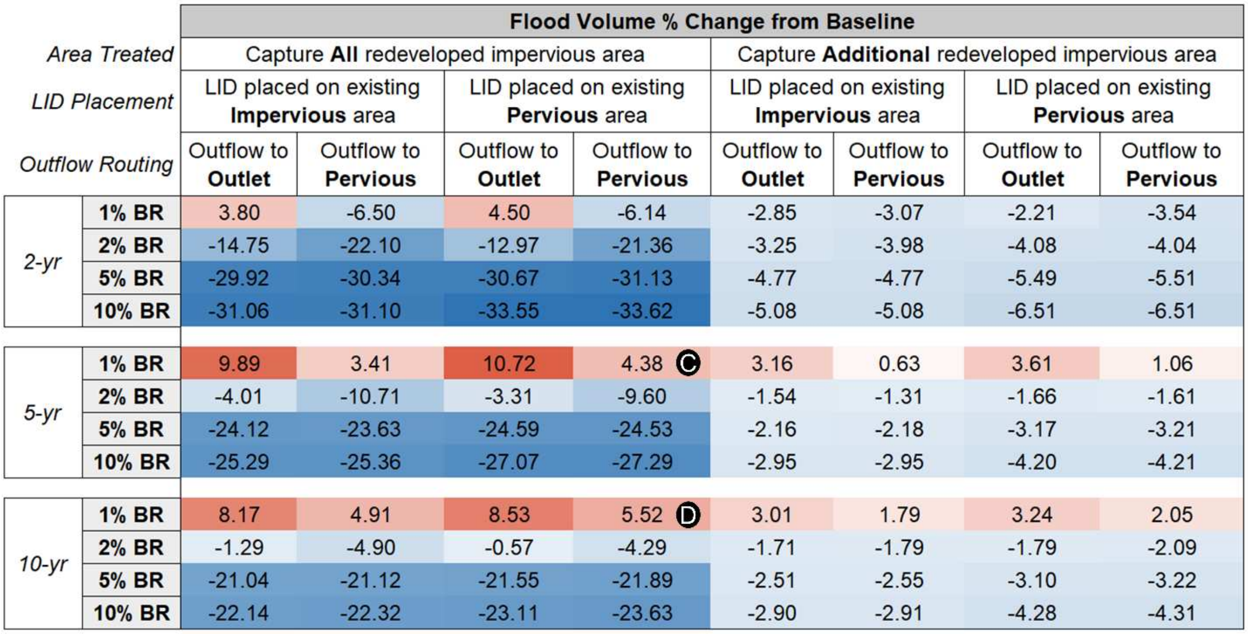
2. **LID Placement.** Assuming LID are placed on *impervious* areas typically results in equal or higher runoff reduction than placing LID on *pervious* areas (Figure 3.7). When LID take the place of *impervious* areas, the impervious percent of the watershed decreases, resulting in less runoff production. LID placement has a lesser effect on model runoff results than other parameters (Figure 3.8). For example, assuming LID is placed on *pervious* area versus *impervious* increases the watershed runoff volume up to 286 m^3 on average across 32 configurations for the 10-yr storm (compared to 1,605 m^3 for an assumption about outflow routing). However, LID placement still plays an important role. For some configurations, results from different sizing scenarios have similar, or even equal, runoff reduction (for example, configurations A and B labeled with black circles in Figure 3.7). This is due to counter-acting model processes (see Discussion section) that occur when imperviousness is adjusted with LID placement on either existing pervious or impervious areas (see Methods section).

3. **Area Treated.** Of the parameters tested, area treated has the largest impact on runoff volume. In fact, to achieve baseline conditions, it is not adequate to only capture *additional* redeveloped impervious areas (0 out of 32 configurations reduce runoff to below baseline). Assuming *additional* redeveloped impervious area is treated versus *all* area results in differences up to 11,873 m^3 of runoff volume on average across 32 configurations for the 10-yr storm (Figure 3.8).

3.4.2 Flood Volume Results

Figure 3.9 shows the percent change in total watershed flood volume, or the volume of stormwater that exceeds the rim elevations of all model nodes, between each LID scenario and the baseline scenario (no redevelopment or BR implementation) for all 32 LID configurations for the 2-yr, 5-yr, and 10-yr, 24-hr design storms. Again, negative percentages indicate configurations that successfully lower flood volumes to below baseline conditions (as typically desired by regulatory standards), while positive percentages indicate configurations that do not meet baseline conditions. Unlike results for runoff, most of the configurations successfully meet baseline conditions for flooding. All scenarios with 2% BR sizing or larger reduce flood volumes to at or below baseline volumes, regardless of other parameter configurations (Figure 3.9); however, no scenario eliminates flooding completely.

The degree of flood volume reduction is still impacted by LID siting and routing parameters in similar ways as runoff volume where area treated has the greatest impact on model output, then outflow routing, then LID placement (Figure 3.10). Outflow routing has a smaller impact on flood volumes than runoff volumes because even if routed outflow produces additional runoff, it may not be enough runoff to cause flooding. Even with the parameter configurations that lead to the greatest flood volume reduction (such as capturing *all* areas, LID placement on *pervious*, and outflow routed to *pervious*), some scenarios are unable to reduce flood volumes to at or below baseline conditions. These include scenarios with smaller sized BR units (e.g. 1% BR), particularly for larger storm events (e.g., 5-yr and 10-yr) (see Figure 3.9; configurations C and D labeled with black circles).



		Flood Volume % Change from Baseline							
Area Treated		Capture **All** redeveloped impervious area				Capture **Additional** redeveloped impervious area			
LID Placement		LID placed on existing **Impervious** area		LID placed on existing **Pervious** area		LID placed on existing **Impervious** area		LID placed on existing **Pervious** area	
Outflow Routing		Outflow to **Outlet**	Outflow to **Pervious**	Outflow to **Outlet**	Outflow to **Pervious**	Outflow to **Outlet**	Outflow to **Pervious**	Outflow to **Outlet**	Outflow to **Pervious**
2-yr	**1% BR**	3.80	-6.50	4.50	-6.14	-2.85	-3.07	-2.21	-3.54
	2% BR	-14.75	-22.10	-12.97	-21.36	-3.25	-3.98	-4.08	-4.04
	5% BR	-29.92	-30.34	-30.67	-31.13	-4.77	-4.77	-5.49	-5.51
	10% BR	-31.06	-31.10	-33.55	-33.62	-5.08	-5.08	-6.51	-6.51
5-yr	**1% BR**	9.89	3.41	10.72	4.38 Ⓒ	3.16	0.63	3.61	1.06
	2% BR	-4.01	-10.71	-3.31	-9.60	-1.54	-1.31	-1.66	-1.61
	5% BR	-24.12	-23.63	-24.59	-24.53	-2.16	-2.18	-3.17	-3.21
	10% BR	-25.29	-25.36	-27.07	-27.29	-2.95	-2.95	-4.20	-4.21
10-yr	**1% BR**	8.17	4.91	8.53	5.52 Ⓓ	3.01	1.79	3.24	2.05
	2% BR	-1.29	-4.90	-0.57	-4.29	-1.71	-1.79	-1.79	-2.09
	5% BR	-21.04	-21.12	-21.55	-21.89	-2.51	-2.55	-3.10	-3.22
	10% BR	-22.14	-22.32	-23.11	-23.63	-2.90	-2.91	-4.28	-4.31

Figure 3.9 Percent change in total watershed flood volume between each LID configuration and the baseline scenario (no redevelopment or BR implementation). Negative percentages shown in blue shading meet baseline conditions; positive percentages shown in red shading do not meet baseline conditions. Darker blue and red shading indicates values that are further away from baseline conditions (0% change). The "C" and "D" labels indicate examples of scenarios that do not return flood volumes to baseline conditions despite favorable parameter configurations for flood volume reduction.

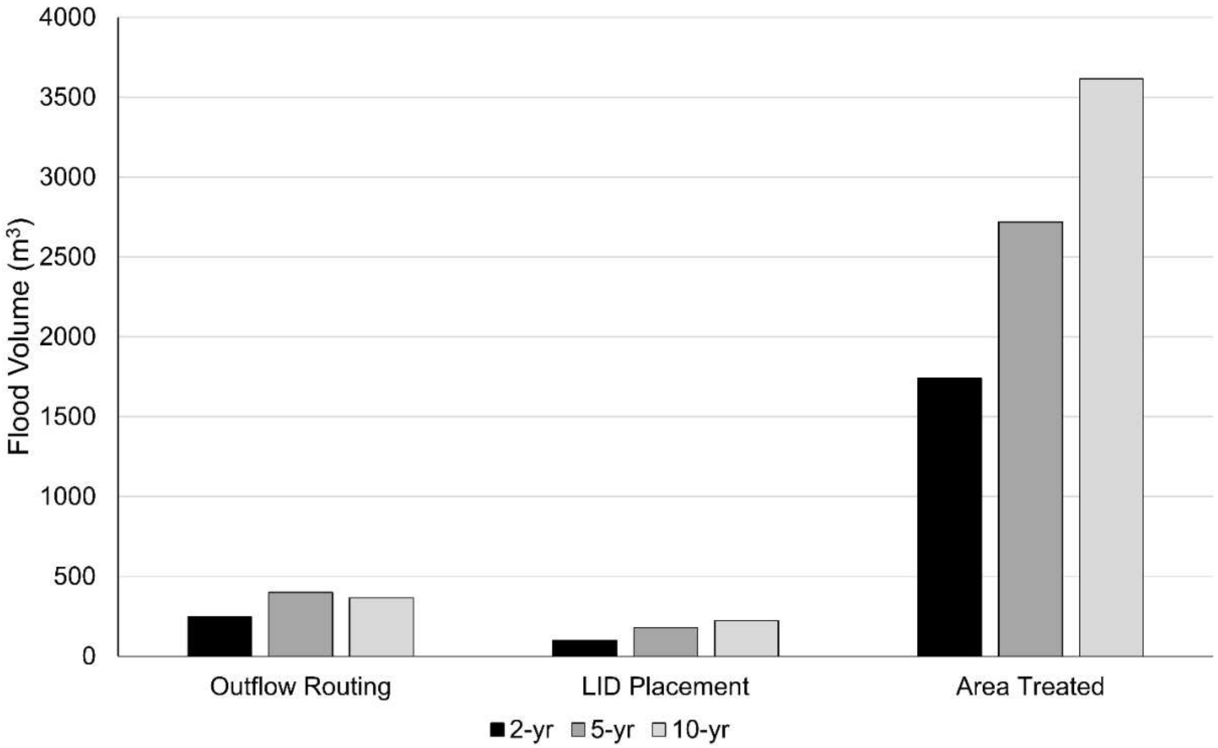


Figure 3.10 Average absolute difference in flood volume (m^3) by storm event between scenarios where one parameterization is different, and all others are the same (e.g., for the first set of bars labeled "Outflow Routing," LID placement, LID sizing, and area treated are the same between scenarios, but outflow routing is different).

3.4.3 Comparisons to Physical LID and Subcatchment Parameter Sensitivity Results

Of the 16 physical LID and nine subcatchment parameters tested in the relative sensitivity analysis, four LID and four subcatchment parameters had sensitivities of 0.01 or greater for runoff volume (meaning at least a 1% change in runoff volume per 1% change in parameter value). For flood volume, six LID and seven subcatchment parameters had sensitivities of 0.01 or greater. Parameters with relative sensitivities of 0.025 or greater are shown in Figure 3.11 in addition to the relative sensitivities of the LID siting and routing parameters. All parameters affect flood volume output more than runoff volume output (Figure 3.11). The three most sensitive subcatchment parameters (Figure 3.11) change flood and runoff volume model outputs by an average of 26.2% and 6.8% per 1% change in model parameter, respectively. The four most sensitive physical LID parameters (Figure 3.11) change flood and runoff volume model outputs by an average of 24.8% and 5.5% per 1% change in model parameter, respectively. Comparatively, LID placement (and subsequent changes to subcatchment imperviousness) changes flood and runoff volume outputs by 155% and 69%, respectively, suggesting this parameter is on average

6.0 and 11.2 times as sensitive as the seven other most sensitive parameters for flood and runoff volume outputs, respectively. Because impervious area is the parameter that is affected by LID placement, it makes sense that it has a large impact on model results as impervious area has been shown to be a sensitive parameter in previous studies (Jewell *et al.*, 1978; Liong *et al.*, 1991; Barco *et al.*, 2008). Results of other sensitive subcatchment parameters (infiltration parameters and depression storages) also agree with previous sensitivity analyses for both water quantity and quality (Tsihrintzis and Hamid, 1998; Barco *et al.*, 2008; Rosa *et al.*, 2015).

Impervious area treated by LID is a little more sensitive for both flood and runoff volume results than the other parameters. Area treated changes flood and runoff volume model outputs by an average of 41.3% and 18.3% per 1% change in model parameter, respectively, making it 1.6 and 3.0 times as sensitive as the seven other parameters. While outflow routing impacts absolute differences in runoff and flood volumes between scenarios (Figure 3.8 and Figure 3.10), the relative sensitivity of outflow routing is low compared to other parameters. Therefore, when assessed against percent change in model parameter, the percent change in model output is small. However, outflow routing is difficult to assess with this method because it is determined by a binary input (0 = outflow routed to the outlet and 1 = outflow routed to pervious).

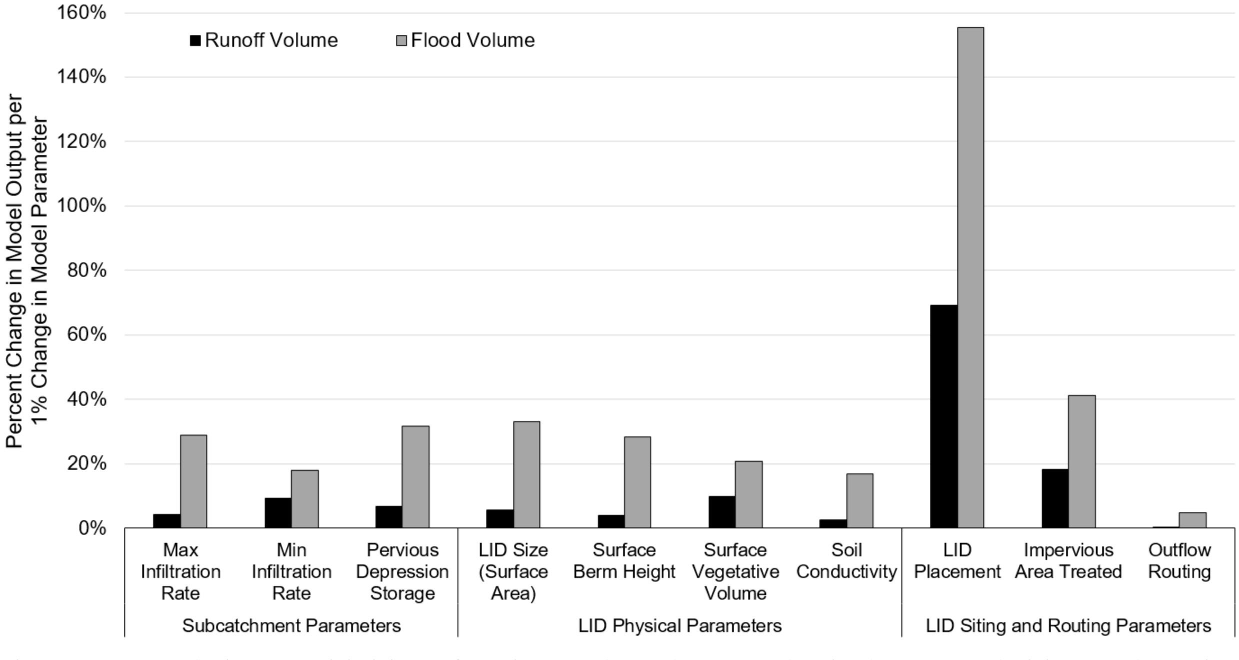


Figure 3.11 Relative sensitivities of various subcatchment, physical LID, and siting and routing LID parameters to runoff volume and flood volume outputs reported as the percent change in model output per 1% change in model parameter.

3.5 Discussion

3.5.1 Counter-acting Model Processes

Certain assumptions in model LID parameterizations can cause counter-acting model processes that lead to muted model runoff results between BR sizing schemes, particularly when area treated is lower, such as when treating only *additional* redeveloped impervious areas. When only *additional* impervious areas are treated by LID, as BR unit size changes, both percent impervious area of the watershed and the percent area treated by LID are strongly affected (Figure 3.12). Changes to these variables are further impacted by LID placement:

1. **LID placed on Impervious**. When BR units are placed on what would have been existing redeveloped *impervious* areas, as BR surface area increases (from 1% BR to 10% BR), the total imperviousness of the watershed decreases (Figure 3.12) leading to lower runoff production. At the same time, because the percent of impervious areas treated by bioretention is calculated based on the total imperviousness, the percent of the watershed runoff treated by the BR units also decreases (Figure 3.12), leading to more runoff bypassing bioretention. These two factors counter-act each other in terms of runoff reduction.
2. **LID placed on Pervious.** When BR units are placed on what would have been existing redeveloped *pervious* areas, as BR surface area increases, the total imperviousness of the watershed also increases (Figure 3.12), leading to higher runoff production. This is because the SWMM model treats LID as a separate area than pervious and impervious areas, and how impervious percentages must be adjusted in the model (Rossman, 2015). At the same time, when a BR unit is placed on *pervious* areas, the percent of impervious areas treated/captured by bioretention stays the same, regardless of BR sizing (Figure 3.12). The percent of impervious area of the watershed and area treated values for all scenarios are presented in Tables 3.1 and 3.2, respectively.

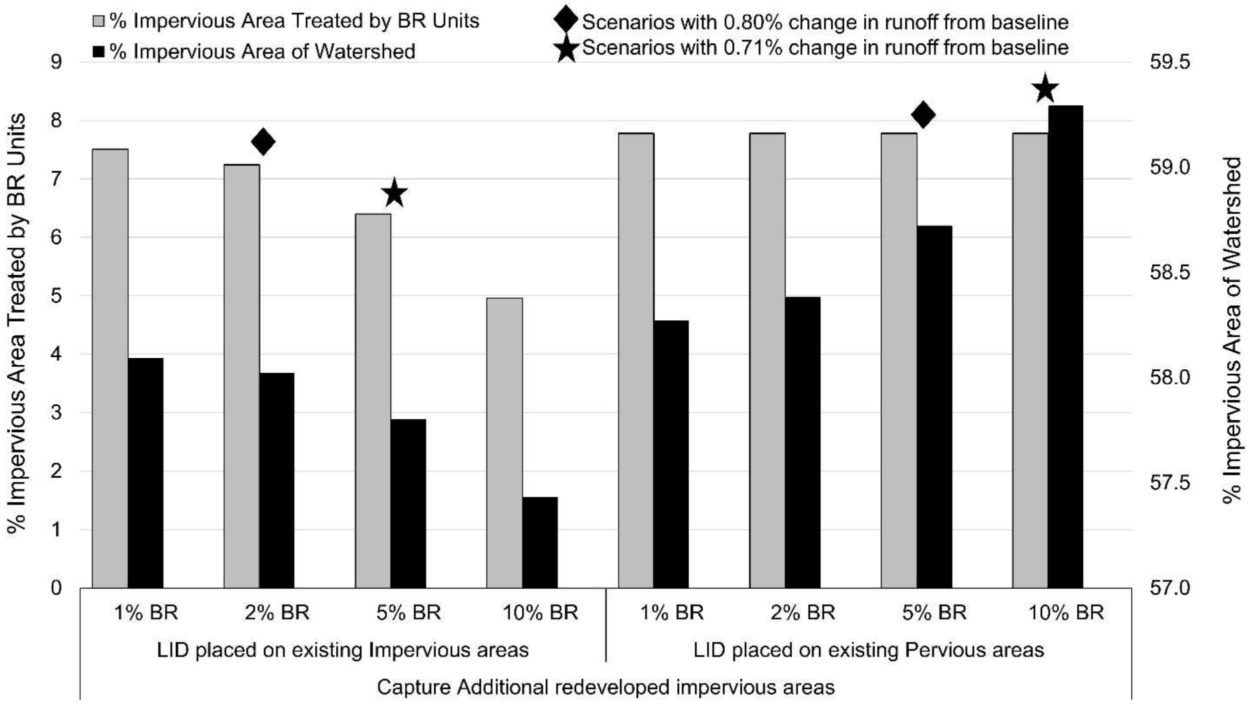


Figure 3.12 Comparison of percent of impervious area treated by bioretention (BR) units and percent of impervious area of the watershed for eight BR scenarios. Scenarios that achieve the same reduction in runoff are indicated with diamond and star symbols.

Due to these trends in the percent impervious area and area treated, it is possible to achieve the same runoff reduction with different assumptions of LID parameterization. For example, replacing existing *impervious* area with 2% BR sizing capturing *additional* runoff achieves the same 0.8% difference in runoff from baseline for the 5-yr storm as replacing existing *pervious* area with 5% BR sizing capturing *additional* runoff (Figure 3.11 and Figure 3.12; diamond symbols). The same result is true for 5% BR/*impervious*/*additional* and 10%BR/*pervious*/*additional* configurations, which both have a 0.71% difference in runoff from baseline (Figure 3.12 and Figure 3.13; star symbols). Both examples refer to scenarios that all route outflow to the outlet. These results suggest that it is possible to achieve the same runoff reduction with LID units half the size, depending what other assumptions are made. Examples of equal runoff reduction results can be found throughout Figure 3.7 for all storm sizes and a variety of parameter configurations. Results also imply that during LID implementation, focus should be put towards impervious area reduction in addition to LID sizing and treated area. This agrees with previous studies that focus on the connection between impervious area and runoff production (Boyd *et al.*, 1993; Arnold and Gibbons, 1996), but couples the concept of impervious area reduction with LID implementation in redeveloped areas.

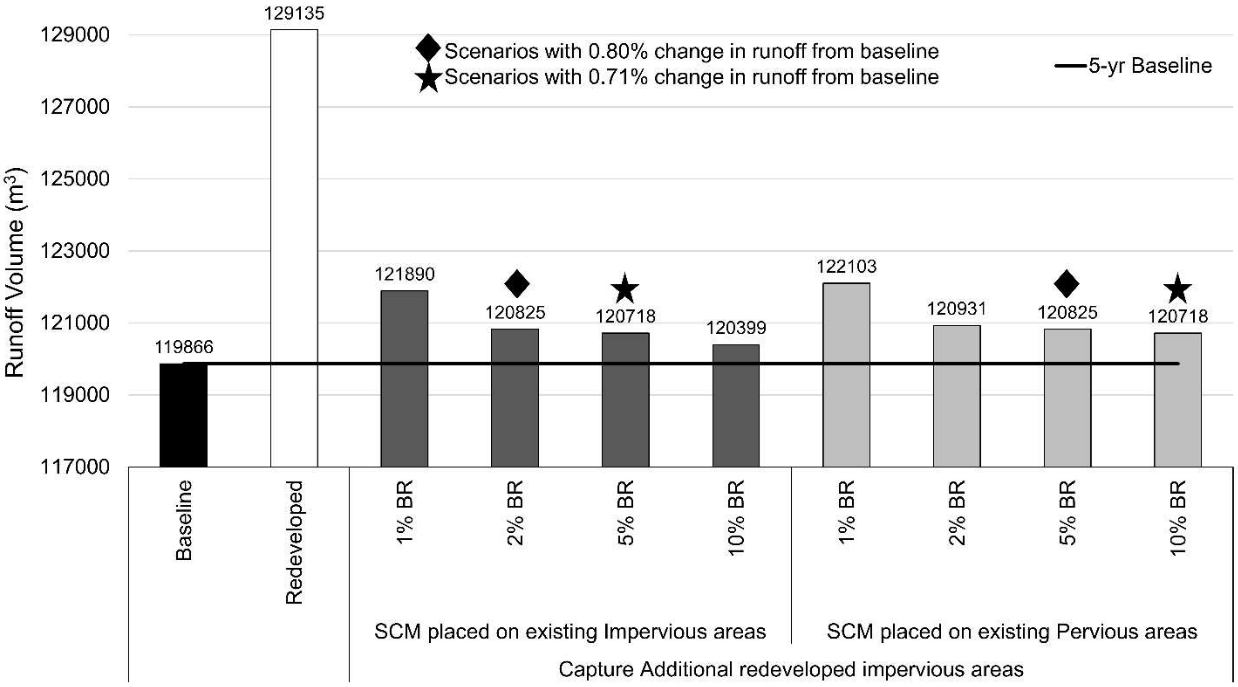


Figure 3.13 Runoff volume (m^3) for baseline and redeveloped conditions (no BR implementation) and for a range of BR scenarios for the 5-yr, 24-hr storm. All BR scenarios assume that BR outflow is routed to the outlet. Scenarios that achieve the same reduction in runoff are indicated with diamond and star symbols. Y-axis does not start at zero.

3.5.2 Implications for Stormwater Management Regulatory Compliance

There are considerable implications of model sensitivity to LID siting and routing parameters when making assumptions during watershed-scale modeling efforts of LID implementation for regulatory compliance. LID scenarios are often modeled with the aim of returning hydrologic conditions to a pre-development (or pre-redevelopment) baseline condition to meet a variety of stormwater management criteria, goals, or regulations (Jefferson *et al.*, 2017). In this context of runoff and flood reduction compliance, our results show that SWMM model sensitivity to siting and routing parameter assumptions about outflow routing, LID placement, and area treated can have large implications. For example, if a modeler either intentionally or inadvertently assumes an LID system will treat runoff from more impervious area than in reality, they may conclude that the system will meet compliance, when it may not. If a modeler focuses on LID sizing and ignores assumptions regarding outflow routing, LID placement, and area treated, they may give incorrect recommendations for sizing LID. In addition, this work demonstrates that there are multiple ways to achieve the same runoff and flood reduction benefits and reach compliance through LID implementation.

Managers and regulators can use the results of this study to improve the regulatory process. For example, revised regulations that aim to mitigate the effects of redevelopment should explicitly consider the design considerations investigated in this study: LID placement, area treated by LID, and outflow routing, in addition to LID sizing. For example, many states (e.g., Georgia, Kentucky, Mississippi, South Carolina, Tennessee, Indiana, Montana, North Dakota, Utah, and Nevada) base current redevelopment standards on capturing a certain size storm, or the first inch of rainfall (EPA, 2016). Other states such as Maine and North Carolina dictate there must be no increase in current stormwater runoff with redevelopment, or "equal or better stormwater control as previous development" (EPA, 2016). These standards would typically be addressed by regulations focused on sizing LID and by focusing on physical LID parameters such as soil characteristics. However, the relative sensitivities of these parameters can be up to 11 times lower on average than model sensitivity to area treated by LID and LID placement. Therefore, our results indicate that in order to best inform regulations, other considerations, particularly area treated by LID and LID placement, must be carefully considered in modeling studies. By making informed assumptions regarding sensitive LID siting and routing parameters, more accurate model results may be obtained to better inform regulations and revised criteria, such as those concerning stormwater management and redevelopment.

3.5.3 Modeling Recommendations

The SWMM model and LID editor are powerful tools for modeling urban hydrologic response to an array of development, redevelopment, and urban stormwater management scenarios (Niazi *et al.*, 2017). However, achieving results that can best inform practitioners and policy makers requires an in-depth understanding of the software, and knowledge of model sensitivity to assumptions made during the modeling process. With LID implementation within existing subcatchments, SWMM separates the subcatchment area into a non-LID and LID fraction. Contrary to common misconceptions, there is no internal adjustment to the percent impervious value of the subcatchment, so it is left to the user to calculate this adjustment based on placement of the LID on existing impervious or pervious surfaces (or a portion of each) (Rossman, 2015). For example, placing LID on existing impervious surfaces is likely when retrofitting or redeveloping a parcel with improved stormwater management. Figure 3.14 shows a conceptual example of correct and incorrect adjustments for an example in which LID is placed on existing impervious area. By making this adjustment, SWMM essentially treats LID as a self-mitigating surface that cannot produce runoff. As demonstrated, this can lead to counter-acting processes depending what other assumptions are made during model parametrization. To assist engineers, managers, and practitioners in this calculation, we developed an Excel-based SWMM impervious area adjustment tool for use by modelers. This Excel file is included in the Supplemental Electronic Files (Appendix C).

Many LID urban hydrologic modeling studies do not report how LID implementation impacts impervious area percentages, nor explicitly state if given impervious percentage metrics are in reference to pre- or post-LID implementation. This work indicates the importance of both adjusting impervious percent values within LID modeling and reporting the correct values to derive accurate relationships between watershed imperviousness and runoff production. Modelers need to be wary of these processes in watershed-scale modeling and ensure that assumptions made in parameterizing outflow routing, LID placement, and area treated represent reality as best as possible, particularly for area treated by LID. By doing so, modelers can better inform data-driven decisions regarding stormwater management criteria such as in the case of redevelopment.

3.6 Conclusions

As the urban population of the world grows, more cities need accurate hydrologic modeling to predict and mitigate the impacts of increased stormwater runoff. SWMM is a popular model for evaluating watershed-scale hydrologic processes, and its LID editor is a useful tool for testing an array of LID scenarios. However, model sensitivity to certain LID siting and routing parameters is poorly understood compared to other physical LID or subcatchment parameters. In this study, we simulated 32 parameter configurations in a calibrated, high-resolution model to test three LID siting and routing parameters involved in assessing the effectiveness of distributed LID implementation in a 419-ha redeveloping, urban neighborhood. Key findings of this work include:

- Modeling assumptions regarding the parameterization of LID outflow routing, LID placement, and area treated by LID all impact model outputs of runoff volume and flood volume. However, LID placement and area treated by LID have the highest relative sensitivity compared to 26 other physical LID and subcatchment parameters.
- Practitioners often focus on the sizing of LID, but water quantity results vary greatly within a single size selection when LID siting and routing parameters are altered.

- In a stormwater criteria or regulatory compliance context, LID siting and routing parameters can dictate whether compliance is met, and incorrect parameterization can lead to incorrect sizing of distributed LID.
- Adjusting impervious area percentages with LID implementation can result in equal runoff reductions across a variety of LID sizing scenarios indicating that correct impervious area adjustment with LID placement should not be overlooked.

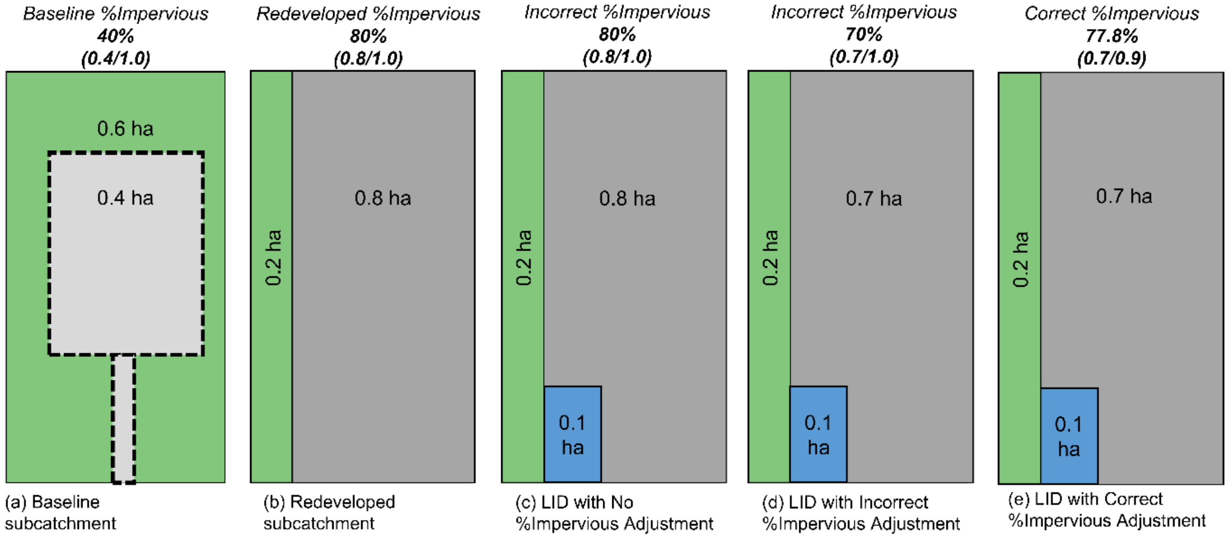


Figure 3.14 Conceptual subcatchments illustrating (a) Baseline subcatchment impervious percent, (b) Redeveloped subcatchment impervious percent, (c) LID model configuration with no impervious percent adjustment, (d) LID model configuration with incorrect impervious percent adjustment, and (e) LID model configuration with correct impervious percent adjustment.

A unique aspect of this study is its focus on using LID to mitigate the impacts of urban redevelopment. Redevelopment provides an opportunity for cities to upgrade their stormwater infrastructure. When implementing LID on small redeveloped parcels, the LID units may occupy a substantial portion of the parcel area (1–10%), but only a small portion of the total watershed area (0.2–1.8%). However, these small units can have a large impact on the runoff and flood volume reduction for the entire watershed (4.4–28%). This suggests implementation of appropriate regulatory standards for redevelopment is a tool that cities can use to modernize and improve their stormwater management at the watershed scale. More work is needed on the impacts of redevelopment on local and regional water management planning, including the benefits that regional and distributed LID may offer.

3.7 Acknowledgements

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3.8 References

Ahiablame, L. M., B. A. Engel, and I. Chaubey. 2012. "Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research." *Water Air Soil Pollut.* 223: 4253-4273. doi.org/10.1007/s11270-012-1189-2

Ahiablame, L., and R. Shakya. 2016. "Modeling flood reduction effects of low impact development at a watershed scale." *J. Environ. Manage.* 171: 81-91. doi.org/10.1016/j.jenvman.2016.01.036

Akan, A. O. and R. J. Houghtalen. 2003. *Urban Hydrology, Hydraulics, and Stormwater Quality: Engineering Applications and Computer Modeling*, John Wiley and Sons, Hoboken, New Jersey.

Alley, W. M. and J. E. Veenhuis. 1983. "Effective Impervious Area in Urban Runoff Modeling." *J. Hydraul. Eng.* 109(2): 313-319. doi.org/10.1061/(ASCE)0733-9429(1983)109:2(313)

Apostolaki, S., C. Jefferies, and T. Wild. 2006. "The social impacts of stormwater management techniques." *Water Practice & Technology.* 1(1). doi.org/10.2166/WPT.2006009

Arnold, C. L., and C. J. Gibbons. 1996. "Impervious Surface Coverage: The Emergence of a Key Environmental Indicator." *J. Am. Plann. Assoc*. 62(2): 243-258. doi.org/10.1080/01944369608975688

Baptiste, A. K., C. Foley, and R. Smardon. 2015. "Understanding urban neighborhood differences in willingness to implement green infrastructure measures: a case study of Syracuse, NY." *Landsc. Urban Plan.* 136: 1-12. doi.org/10.1016/j.landurbplan.2014.11.012

Barco, J., K. M. Wong, and M. K. Stenstrom. 2008. "Automatic Calibration of the U.S. EPA SWMM Model for a Large Urban Catchment." *J. Hydraul. Eng*. 134(4): 466-474. doi.org/10.1061/(ASCE)0733-9429(2008)134:4(466)

Bedan, E. S., and J. C. Clausen. 2009. "Stormwater runoff quality and quantity from traditional and low impact development watersheds." *J. Am. Water Resour. Assoc*. 4: 998-1008. doi.org/10.1111/j.1752-1688.2009.00342.x

Booth, D. B., and C. R. Jackson. 1997. "Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation." *J. Am. Water Resour. Assoc*. 33(5): 1077-1090. doi.org/10.1111/j.1752-1688.1997.tb04126.x

Boyd, M. J., M. C. Bufill, and R. M. Knee. 1993. "Pervious and impervious runoff in urban catchments." *Hydrolog. Sci. J.* 38(6): 463-478. doi.org/10.1080/02626669309492699

Brown, H. L., D. G. Bos, C. J. Walsh, T. D. Fletcher, and S. RossRakesh. 2016. "More than money: how multiple factors influence householder participation in at-source stormwater management." *J. Environ. Plann. Manage*. 59(1): 79-97. doi.org/10.1080/09640568.2014.984017

Burchell, R. W., D. Listokin, and C. C. Galley. 2000. "Smart growth: More than a ghost of urban policy past, less than a bold new horizon." *Housing Policy Debate*. 11(4): 821-879. doi.org/10.1080/10511482.2000.9521390

Cherry, L., D. Mollendor, B. Eisenstein, T. S. Hogue, K. Peterman, and J. E. McCray. 2019. "Predicting Parcel-Scale Redevelopment Using Linear and Logistic Regression – the Berkeley Neighborhood Denver, Colorado Case Study." *Sustainability.* 11(7): 1882. doi.org/10.3390/su11071882

Denver Department of Public Works (DPW), Wastewater Management Division, Engineering Division. 2013. "City and County of Denver Storm Drainage Design & Technical Criteria Manual." denvergov.org

Dietz, M. E. 2007. "Low impact development practices: a review of current research and recommendations for future directions." *Water Air Soil Pollut.* 186: 351-363. doi.org/10.1007/s11270-007-9484-z

Eckart, K., Z. McPhee, and T. Bolisetti. 2017. "Performance and implementation of low impact development – A review." *Sci. Total Environ*. 607-608: 413-432. doi.org/10.1016/j.scitotenv.2017.06.254

Environmental Protection Agency (EPA). 2016. *Summary of State Post Construction Stormwater Standards*. EPA: Office of Water, Office of Wastewater Management, Water Permits Division.

Fletcher, T. D., W. Shuster, W. F. Hun, R. Ashley, D. Butler, S. Arthur, S. Trowsdale, S. Barraud, A. Semadeni-Davies, J. Bertrand-Krajewski, P. S. Mikkelson, G. Rivard, D. Dagenais, and M. Viklander. 2015. "SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage." *Urban Water J.* 12(7): 525-542. doi.org/10.1080/1573062X.2014.916314

Fry, T. J., and R. M. Maxwell. 2017. "Evaluation of distributed BMPs in an urban watershed –

High resolution modeling for stormwater management." *Hydrol. Process*. 31 (15): 2700-2712. doi.org/10.1002/hyp.11177

Gao, J., J. Pan, N. Hu, and C. Xie. 2018. "Hydrologic performance of bioretention in an expressway service area." *Wat. Sci. Tech.* 77(7). doi.org/10.2166/wst.2018.048

Goetz, A. 2013. "Suburban Sprawl or Urban Centres: Tensions and Contradictions of Smart Growth Approaches in Denver, Colorado." *Urban Studies*. 50: 2178-2195. doi.org/10.1177/0042098013478238

Gülbaz, S., and C. M. Kazezyılmaz-Alhan. 2017. "An evaluation of hydrologic modeling performance of EPA SWMM for bioretention." *Wat. Sci. Tech*. 76(11): 3035-3043. doi.org/10.2166/wst.2017.464

Han, W. S., and S. J. Burian. 2009. "Determining Effective Impervious Area for Urban Hydrologic Modeling." *J. Hydrol. Eng*. 14(2): 111-120. doi.org/10.1061/(ASCE)1084-0699(2009)14:2(111)

Hu, M., T. Syama, X. Zhang, K. Tanaka, and H. Yang. 2017. "Evaluation of low impact development approach for mitigating flood inundation at a watershed scale in China." J. Environ. Manage. 193: 430-438. doi.org/10.1016/j.jenvman.2017.02.020

James, L. D., and S. J. Burges. 1982. Selection, Calibration, and Testing of Hydrologic Models. In: Hydrologic Modeling of Small Watersheds, C. T. Haan (Editor). American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 437-472.

Jefferson, A. J., A. S. Bhaskar, K. G. Hopkins, R. Fanelli, P. M. Avellaneda, and S. K. McMillan. 2017. "Stormwater management network effectiveness and implications for urban watershed function: A critical review." *Hydrol. Process* 31: 4056-4080. doi.org/10.1002/hyp.11347

Jewell, T. K., D. D. Adrian, and T. J. Nunno. 1978. "Methodology for Calibrating Stormwater Models." *Journal of the Environmental Engineering Division*. 104(3): 485-501.

Johnson, M. P. 2001. "Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda." *Environment and Planning A.* 33 (4): 717-735. doi.org/10.1068/a3327

Kaykhosravi, S., U. T. Khan, and A. Jadidi. 2018. "A Comprehensive Review of Low Impact Development Models for Research, Conceptual, Preliminary and Detailed Design Applications." *Water.* 10(11): 1541. doi.org/10.3390/w10111541

Lee, J. G., and J. P. Heaney. 2003. "Estimation of urban imperviousness and its impact on storm-water systems." J. *Water Resour. Plann. Manage*. 129(5): 419-426. doi.org/10.1061/(ASCE)0733-9496(2003)129:5(419)

Lee, J. G., A. Selvakumar, K. Alvi, J. Riverson, J. X. Zhen, L. Shoemaker, and F. Lai. 2012. "A watershed-scale design optimization model for stormwater best management practices."

Environ. Modell. Softw. 37: 6-18. doi.org/10.1016/j.envsoft.2012.04.011

Liong, S. Y., W. T. Chan, and L. H. Lum. 1991. "Knowledge-Based System for SWMM Runoff Component Calibration." *J. Water Resourc. Plann. Manage*. 117(5): 507-524. doi.org/10.1061/(ASCE)0733-9496(1991)117:5(507)

Los Angeles Department of Public Works (LA DPW). 2010. *Stormwater best management practice design and maintenance manual*. Los Angeles: County of Los Angeles Dept. of Public Works.

Mao, X., H. Jia, and S. L. Yu. 2017. "Assessing the ecological benefits of aggregate LID-BMPs through modelling." *Ecol. Modell*. 353: 139-149. doi.org/10.1016/j.ecolmodel.2016.10.018

Niazi, M., C. Nietch, M. Maghrebi, N. Jackson, B. R. Bennett, M. Tryby, A. Massoudieh. 2017. "Storm Water Management Model: Performance Review and Gap Analysis." *J. Sustainable Water Built Environ*. 3 (2). doi.org/10.1061/JSWBAY.0000817

Palla, A., and I. Gnecco. 2015. "Hydrologic modeling of Low Impact Development systems at the urban catchment scale." *J. Hydrol*. 528: 361-368. doi.org/10.1016/j.jhydrol.2015.06.050

Panos, C. L., T. S. Hogue, R. L. Gilliom, and J. E. McCray. 2018. "High-resolution modeling of infill development impact on stormwater dynamics in Denver, Colorado." *J. Sustainable Water Built Environ*. 4(4). doi.org/10.1061/JSWBAY.0000863

Pond, M. C. and G. Kacvinsky. 2006. "Tear-downs - controlling stormwater impacts." <http://waterbucket.ca/gi/files/2013/03/Teardowns-controlling-stormwater-impacts.pdf> (Accessed June 19, 2017).

Qin, H., Z. Li, and G. Fu. 2013. "The effects of low impact development on urban flooding under different rainfall characteristics." *J. Environ. Manage*. 129: 577-585. doi.org/10.1016/j.jenvman.2013.08.026

Rosa, D. J., J. C. Clausen, and M. E. Dietz. 2015. "Calibration and Verification of SWMM for Low Impact Development." *J. Am. Water Resour. Assoc*., 51(3): 746-757. doi.org/10.1111/jawr.12272

Rossman, L. A. 2015. *Storm Water Management Model User's Manual Version 5.1*. Cincinnati, OH: National Risk Management Research Laboratory, United States Environmental Protection Agency.

Rossman, L. A., and W. Huber. 2016. *Storm Water Management Model Reference Manual Volume III – Water Quality*. US EPA Office of Research and Development, Washington, DC, EPA/600/R-16/093.

Tsihrintzis, V. A., and R. Hamid. 1998. "Runoff quality prediction from small urban catchments using SWMM." *Hydrol. Process*. 12(2): 311-329. doi.org/10.1002/(SICI)1099-1085(199802)12:2<311::AID-HYP579>3.0.CO;2-R

United Nations, Department of Economic and Social Affairs, Population Division. 2018. *World Urbanization Prospects: The 2018 Revision*. New York: United Nations.

Urban Drainage and Flood Control District (UDFCD). 2011. “Calculating the WQCV and volume reduction.” Chapter 3 in: *Urban storm drainage criteria manual: Volume 3*. Denver: UDFCD.

Urban Drainage and Flood Control District (UDFCD). 2015. “Memorandum: New Colorado Revised Statute §37-92-602 (8) ‘Concerning a Determination that Water Detention Facilities Designed to Mitigate the Adverse Effects of Storm Water Runoff Do Not Materially Injure Water Rights.’” <https://udfcd.org/crs-37-93-6028-explanation-memo-and-faqs/> (Accessed March 3, 2019).

Urban Drainage and Flood Control District (UDFCD). 2018. “Treatment BMP Fact Sheets.” Chapter 4 Section 2.0 in: *Urban storm drainage criteria manual: Volume 3*. Denver: UDFCD.

Walsh, T. C., C. A. Pomeroy, and S. J. Burian. 2014. “Hydrologic modeling analysis of a passive, residential rainwater harvesting program in an urbanized, semi-arid watershed.” *J. Hydrol.* 508: 204-253. doi.org/10.1016/j.jhydrol.2013.10.038

Wang, M., D. Zhang, S. Lou, Q. Hou, Y. Liu, Y. Cheng, J. Qi, and S. K. Tan. 2019. “Assessing Hydrological Effects of Bioretention Cells for Urban Stormwater Runoff in Response to Climatic Changes.” *Water.* 11: 997. doi.org/10.3390/w11050997

Wolfand, J. M., C. D. Bell, A. B. Boehm, T. S. Hogue, and R. G. Luthy. 2018. “Multiple Pathways to Bacterial Load Reduction by Stormwater Best Management Practices: Trade-Offs in Performance, Volume, and Treated Area.” *Environ. Sci. Technol.* 52(11): 6370-6379. doi.org/10.1021/acs.est.8b00408

Wright, T. J., Y. Liu, N. J. Carroll, L. M. Ahiablame, and B. A. Engel. 2016. “Retrofitting LID Practices into Existing Neighborhoods: Is It Worth It?” *Environ. Manage*. 57 (4): 856-867. doi.org/10.1007/s00267-015-0651-5

CHAPTER 4

ASSESSING RESILIENCE OF A DUAL DRAINAGE URBAN SYSTEM TO REDEVELOPMENT LAND USE CHANGE AND CLIMATE CHANGE

Modified from a manuscript in preparation for publication

Chelsea L. Panos, Jordyn M. Wolfand, and Terri S. Hogue

4.1 Abstract

Dual drainage systems in urban areas were historically designed and built to convey certain size storms on an assumption of stationarity. However, changes to rainfall from climate change and increases in impervious area from land use change, specifically due to redevelopment, violate this assumption. Hydrologic models can be used to quantify impacts to stormwater from both climate and land use changes. However, many modeling studies evaluate the impact of either climate change or land use change on urban hydrology, but not both concurrently. Uncertain climate projections can complicate modeling efforts using "predict-then-adapt" strategies. Therefore, this study used a "tipping point" resilience assessment to determine at what changes in rainfall (tipping points) the dual drainage stormwater system of a redeveloping urban neighborhood will exceed regulatory standards for flooding for both minor (5-yr) and major (100-yr) storm events at different levels of redevelopment. We found that the pre-redevelopment system reaches the minor event tipping point at a 7% increase in rainfall, and that redevelopment can increase impervious areas up to 8.1% before exceeding minor standards at current rainfall, suggesting similar stormwater quantity impacts from both climate and land use changes. Adding distributed LID adaptation options (bioretention) in redeveloped areas can increase tipping points by 12-13%, which presents redevelopment as a unique opportunity for implementing LID and building system resilience.

4.2 Introduction

Climate change and land use change are both drivers of hydrologic disturbance in urban environments. Understanding the impacts of these drivers on stormwater runoff, flooding potential, and water quality is critical for the future of water resources. It is predicted that climate change will impact hydrologic processes by affecting the frequency, duration, and intensity of extreme precipitation events, and increasing hydrologic variability leading to "flashier" runoff events (Praskievicz and Chang, 2009; Forsee and Ahmad, 2011; Paerl *et al.*, 2016). Land use change in urban areas is recently manifesting as *infill development*, or *redevelopment*, where existing land uses with lower impervious areas are densified to land uses with increases in impervious areas (Thomas, 2009; EPA, 2016a).

Several computational modeling studies have investigated the impacts of climate change on urban hydrologic processes. For example, Moore *et al.* (2016) studied the vulnerability of stormwater drainage systems within the built environment to climate change uncertainty. Waters *et al.* (2003) determined how increases in rainfall intensities impact hydrologic processes in an urban southern Ontario catchment. Alamdari *et al.* (2017) used an auto-calibration tool to assess how climate change, and associated changes in seasonal variability, impacts water quality and quantity in an urban watershed. Zahmatkesh *et al.* (2014) analyzed multiple scenarios of maximum, mean, and minimum changes in rainfall due to climate change and found increases in the frequency of extreme events and magnitude of peak flows.

Other hydrologic modeling studies have investigated the impacts of land use change through redevelopment on stormwater. Redevelopment is estimated to comprise 21% of new home constructions in the 209 largest U.S. metropolitan areas, and the demand for redevelopment is expected to be sustained, particularly for the next 15 to 20 years (EPA, 2014). Panos *et al.* (2018) found that changes to land use through redevelopment in a Denver, Colorado neighborhood can result in increased runoff volumes of 1.27% per 1% increase in impervious area. Hekl and Dymond (2016) found similar, but slightly lower results of a 0.8% increase in runoff volume per 1% increase in impervious area for a watershed in Virginia. A study by Pond and Kacvinsky (2006) determined a 1.04% increase in peak flows per 1% increase in impervious area due to redevelopment. Studies regarding redevelopment land use change highlight the increases to both runoff volumes and peak flows, and potential consequences for increased flooding.

As evidenced, many studies have assessed climate change and land use change impacts on urban hydrology separately. However, fewer studies have modeled the effects of climate change alongside those of land use change, especially in urban catchments. Li *et al.* (2009) assessed the impacts of both climate variability and land use change on an agricultural catchment in China, finding that climate influenced hydrologic response more strongly than land use change. Other studies that have examined both climate and land use suggest that land use change may have a larger impact on runoff and other hydrological and ecological processes than climate change. For example, Sala *et al.* (2000) ranked land use change as the largest driver of impacts to biodiversity in terrestrial ecosystems by the year 2100, with climate change as the second largest driver. Liu *et al.* (2016) determined that land use had a greater impact on runoff volumes and pollutant loads than climate in an Indiana watershed. Praskievicz and Chang (2009) conclude that different studies find either climate or land use change to be more significant based on many factors such as hydrologic modeling assumptions and basin characteristics, but that both climate and land use changes will be important to future water resources management, which includes the continued functionality of existing urban drainage networks.

Many urban drainage networks in the U.S. were originally sized to convey design storms up to the 5-yr and 10-yr storm based on statistical analysis of historic extreme rainfall events (Waters *et al.*, 2003; Mailhot and Duchesne, 2010; Moore *et al.*, 2016). By contrast, systems in Europe are designed to prevent floods from return periods ranging from the 10-yr to 50-yr storm (Salvadore *et al.*, 2015). In general, urban drainage design was built on the assumption of stationarity. Problems arise when non-stationary factors such as changes to precipitation patterns from climate change, or increasing impervious area due to redevelopment, violate this assumption (Arisz and Burrell, 2006; Milly *et al.*, 2008). Increases in the runoff amounts generated by storms that drainage systems were historically designed to handle could mean a decrease in system functionality and exceedance of regulatory standards.

It has been shown that low impact development (LID), or stormwater control measures (SCMs), may be capable of mitigating increases in stormwater runoff due to redevelopment when land use change is the only consideration (Panos *et al.*, 2020). However, it is unknown how climate change may compound impacts of redevelopment on stormwater runoff and flooding. Cities are focusing on how to adapt existing stormwater systems to climate change and build resilience into stormwater solutions (Gersonius *et al.*, 2012; Moore *et al.*, 2016). For example, China has launched the “sponge city” policy initiative which focuses on sustainable urban stormwater management using tools such as LID (Jiang *et al.*, 2017). Adaptation approaches typically follow a “predict-then-adapt” method in which climate change scenarios are predicted, such as increases in rainfall intensities, then the system effectiveness is assessed under this new climate (Waters *et al.*, 2003; Arisz and Burrell, 2006; Semadeni-Davies *et al.*, 2008). Issues with this top-down approach are that it is causal-based, neglects location-specific considerations, and has heavy reliance climate change estimates. These problems are exacerbated in areas of particularly uncertain climate change estimates, such as regions in the central U.S. where precipitation change estimates range as wide as a 20.5% decrease to a 65.6% increase (Mahoney *et al.*, 2013).

To address these issues, Gersonius *et al.* (2012) present a flipped approach called the *mainstreaming method* in which acceptable performance thresholds for a local system are identified first, then tipping points are identified where thresholds are crossed as a result of climate change, and adaptive measures (e.g., LID) are used to improve tipping points. For example, Gersonius *et al.* (2012) found that a minor/major stormwater system in a neighborhood in the Netherlands exceeds acceptable standards and floods properties (i.e., reaches a tipping point) at an increase in rainfall of 40% due to climate change, but with adaptive measures, the tipping point is improved and the system can handle an additional 10% increase in rainfall before failing. This method is effect-based and follows a bottom-up approach that considers local conditions and constraints, which is critical in the context of redevelopment. The current study uses this novel approach to assess the adaptive potential and resilience of different components of an existing stormwater system in a redeveloping neighborhood to climate change.

Moving forward, growing cities across the U.S. and the world will face changes to the urban hydrologic regime due both to land use change and climate change. The goal of this work is to analyze several dynamic factors such as increases in impervious areas and changes in rainfall in tandem, along with LID implementation, to predict the adaptive capacity of stormwater management for redeveloping cities into the future.

4.3 Methods

4.3.1 Study Area

The study area includes the 419-ha Berkeley neighborhood in northwest Denver, Colorado (39.776110, -105.039245) as investigated in Panos *et al.* (2018 and 2020) (Figure 4.1). Denver is cited as a leader in promoting growth management through redevelopment alongside Portland, Sacramento, and Atlanta (Thomas, 2009). Between the years 2000 and 2012, the number of downtown Denver households grew by 110% (EPA, 2014). Berkeley has experienced significant redevelopment, particularly around the Tennyson business corridor (Cherry *et al.*, 2019). In 2014, the impervious area of the neighborhood was 53.5%. Cherry (2016) estimated that future land covered by redevelopment in the study area would increase by 15% of total neighborhood parcels by the year 2024 resulting in an increase in impervious area of 1%. Berkeley experiences a historical 458 mm annual average rainfall. The neighborhood uses a dual drainage stormwater network with a storm sewer as the minor system and street conveyance as the major system. Streets within the neighborhood are classified as *local*, *collector*, or *arterial* (Figure 4.1) based on function and number of lanes (UDFCD, 2016). The Berkeley catchment contains no rivers or streams, but stormwater collected by the dual drainage network eventually discharges into Clear Creek and ultimately the South Platte River. The neighborhood includes two manmade lakes, Berkeley Lake and Rocky Mountain Lake (Figure 4.1).

4.3.2 Model Application

The Storm Water Management Model (SWMM) Version 5.1.013 was used as a part of the PCSWMM software (CHI Water) to model the Berkeley neighborhood sewershed. A dual drainage model was built from the existing PCSWMM model used in previous studies (Panos *et al.*, 2018 and 2020). The model includes 170 subcatchments (Figure 4.1) that were calibrated and validated at a 5-minute time step to three locations of observed flow and water level data (indicated by circles in Figure 4.1). Table 4.1 summarizes performance statistics for model calibration and validation. Calibration and validation resulted in good to very good model performance on average, as defined by Moriasi *et al.* (2007), with an average NSE values of 0.727 and 0.730, and a low average percent bias values of 6.12% and 7.53% (absolute bias) at the 5-min time step, for calibration and validation, respectively.

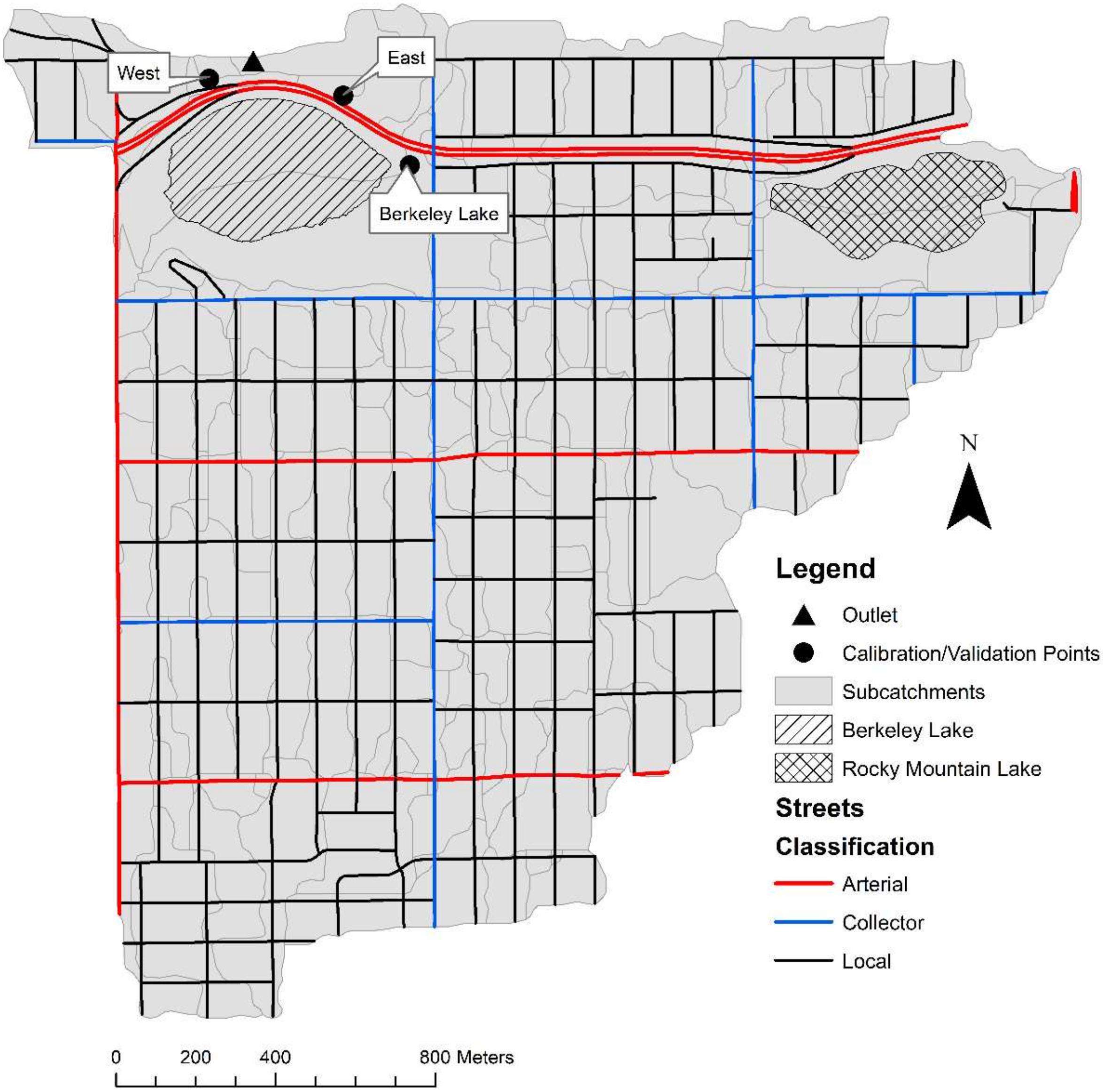


Figure 4.1 Map of the Berkeley neighborhood study area including subcatchments, calibration/validation points, the catchment outlet, Berkley and Rocky Mountain Lakes, and street classifications.

Table 4.1 Performance statistics for PCSWMM model calibration and validation.

	Simulation Dates	Number of Observed Data Points	Basin	NSE	R^2	Percent Bias (%)
Calibration	4/17/2017 – 6/3/2017	13,362	West Basin	0.683	0.748	15.53%
	7/14/2016 – 9/5/2016	15,205	Berkeley Lake Basin	0.963	0.964	-1.39%
	4/17/2017 – 6/3/2017	13,362	East Basin	0.535	0.667	-1.44%
Validation	6/4/2017 – 7/27/2017	15,366	West Basin	0.428	0.503	15.75%
	9/2/2015 – 10/15/2015	12,175	Berkeley Lake Basin	0.966	0.967	-4.01%
	6/4/2017 – 7/27/2017	15,366	East Basin	0.797	0.807	-2.83%

Runoff in each subcatchment was routed to the furthest downstream minor junction of that subcatchment. All model simulations were run with dynamic wave routing, five antecedent dry days, and monthly evaporation estimates. The dual drainage components include storm sewer pipes for the minor system and streets for the major system. All minor system geospatial coordinates, lengths, diameters, slopes, and roughness values were imported from GIS data provided by the City of Denver. Street conduits were classified as either local, collector, or arterial based on GIS data from the Denver Open Data Catalog (denvergov.org/opendata). PCSWMM's dual drainage creator tool was used to generate street conduits parallel to all existing minor system conduits. All other street conduits were manually added to the model. Street conduits are assigned a transect based on street classification and minor or major event standards as described further in Section 4.3.5. Full descriptions of all PCSWMM components are presented in Table 4.2.

Table 4.2 Inventory of PCSWMM entities in the Berkeley dual drainage model. (Some descriptions from Randall *et al.*, 2017).

Model component	Number	Description
Minor junctions	186	Manholes
Major junctions	353	Junctions of major system streets
Minor conduits	188	Storm sewer pipes
Major conduits	506	Streets
Subcatchments	170	Drainage areas
Outfalls	1	Flow at catchment outlet
Outlets	348	Links from minor to major systems
Transects	5	Street conduit geometry for local, collector, and arterial classifications for minor and major events

4.3.3 Redevelopment Land Use Change

Three scenarios for future redevelopment are utilized in this study, as developed by Panos *et al.* (2018), based on parcel-scale predictions of redevelopment land use change from Cherry *et al.* (2019). The redevelopment scenarios have an associated 1.2%, 4.7%, and 8.1% increase in impervious area above baseline conditions, respectively, representing *low*, *moderate*, and *high* cases of potential redevelopment. These estimates are based on linear and logistic regression analyses performed for the Berkeley neighborhood study area using county assessor's office data (Cherry *et al.*, 2019) and are comparable to impervious area increases investigated in other redevelopment studies. For example, Hekl and Dymond (2016) assessed a 7% increase in impervious area in Fairfax County, Virginia, and Pond and Kacvinsky (2006) assessed a 6.7% increase in impervious area. For the current study, *baseline* represents *pre-redevelopment* watershed conditions in 2014 with an impervious area of 53.5% and no LID implementation except for a few existing bioretention cells that were built into the calibrated PCSWMM model.

4.3.4 Climate Change

There are extensive, complex methods of modeling climate change scenarios for urban catchments such as downscaling projections from global climate models (GCM) (Moore *et al.*, 2016), applying delta change factors (Forsee and Ahmad, 2011; Zahmatkesh *et al.*, 2014; Moore *et al.*, 2016), or changing regional intensity-duration-frequency (IDF) curves (Guo, 2006; Mirhosseini *et al.*, 2013). Colorado-specific literature indicates little agreement between climate models on how precipitation will be impacted by climate change. A Colorado Water Conservation Board report by Lukas *et al.* (2014) notes changes in precipitation in Colorado from a 5% decrease to an 8% increase for two emissions scenarios. Global climate models show that the average annual precipitation for Colorado may not significantly change in the future, but the frequency of larger events is changing along with the seasonality of precipitation towards wetter winters (Lukas *et al.*, 2014). Other Colorado-specific literature that uses high-resolution downscaled simulations in an array of climate models have found an even wider spread of possible precipitation changes from a 20.5% decrease to a 65.6% increase (Mahoney *et al.*, 2013). Given the high variability of climate projections for the Colorado region, we addressed the study objectives using a resilience assessment based on the 'mainstreaming method' presented by Gersonius *et al.* (2012).

4.3.5 Resilience Assessment

A resilience assessment was performed for the study area, which includes several steps from the previously developed mainstreaming method (Gersonius *et al.*, 2012). Following the steps of the flowchart in Figure 4.2, we first identified climate change effects of interest to be changes in rainfall, and the hydrologic function of interest to be flood volumes. Next, we determined flooding threshold values (acceptable standard line/x-axis in Figure 4.3) based on current standards for the City of Denver for both minor and major events as discussed in Sections 4.3.5.1 and 4.3.5.2, respectively. Then, we assessed the tipping points at which baseline and redevelopment (low, moderate, and high) scenarios cross the acceptable standards in terms of a *rainfall multiplier*. The rainfall multiplier indicates changes in rainfall (increases or decreases), where a rainfall multiplier of 1 represents historic rainfall, 1.2 is a 20% increase in rainfall, 0.9 is a 10% decrease in rainfall, etc. Adaptation options were added to the redeveloped scenarios as distributed and regional LID, and new tipping points were calculated. Finally, adaptation options were assessed and compared to determine which option provides the most system resilience. We define resilience for this study as a system that reaches its tipping point/crosses the acceptable standard threshold at a higher rainfall multiplier than other options. This indicates that the system can perform to standard under wider changes to rainfall, which is desirable in a future of uncertain climate projections. A conceptual diagram of expected model results is presented in Figure 4.3.

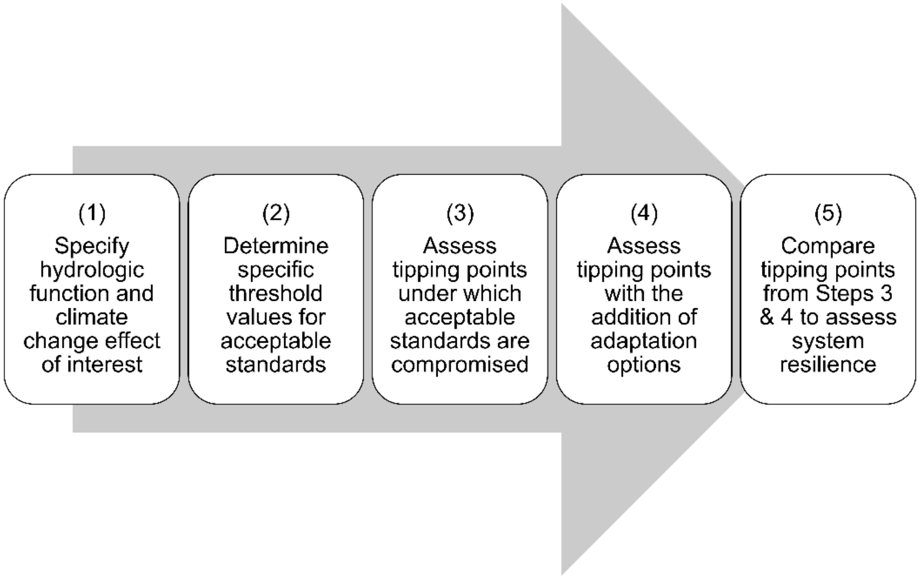


Figure 4.2 Flow chart of the mainstreaming method as applied in this study (adapted from Figure 1 in Gersonius *et al.* (2012)).

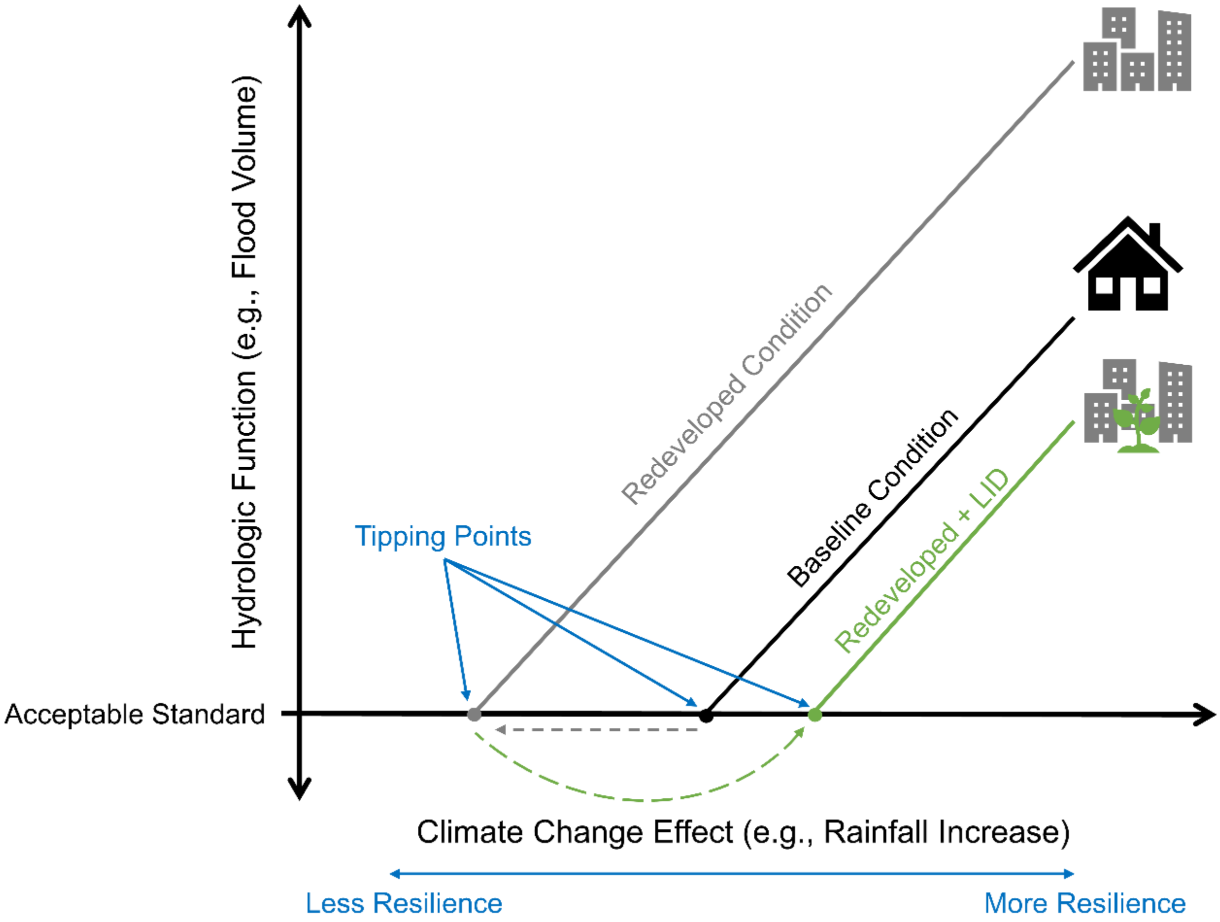


Figure 4.3 Conceptual diagram of expected modeling results showing climate change effect on the x-axis, hydrologic function on the y-axis, and how tipping point results are expected to shift between baseline, redeveloped, and redeveloped + LID scenarios to a state of more or less system resilience. LID = low impact development.

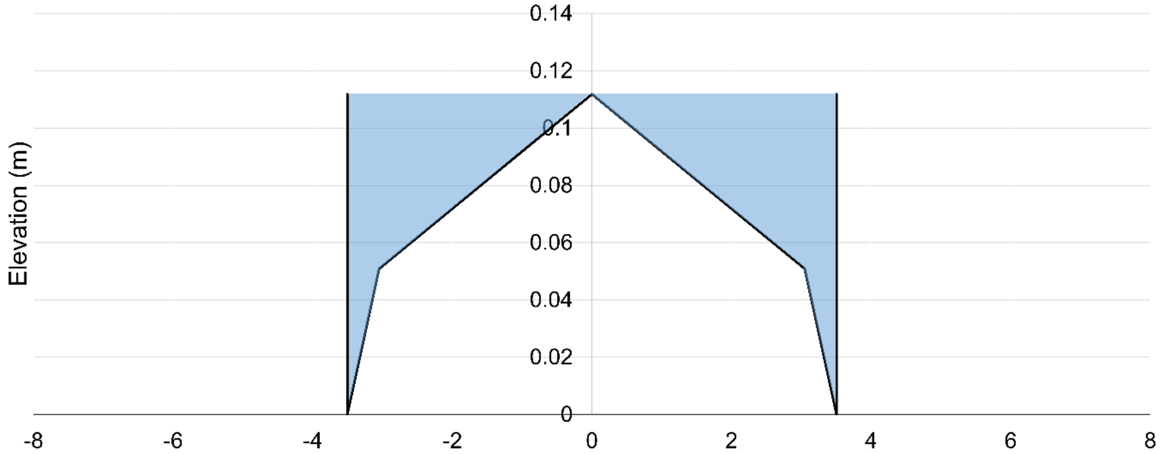
4.3.5.1 Minor Storm Event Standards

The Urban Drainage and Flood Control District (UDFCD) Drainage Criteria Manual states specific objectives and standards for both the minor and major events in the study area (UDFCD, 2016). The objective for the minor storm event (5-yr) is to reduce water nuisance by containing stormwater to the streets and storm sewer with specific maximum encroachment and inundation standards for different street classifications (Table 4.3). The minor event was modeled as the 5-yr, 6-hr rainfall event for the study area (31.2 mm total rainfall depth) as generated using the Colorado Urban Hydrograph Procedure (CUHP) Excel-based model. Rainfall multipliers were applied uniformly across the hyetograph.

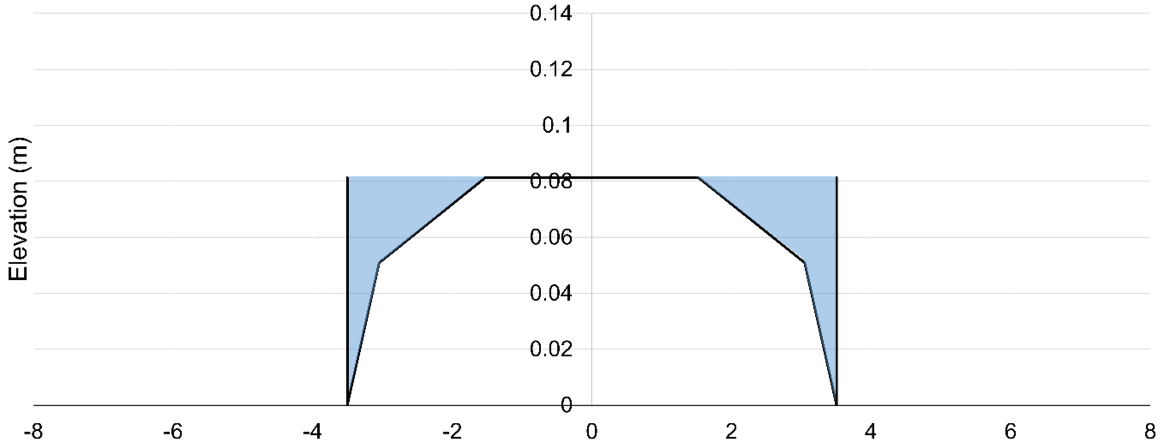
Street conduit transects in PCSWMM were built based on the following standards. For all streets, we assumed a 2% crown slope, 0.457 m (1.5 ft) curb width, 3.048 m (10 ft) lane width, and symmetric street geometry. Street transects for each classification are shown in Figure 4.4. Because the street conduit transects were designed based on the minor event standards, the system exceeds the minor event standards (reaches a tipping point) when any major system junction (defined in Table 4.2) floods. This means that minor system junctions may flood into connected major system conduits (i.e., the storm sewer may flood into streets up to minor storm encroachment and inundation standards). *Flooding* in this study is defined as a flood volume of 3.8 m^3 (1,000 gallons) or larger.

Table 4.3 Street inundation standards for the minor (5-yr, 6-hr) storm event (reproduced from Table 7-2 in UDFCD, 2016).

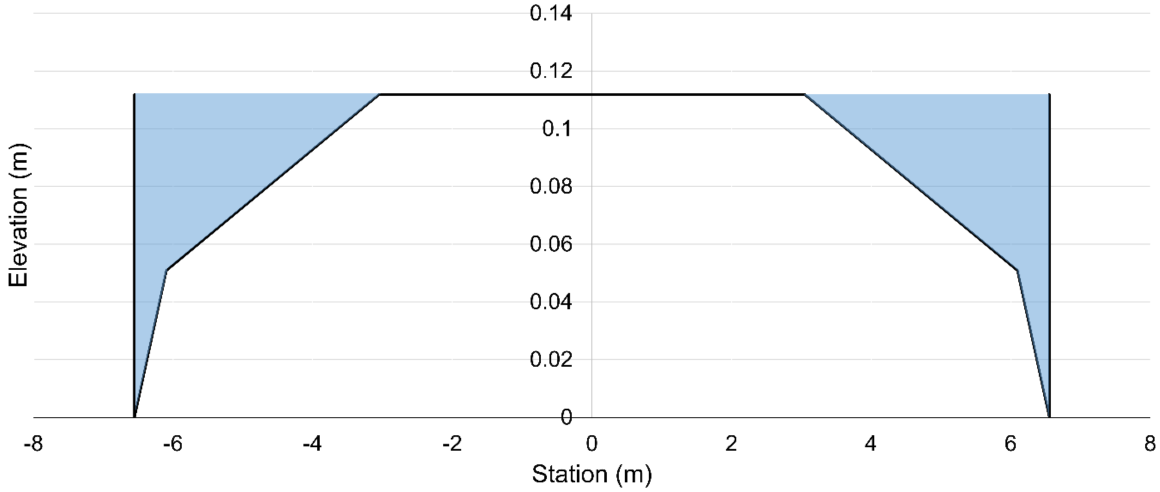
Street Classification	Maximum Encroachment and Inundation Standards
Local	No curb overtopping. Flow may spread to crown of street.
Collector	No curb overtopping. Flow spread must leave at least one lane free of water.
Arterial	No curb overtopping. Flow spread must leave at least one lane free of water in each direction and should not flood more than two lanes in each direction.



(a) Minor Local



(b) Minor Collector



(c) Minor Arterial

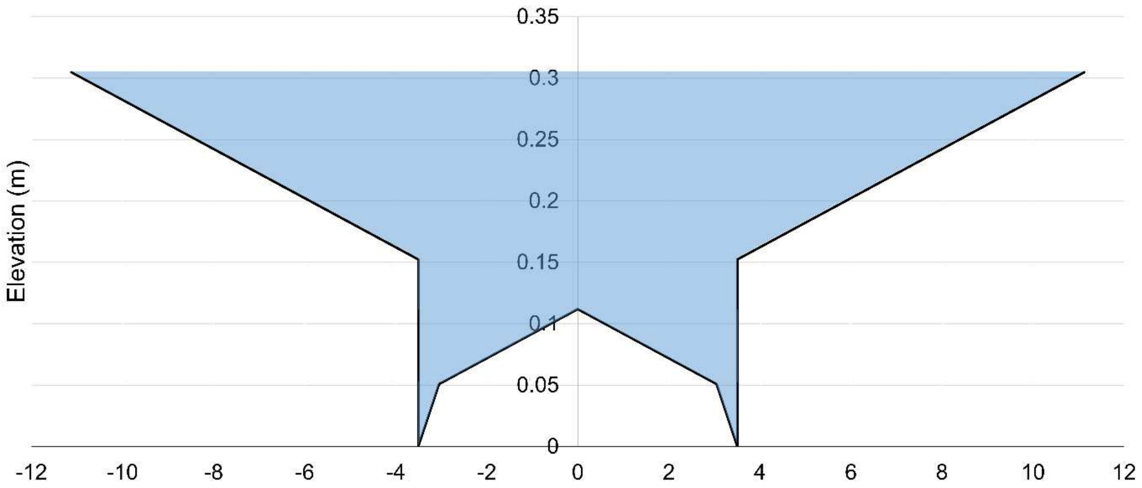
Figure 4.4 Conduit transects for (a) local, (b) collector, and (c) arterial street classifications for the minor storm event. Note that the scale of the x-axis is not proportional to the y-axis.

4.3.5.2 Major Storm Event Standards

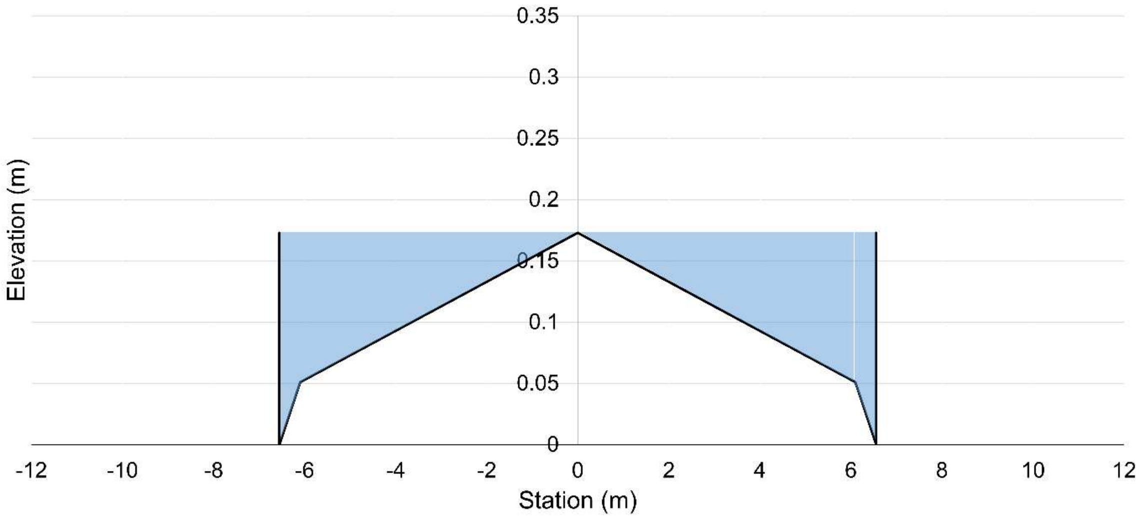
The objective for the major storm event (100-yr) is to minimize property damage by containing stormwater to an acceptable level below residential dwellings and public buildings, or below a certain water depth above the gutter flow line (Table 4.4). The major event was modeled as the 100-yr, 6-hr rainfall event for the study area (66.1 mm total rainfall depth) as generated by CUHP. Rainfall multipliers were applied uniformly across the hyetograph. New street conduit transects in PCSWMM were built based on these major event standards for the various street classifications (Figure 4.5). For local and collector streets, it was assumed that the depth of water over the gutter flow line would not exceed 304.8 mm with a back slope of 2% as indicated in the Drainage Criteria Manual (UDFCD, 2016). Similar to the minor event, because the street conduit transects were designed based on the major event standards, the system exceeds the major event standards (reaches a tipping point) when any major system junction (defined in Table 4.2) floods.

Table 4.4 Street inundation standards for the major (100-yr, 6-hr) storm event (reproduced from Table 7-3 in UDFCD, 2016).

Street Classification	Maximum Depth and Inundated Area
Local and Collector	Residential dwellings and public, commercial, and industrial buildings should be no less than 304.8 mm (12 inches) above the 100-year flood at the ground line or lowest water entry of the building. The depth of water over the gutter flow line should not exceed 304.8 mm (12 inches).
Arterial	Residential dwellings and public, commercial, and industrial buildings should be no less than 304.8 mm (12 inches) above the 100-year flood at the ground line or lowest water entry of the building. The depth of water should not exceed the street crown to allow operation of emergency vehicles. The depth of water over the gutter flow line should not exceed 304.8 mm (12 inches).



(a) Major Local/Collector



(b) Major Arterial

Figure 4.5 Conduit transects for (a) local and collector, and (b) arterial street classifications for the major storm event. Note that the scale of the x-axis is much larger than the y-axis.

4.3.6 LID Scenarios

Two proposed options for implementing LID with redevelopment include distributed and regional LID. Distributed LID, such as rain gardens and bioretention units, are smaller in size and are installed to specifically capture the runoff of a single redeveloped parcel. Therefore, the construction, economic, and maintenance burdens of the LID generally falls upon the individual developer and owner of the redeveloped parcel. Regional LID are larger management practices such as infiltration trenches and vegetative swales that require larger areas of land to implement. With this option, developers and landowners are not directly responsible for the LID and would instead pay a stormwater fee towards the construction and upkeep of the regional LID facility, which would collect runoff from a section of redeveloped parcels.

One distributed and one regional LID scenario was modeled in this study, with distributed bioretention units and regional permeable pavement, respectively. For the distributed bioretention scenario, one bioretention unit was placed on each redeveloped parcel following the approach in Panos *et al.* (2020). The distributed bioretention units were sized to 2% of the redeveloped parcel area, placed on existing redeveloped pervious areas, and capture runoff from all redeveloped impervious areas to achieve that highest flood reduction benefits based on previous modeling of the Berkeley neighborhood (Panos *et al.*, 2020) Subcatchment impervious percentages were adjusted accordingly (Panos *et al.*, 2020).

Regional permeable pavement was placed in locations with large parking lots, such as schools and commercial buildings. Aerial imagery, land use data, and impervious cover data provided by the City of Denver were used to identify parking areas larger than 0.05 hectares that would be suitable for regional LID implementation. Because it was assumed that regional permeable pavement implementation would be funded by contributions from developers, with each successive redevelopment scenario, there is more permeable pavement installation. Pavement implementation was proportional to redeveloped area. This means that 100% of the suitable permeable pavement area was used for permeable pavement implementation in the high redevelopment scenario, and 50% and 13% for the moderate and low scenarios, respectively. Given the total area of parking lots available in the catchment, 56 m^2 of permeable pavement was added per 1,000 m^2 of redeveloped area. The spatial distribution of permeable pavement areas for each scenario is shown in Figure 4.6. The permeable pavement was placed on existing impervious areas in the model with subcatchment impervious percentages adjusted accordingly (Panos *et al.*, 2020). All redeveloped impervious areas were routed to permeable pavement in subcatchments that contained permeable pavement implementation. All LID parameters are summarized in Table D.1 and Table D.2.

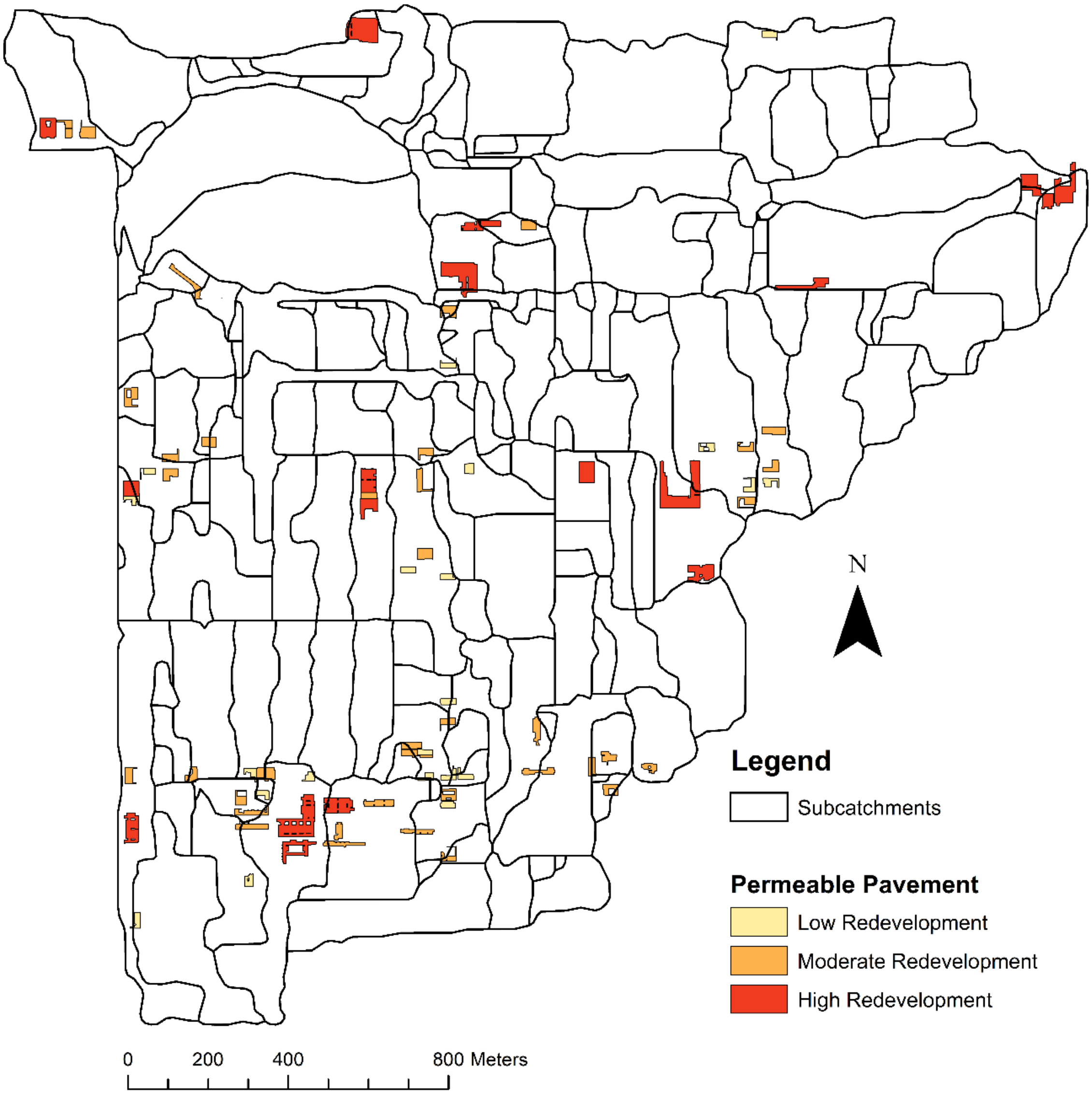


Figure 4.6 Map of permeable pavement implementation by redevelopment scenario. All permeable pavement in the low redevelopment scenario was also modeled in the moderate and high scenarios. All permeable pavement in the moderate redevelopment scenario was also modeled in the high scenario.

4.4 Results

4.4.1 Minor Storm Event Tipping Points

4.4.1.1 Pre-LID

In the pre-redevelopment scenario (baseline), the existing stormwater system exceeds the minor event standards at a rainfall multiplier of 1.07 (Figure 4.7a and 4.7b, black solid line). In other words, at baseline land use conditions without LID implementation, the system does not fail minor event standards until a 7.0% increase in rainfall occurs due to climate change. With subsequent redevelopment and increases in impervious area, the tipping points decrease to 1.066, 1.046, and 1.0, or a 6.6%, 4.6%, and 0.0% increase in rainfall, for the low, moderate, and high redevelopment scenarios, respectively (Figure 4.7a and 4.7b, grey solid lines; Table 4.5).

Table 4.5 Minor event tipping point rainfall multipliers pre- and post-LID implementation. Low, moderate, and high refer to redevelopment scenarios.

Scenario	Pre-LID Tipping Point	Bioretention Tipping Point	Difference between bioretention and Pre-LID	Permeable Pavement Tipping Point	Difference between permeable pavement and Pre-LID
Baseline	1.070	-	-	-	-
Low	1.066	1.079	0.013	1.098	0.032
Moderate	1.046	1.105	0.059	1.068	0.022
High	1.000	1.125	0.125	1.026	0.026

The pre-LID relationship between the tipping point rainfall multipliers and absolute percent increases in impervious area is polynomial for the minor event with more drastic changes in the tipping point with increasing impervious area (Figure 4.8, red solid line with black dotted trendline). At an absolute percent impervious increase of 8.1%, the system reaches the minor storm tipping point at a rainfall multiplier of 1, meaning that the system would exceed acceptable standards with no increase in rainfall. This 8.1% increase in impervious area corresponds to the high redevelopment scenario in this study (Figure 4.8, triangle symbols). Conversely, if a decrease in rainfall is expected with climate change, such as the potential 5% decrease in rainfall possible in the Colorado region (Lukas *et al.*, 2014), development could extend to a 10.8% increase in impervious area before reaching the minor storm tipping point, according to the polynomial trend (Figure 4.8, pre-LID trendline extended to a rainfall multiplier of 0.95).

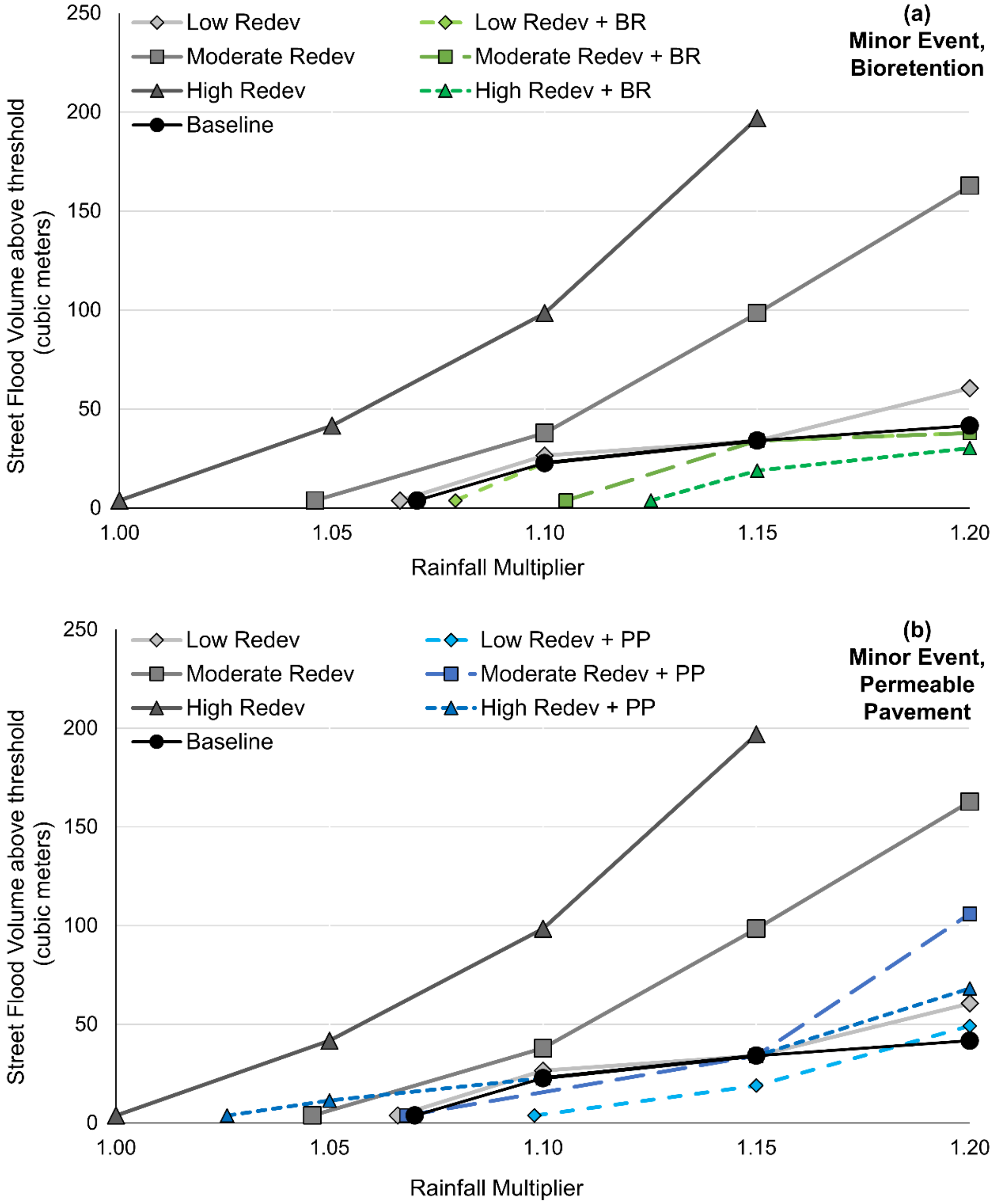


Figure 4.7 Street flood volumes above the minor storm event acceptable threshold for increasing rainfall multipliers for the baseline and three redeveloped scenarios with and without (a) distributed bioretention, and (b) regional permeable pavement. Redev = Redevelopment; BR = bioretention; PP = permeable pavement.

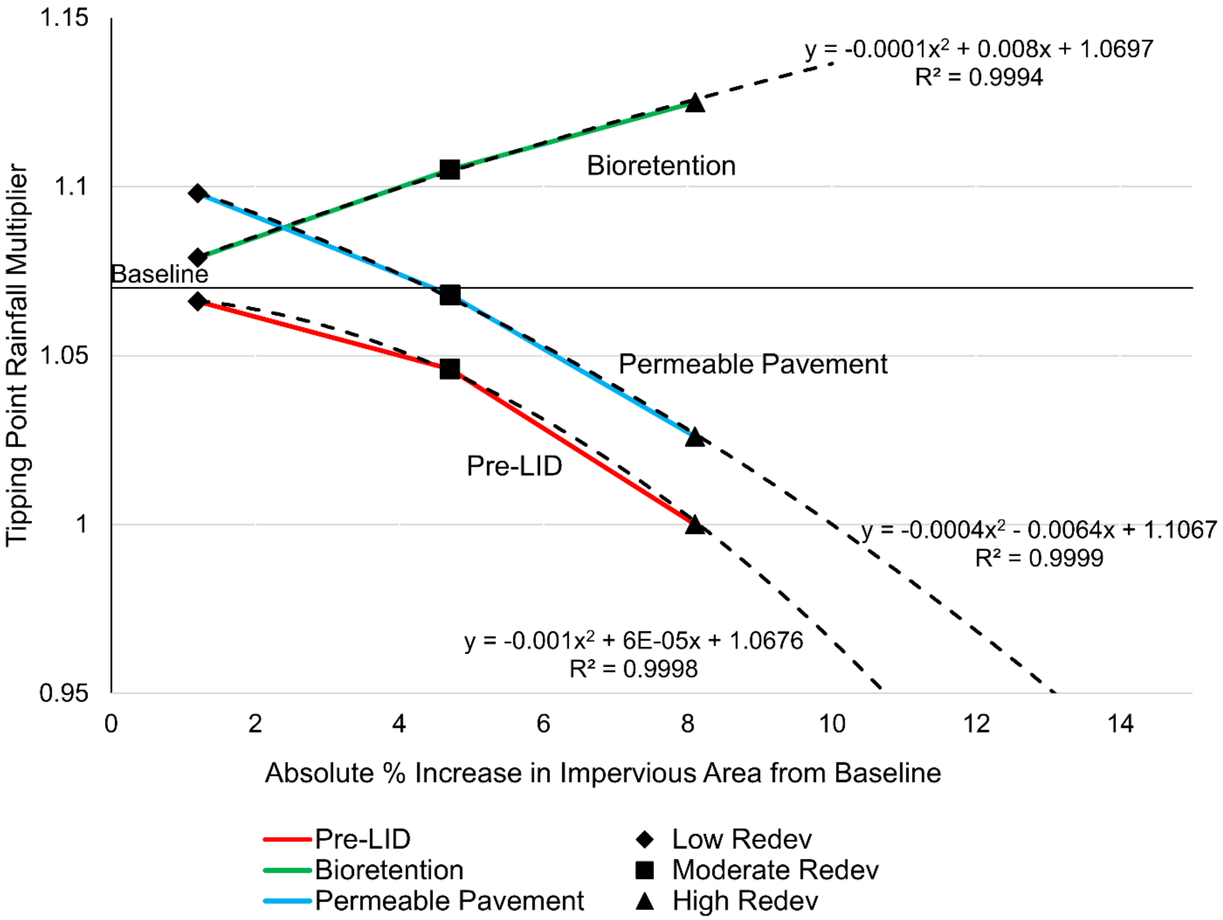


Figure 4.8 Second order polynomial relationships between the tipping point rainfall multiplier and absolute percent increase in impervious area from baseline pre- and post-LID implementation for the minor storm event. Black dotted lines are second order polynomial trendlines with associated equations. Redev = Redevelopment; LID = low impact development.

4.4.1.2 Post-LID

With distributed bioretention implementation on all redeveloped parcels, the minor event tipping points for the low, moderate, and high redevelopment scenarios improved to rainfall multipliers of 1.079, 1.105, and 1.125, or a 7.9%, 10.5%, and 12.5% increase in rainfall, respectively (Figure 4.7a, green dotted lines; Table 4.5). Compared to the baseline condition (tipping point of 1.07), the tipping points for all redevelopment scenarios with bioretention are above baseline indicating more resilience in the system. In fact, the tipping points *increase* with each subsequent redevelopment scenario, which is the opposite trend of the pre-LID analysis (Figure 4.8, green solid line with black dotted trendline). If redevelopment increases impervious area by 10%, but bioretention is implemented at the same time, the system can handle an increase in rainfall up to 13.7% before failing the minor event standards (Figure 4.8, bioretention trendline extended to an absolute impervious increase of 10%).

With regional permeable pavement implementation, the minor event tipping points for the low, moderate, and high redevelopment scenarios improved to rainfall multipliers of 1.098, 1.068, and 1.026, or a 9.8%, 6.8%, and 2.6% increase in rainfall, respectively (Figure 4.7b, blue dotted lines; Table 4.5). Although all three tipping points showed more resilience over the corresponding scenario pre-LID tipping points, only the tipping point for the low redevelopment scenario shows improvement that exceeds baseline conditions (tipping point of 1.070) (Figure 4.8, blue solid line and diamond symbols). In addition, the trendline relationship between tipping points and absolute percent increase in impervious area from baseline for the minor event with permeable pavement is decreasing (Figure 4.8, blue sold line and black dotted trendline). Again, if a decrease in rainfall is expected with climate change, but permeable pavement is implemented along with redevelopment, development could extend to a 13.1% increase in impervious area before reaching the minor storm tipping point, according to the polynomial trend (Figure 4.8, permeable pavement trendline extended to a rainfall multiplier of 0.95) as compared to 10.8% before permeable pavement implementation.

4.4.2 Major Storm Event Tipping Points

4.4.2.1 Pre-LID

The analysis of the major event resulted in tipping points below 1 for all scenarios, meaning that there is not enough street storage to prevent flooding that exceeds major event standards at current rainfall conditions, even for the baseline land use condition. For the baseline scenario, the existing stormwater system exceeds the major event standards at a rainfall multiplier of 0.725 (Figure 4.9a and 4.9b, solid black line). In other words, at baseline land use conditions without LID implementation, the system reaches the major event tipping point at a 27.5% *decrease* in rainfall. With subsequent land use change due to redevelopment and increases in impervious area, the tipping points decrease further to rainfall multipliers of 0.715, 0.690, and 0.660, or a 28.5%, 31.0%, and 34.0% decrease in rainfall, for the low, moderate, and high redevelopment scenarios, respectively (Figure 4.9a and 4.9b, grey solid lines; Table 4.6).

Table 4.6 Major event tipping point rainfall multipliers pre- and post-LID implementation. Low, moderate, and high refer to redevelopment scenarios.

Scenario	Pre-LID Tipping Point	Bioretention Tipping Point	Difference between bioretention and Pre-LID	Permeable Pavement Tipping Point	Difference between permeable pavement and Pre-LID
Baseline	0.725	-	-	-	-
Low	0.715	0.730	0.015	0.725	0.010
Moderate	0.690	0.740	0.050	0.720	0.030
High	0.660	0.745	0.085	0.730	0.070

Similar to the minor event, there is a second order polynomial relationship between the tipping point rainfall multipliers and absolute percent impervious increases from baseline for the pre-LID major event (Figure 4.10, red solid line with black dotted trendline). There is a similar range of tipping points for both the minor and major events. There is a range of 0.07 between the highest and lowest minor event tipping points, and a range of 0.065 between the highest and lowest major event tipping points (Tables 4.5 and 4.6).

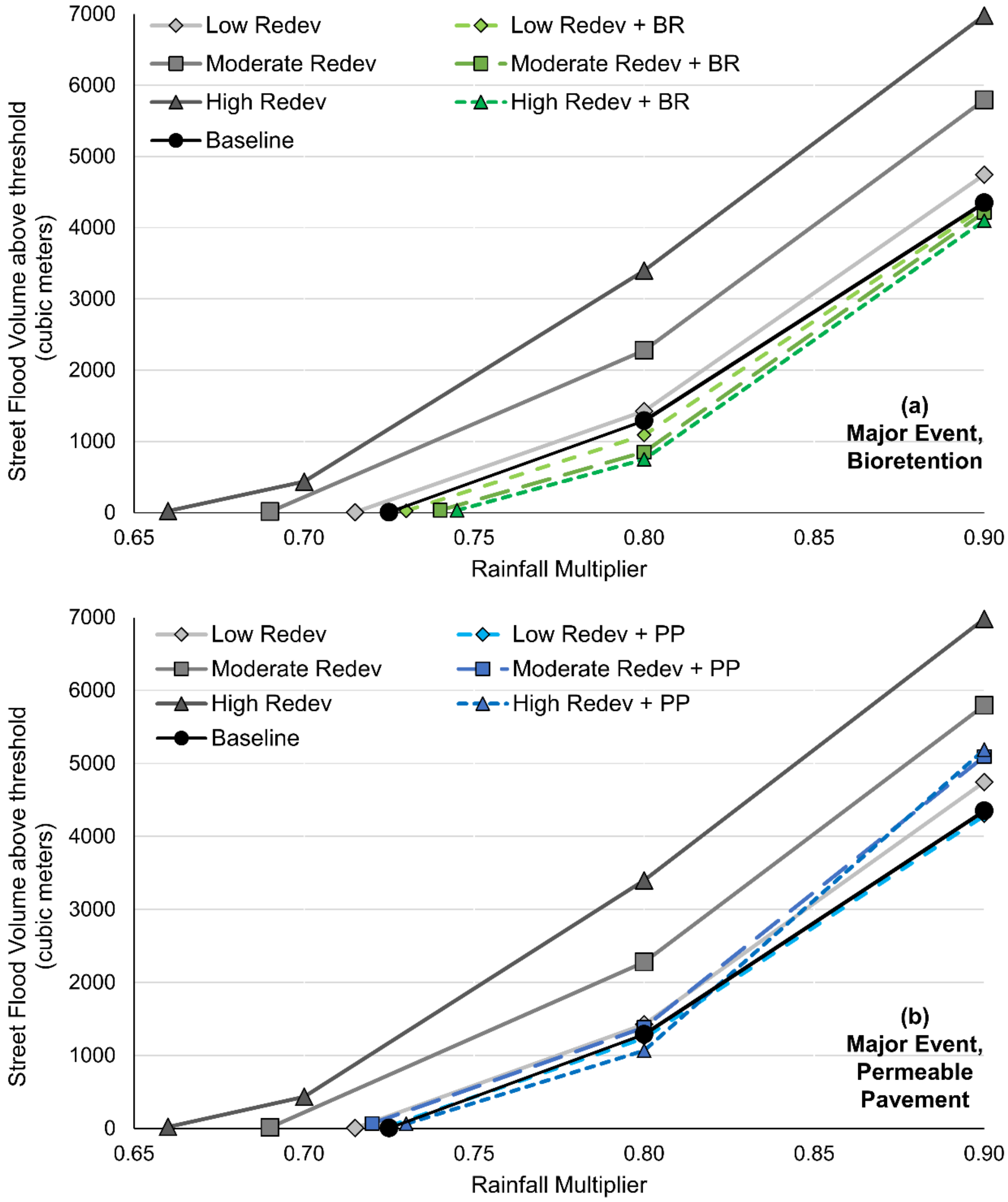


Figure 4.9 Street flood volumes above the major storm event acceptable threshold for increasing rainfall multipliers for the baseline and three redeveloped scenarios with and without (a) distributed bioretention, and (b) regional permeable pavement. Redev = Redevelopment; BR = bioretention; PP = permeable pavement.

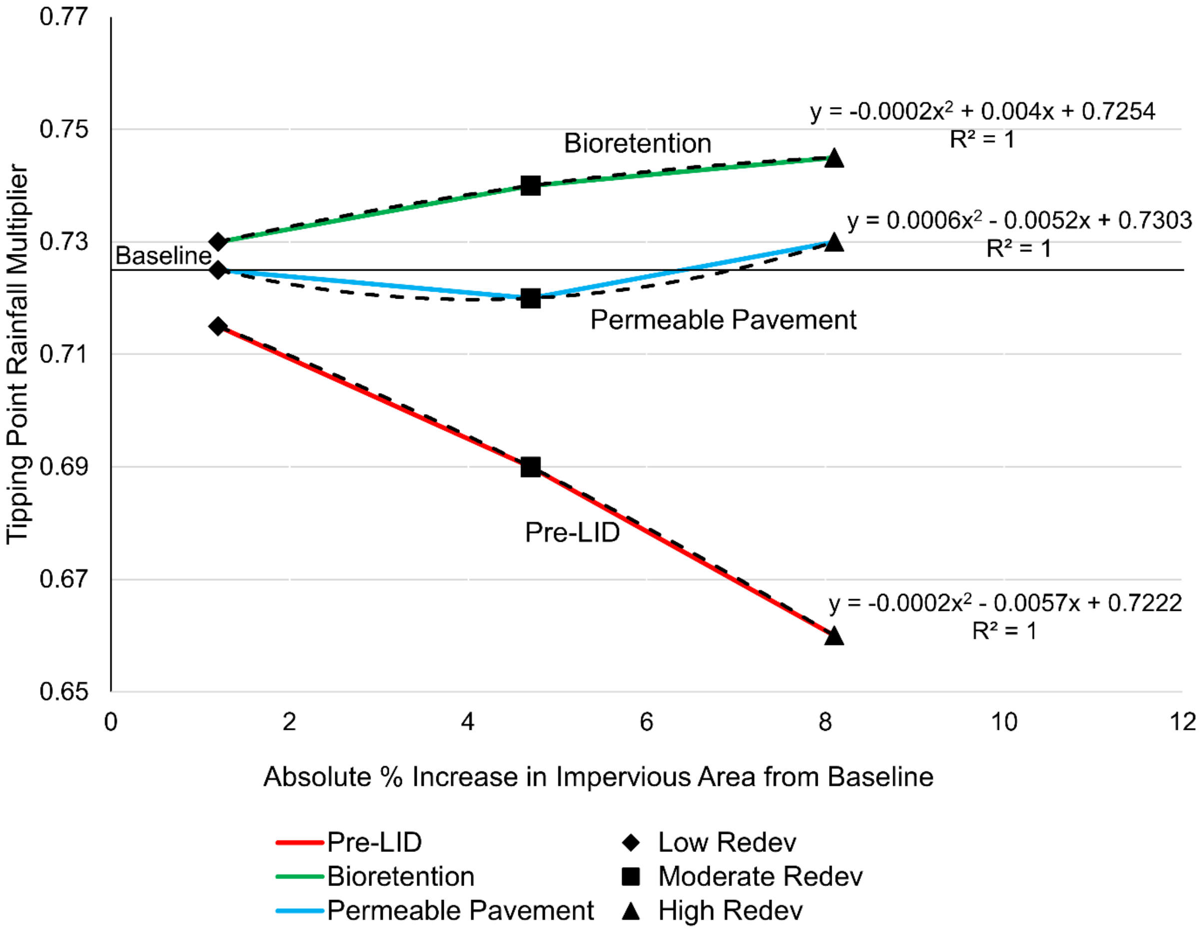


Figure 4.10 Second order polynomial relationships between the tipping point rainfall multiplier and absolute percent increase in impervious area from baseline pre- and post-LID implementation for the major storm event. Black dotted lines are second order polynomial trendlines with associated equations. Redev = Redevelopment; LID = low impact development.

4.4.2.2 Post-LID

Similar results were found for the bioretention implementation with the major event, but with less variation in flooding between scenarios (Figure 4.9a, green dotted lines). Tipping point rainfall multipliers increased to 0.730, 0.740, and 0.745, or a 27.0%, 26.0%, and 25.5% decrease in rainfall, for the low, moderate, and high redevelopment scenarios, respectively (Table 4.6), which are all improved over the baseline tipping point (0.725) (Figure 4.10, green solid line with black dotted trendline).

Similar permeable pavement results were also found for the major event as compared to the minor event. Tipping point rainfall multipliers increased to 0.725, 0.720, and 0.730 or a 27.5%, 28.0%, and 27.0% decrease in rainfall, for the low, moderate, and high redevelopment scenarios, respectively (Figure 4.9b, blue dotted lines; Table 4.6), in which only the high redevelopment scenario is improved over the baseline tipping point (0.725), and the low redevelopment scenario equals the baseline tipping point. Unlike the minor event, the trendline relationship between tipping points and absolute percent increase in impervious area from baseline for the major event with permeable pavement is not decreasing (Figure 4.10, blue sold line and black dotted trendline). Lastly, even if redeveloped scenarios have less flooding than baseline at lower rainfall multipliers, all redeveloped scenarios with permeable pavement exceed baseline flooding at higher rainfall multipliers (i.e., 1.2 for the minor event and 0.90 for the major event) (Figure 4.7b and Figure 4.9b, blue dotted lines).

4.5 Discussion

4.5.1 Minor and Major Event Differences

According to the resilience assessments performed in this study, the Berkeley neighborhood dual drainage system is more resilient to rainfall climate change in combination with changes in land use due to redevelopment for the *minor* storm event than the *major* storm event. We found that at baseline conditions (pre-redevelopment), the system can handle a 7% increase in rainfall before exceeding acceptable standards for the minor event. We also found that redevelopment can increase impervious areas up to 8.1% before exceeding minor event standards at current rainfall conditions. These percentages suggest that the Berkeley neighborhood is similarly impacted by both climate changes and land use changes with respect to minor event flooding standards.

By contrast, the Berkeley neighborhood drainage system is very susceptible to flooding and exceeding major storm event standards even at baseline conditions. In fact, major event standards are exceeded with a 27.5% decrease in rainfall at baseline, representing a rainfall depth of 47.9 mm, which is close to a current/historical 25-yr storm for the area (48.4 mm rainfall depth). The assumptions made in this modeling study were conservative; it is likely that results for major event flooding for redeveloped scenarios could be worse than simulated in this work. Specifically, one consequence of redevelopment is that redeveloped buildings often extend closer to the street than existing buildings, and existing buildings are typically built at a higher grade than redeveloped buildings in the study area. However, these building changes were not included in the redevelopment scenarios of this modeling effort. Therefore, it is possible that major event standards would be exceeded at lower rainfall multipliers for redeveloped conditions because the buildings are built at a lower grade than existing buildings.

4.5.2 Adaptive Capacity from LID Implementation

Results show that LID implementation with redevelopment can positively impact resilience assessment tipping points. However, distributed bioretention implementation more drastically impacts results than regional permeable pavement. Adding bioretention units to all redeveloped parcels increases the adaptive capacity of the system by increasing all tipping points above the baseline condition for both the minor and major storm events. By contrast, permeable pavement increases the dual drainage system performance compared to pre-LID conditions, but not always enough to exceed baseline/pre-redevelopment conditions. The difference in performance is likely due to the locations of the permeable pavement units in comparison to the locations of redevelopment, which do not always align. Because of this, the percent of watershed impervious area treated by LID is much higher for the bioretention scenarios than permeable pavement scenarios, despite the physical surface area of permeable pavement being larger than bioretention in each scenario (Table 4.7). These results agree with previous studies that point to the importance of LID placement and area treated for effective runoff and flood management (Wright *et al.*, 2016; Fry and Maxwell, 2017; Wolfand *et al.*, 2018; Panos *et al.*, 2020).

Table 4.7 Metrics for permeable pavement (PP) and bioretention (BR) implementation for the low, moderate, and high redevelopment scenarios. Redev = redevelopment.

Scenario	Total PP Area (ha)	Watershed Impervious Area (%) with PP	Watershed Impervious Area Routed to PP(%)	Total BR area (ha)	Watershed impervious area (%) with BR	Watershed impervious area routed to BR (%)
Low Redev	1.20	54.55	1.54	0.39	54.72	5.90
Moderate Redev	4.65	57.71	8.54	1.52	58.38	21.36
High Redev	9.43	61.81	28.43	3.06	63.24	56.37

Although regional permeable pavement generally did not improve tipping points as well as distributed bioretention, compared to baseline conditions, permeable pavement did increase tipping points more (from pre- to post-LID) for the major storm event than bioretention. Permeable pavement improved major event tipping points by 0.010, 0.030, and 0.070 for the low, moderate, and high redevelopment scenarios, respectively (Table 4.6), while bioretention improved the same tipping points by 0.032, 0.022, and 0.026 (Table 4.5). This suggests that regional LID may provide more storage capacity for handling runoff from larger storm sizes than distributed LID, particularly for higher redeveloped conditions.

A simple cost estimation of bioretention versus permeable pavement implementation using the EPA's National Stormwater Calculator (EPA, 2020) revealed that the cost (capital and average annual maintenance) on average for the three redeveloped scenarios is $50.30 and $52.43/square meter ($4.67 and $4.87/square foot) for bioretention and permeable pavement, respectively. Given the surface areas of bioretention and permeable pavement in the scenarios, the total average costs are estimated at $840,000 for bioretention and $2,670,000 for permeable pavement. In other words, permeable pavement is over three times more expensive than bioretention, and it does not perform as well in terms of the flooding metrics of this study. It has also been found that bioretention can provide more water quality benefits than permeable pavement (Jaber, 2015). Therefore, it may be more beneficial for water quantity, water quality, and costs to implement distributed bioretention versus regional permeable pavement in a redeveloping neighborhood.

4.5.3 Redevelopment as an Opportunity for Building Resilience through LID

Based on our results, it is recommended that distributed LID options are implemented with redevelopment, and that 100% of redeveloped impervious area runoff is routed to the LID. This recommendation would include changing the current criteria threshold of 0.2 ha (1/2 acre) to require stormwater detention for redevelopments of any size, or at least those 0.05 ha (1/8 acre) and larger. Note that 99% of redeveloped parcels modeled in this study are less than 0.2 ha, and 38% are less than 0.05 ha, on average. Implementing distributed LID adaptation options in redeveloping areas on only 0.36% of the total watershed surface area can increase the tipping points of the system by up to 12.5% and 12.9% from pre-LID conditions for the high redevelopment scenario for the minor and major storm events, respectively. Therefore, large increases in tipping points can be achieved with small areas of LID, which presents redevelopment as a unique opportunity for implementing stormwater management through practices such as LID to build system resilience.

This perspective agrees with Gersonius *et al.* (2012) that urban renewal cycles, including "regeneration" and redevelopment should be used as a driver for adaptation. Implementing LID in tandem with redevelopment means LID can be incorporated in building and infrastructure design rather than added separately, which can lead to potential cost reductions. Redevelopment offers an opportunity for LID to be installed at minimal cost as a no/low-regret strategy in which system resilience is greatly enhanced with little to moderate additional investment (Gersonius *et al.*, 2012). For seven case studies of redevelopment projects from cities around the U.S., the stormwater management component averaged only 2.7% of total project costs and were as low as 0.5% (EPA, 2016b). In addition, LID implemented with redevelopment can help drive economic development (EPA, 2016b). For example, a $15.5 million redevelopment project in Normal, Illinois that incorporated stormwater management in the form of a "stormwater park" has produced $160 million in private business investment (EPA, 2016b). While there are many benefits to LID implementation for stormwater management, redevelopment offers a unique context and opportunity for installing LID with minimal costs and maximum benefits.

4.6 Conclusions

As urban populations grow and cities densify through redevelopment, increases in impervious area are impacting stormwater runoff and flood volumes. Concurrently, changes in rainfall patterns due to climate change are also influencing urban runoff. A resilience assessment was performed to determine at what changes in rainfall (tipping points) the urban stormwater system of a redeveloping neighborhood will exceed regulatory standards for flooding for both a minor (5-yr) and major (100-yr) storm event. We also investigated how low impact development (LID) adaptive management can be used to improve these tipping points and add resilience to the system. Key conclusions and contributions from this research include:

- When changes in precipitation due to climate change are uncertain, a "tipping point" approach can effectively assess system resilience.
- The existing stormwater system of the Berkeley, CO neighborhood effectively meets flood protection requirements for minor storm event standards but not for major storm event standards.
- Existing stormwater systems in redeveloping neighborhoods such as Berkeley, CO may be able to handle increases in runoff and flooding from redevelopment land use changes or climate changes alone, but likely not both.
- Multiple LID options can improve the resilience of a redeveloping urban system facing climate change. Distributed LID provides more system resilience compared to regional LID due to the capture of more impervious areas.
- Redevelopment presents a unique opportunity to install LID and increase the resilience of cities to changes in precipitation due to climate change.

4.7 Acknowledgements

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4.8 References

Alamdari, N., D. J. Sample, P. Steinberg, A. C. Ross, and Z. M. Easton. 2017. "Assessing the Effects of Climate Change on Water Quantity and Quality in an Urban Watershed Using a Calibrated Stormwater Model." *Water*. 9(7). doi.org/10.3390/w9070464

Arisz, H., and B. C. Burrell. 2006. "Urban drainage infrastructure planning and design considering climate change." Published in IEEE EIC Climate Change Conference. doi.org/10.1109/EICCCC.2006.277251

Cherry, L. 2016. “Predicting Parcel Scale Redevelopment within the Berkeley Neighborhood in Denver Colorado Using Linear and Logistic Regression.” M.S. thesis, Colorado School of Mines, <http://hdl.handle.net/11124/170658> (Accessed May 24, 2017).

Cherry, L., D. Mollendor, B. Eisenstein, T. S. Hogue, K. Peterman, and J. E. McCray. 2019. “Predicting Parcel-Scale Redevelopment Using Linear and Logistic Regression – the Berkeley Neighborhood Denver, Colorado Case Study.” *Sustainability.* 11(7): 1882. doi.org/10.3390/su11071882

Environmental Protection Agency (EPA). 2014. *Smart Growth and Economic Success: Investing in Infill Development*. EPA: Office of Sustainable Communities, Smart Growth Program.

Environmental Protection Agency (EPA). 2016a. *Summary of State Post Construction Stormwater Standards*. EPA: Office of Water, Office of Wastewater Management, Water Permits Division.

Environmental Protection Agency (EPA). 2016b. *City Green: Innovative Green Infrastructure Solutions for Downtowns and Infill Locations*. www.epa.gov/smartgrowth

Environmental Protection Agency (EPA). 2020. *National Stormwater Calculator: Tool to help control runoff and promote the natural movement of water*. <https://www.epa.gov/water-research/national-stormwater-calculator> (Accessed January 13, 2020)

Forsee, W. J., and S. Ahmad. 2011. “Evaluating urban storm-water infrastructure design in response to projected climate change.” *J. Hydrol. Eng*. 16(11). doi.org/10.1061/(ASCE)HE.1943-5584.0000383

Fry, T. J., and R. M. Maxwell. 2017. “Evaluation of distributed BMPs in an urban watershed – High resolution modeling for stormwater management.” *Hydrol. Process*. 31 (15): 2700-2712. doi.org/10.1002/hyp.11177

Gersonius, B., F. Nasruddin, R. Ashley, A. Jeuken, A. Pathirana, and C. Zevenbergen. 2012. “Developing the evidence bae for mainstreaming adaptation of stormwater systems to climate change.” *Water Res*. 46: 6824-6835. doi.org/10.1016/j.watres.2012.03.060

Guo, Y. 2006. “Updating Rainfall IDF Relationships to Maintain Urban Drainage Design Standards.” *J. Hydrol. Eng*. 11(5). doi.org/10.1061/(ASCE)1084-0699(2006)11:5(506)

Hekl, J. A. and R. L. Dymond. 2016. “Runoff Impacts and LID Techniques for Mansionization-Based Stormwater Effects in Fairfax County, Virginia.” *J. Sustainable Water in the Built Environ.* doi.org/10.1061/JSWBAY.0000815

Jaber, F. H. 2015. “Bioretention and Permeable Pavement Performance in Clay Soil.” International Low Impact Development Conference. Houston, Texas. doi.org/10.1061/9780784479025.015

Jiang, Y., C. Zevenbergen, and D. Fu. 2017. “Understanding the challenges for the governance of China’s ‘sponge cities’ initiative to sustainably manage urban stormwater and flooding.” *Natural Hazards*. 89: 521-529. doi.org/10.1007/s11069-017-2977-1

Li, A., W. Liu, X. Zhang, and F. Zheng. 2009. “Impacts of land use change and climate Variability on hydrology in an agricultural catchment on the Loess Plateau of China.” *J. Hydol*. 377(1-2): 35-42. doi.org/10.1016/j.jhydrol.2009.08.007

Liu, Y., L. O. Theller, B. C. Pijanowski, and B. A. Engel. 2016. “Optimal selection and placement of green infrastructure to reduce impacts of land use change and climate change on hydrology and water quality: An application to the Trail Creek Watershed, Indiana.” *Sci. Total Environ*. 553: 149-163. doi.org/10.1016/j.scitotenv.2016.02.116

Lukas, J., J. Barsugli, N. Doesken, I. Rangwala, and K. Wolter. 2014. “Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation.” A Report for the Colorado Water Conservation Board. doi.org/10.13140/RG.2.2.36741.35043

Mahoney, K., M. Alexander, J. D. Scott, and J. Barsugli. 2013. “High-resolution downscaled simulations of warm-season extreme precipitation events in the Colorado Front Range under past and future climates.” *Journal of Climate*. 26: 8671-8689. doi.org/10.1175/JCLI-D-12-00744.1

Mailhot, A., and S. Duchesne. 2010. “Design Criteria of Urban Drainage Infrastructures under Climate Change.” *J. Water Res. Plan. Man*. 136(2). doi.org/10.1061/(ASCE)WR.1943-5452.0000023

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity Is Dead: Whither Water Management? *Science.* 319(573): LP-574. doi.org/10.1126/science.1151915

Mirhosseini, G., P. Srivastava, and L. Stefanova. 2013. “The impact of climate change on rainfall Intensity-Duration-Frequency (IDF) curves in Alabama.” *Regional Environmental Change.* 13(Suppl 1): 25-33. doi.org/10.1007/s10113-012-0375-5

Moore, T. L., J. S. Gulliver, L. Stack, and M. H. Simpson. 2016. “Stormwater management And climate change: Vulnerability and capacity for adaptation in urban and suburban contexts.” *Clim. Change*. 138: 491-504. doi.org/10.1007/s10584-016-1766-2

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. “Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations.” *J. Am. Soc. Agric. Biol. Eng.* 50(3): 885-900. doi.org/10.13031/2013.23153

Paerl, H. W., W. S. Gardner, K. E. Havens, A. R. Joyner, M. J. McCarthy, S. E. Newell, B. Qin, and J. T. Scott. 2016. “Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients.” *Harmful Algae*. 54: 213-222. doi.org/10.1016/j.hal.2015.09.009

Panos, C. L., T. S. Hogue, R. L. Gilliom, and J. E. McCray. 2018. “High-resolution modeling of infill development impact on stormwater dynamics in Denver, Colorado.” *J. Sustainable Water Built Environ*. 4(4). doi.org/10.1061/JSWBAY.0000863

Panos, C. L., J. M. Wolfand, and T. S. Hogue. 2020. “SWMM Sensitivity to LID Siting and Routing Parameters: Implications for Stormwater Regulatory Compliance.” *J. Am. Water Resour. As*. In Review.

Pond, M. C. and G. Kacvinsky. 2006. “Tear-downs - controlling stormwater impacts.” <http://waterbucket.ca/gi/files/2013/03/Teardowns-controlling-stormwater-impacts.pdf> (Accessed June 19, 2017).

Praskievicz, S., and H. Chang. 2009. “A review of hydrological modelling of basin-scale climate change and urban development impacts.” *Progress in Physical Geography: Earth and Environment*. 33(5): 650-671. doi.org/10.1177/0309133309348098

Randall, M., N. Perera, N. Gupta, and M. Ahmad. 2017. “Development and Calibration of a Dual Drainage Model for the Cooksville Creek Watershed, Canada.” *J. Water Manag. Model*. doi.org/10.14796/JWMM.C419

Sala, O. E., F. S. I. Chapin, J. J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L. F. Huenneke, R. B. Jackson, A. Kinzig, R. Leemans, D. M. Lodge, H. A. Mooney, M. Oesterheld, N. L. Poff, M. T. Sykes, B. H. Walker, M. Walker, D. H. Wall. 2000. “Global biodiversity scenarios for the year 2100.” *Science*. 287: 1770-1774. doi.org/10.1126/science.287.5459.1770

Salvadore, E., J. Bronders, & O. Batelaan. 2015. “Hydrological modelling of urbanized catchments: A review and future directions.” *J. Hydrol.* 529: 62-81. doi.org/10.1016/j.jhydrol.2015.06.028

Semadeni-Davies, A., C. Hernebring, G. Svensson, and L. Gustafsson. 2008. “The impacts of climate change and urbanization on drainage in Helsingborg, Sweden: Combined sewer system.” *J. Hydrol*. 350: 100-113. doi.org/10.1016/j.jhydrol.2007.05.028

Thomas, J. V. 2009. *Residential Construction Trends in America’s Metropolitan Regions*. U.S. Environmental Protection Agency: Development, Community, and Environment Division.

Urban Drainage and Flood Control District (UDFCD). 2016. Urban Storm Drainage Criteria Manual Volume 1. Chapter 7: Streets, Inlets, & Storm Drains. udfcd.org

Waters, D., W. E. Watt, J. Marsalek, and B. C. Anderson. 2003. “Adaptation of a storm drainage system to accommodate increased rainfall resulting from climate change.” *J. Environ. Plann. Man*. 46(5). doi.org/10.1080/0964056032000138472

Wolfand, J. M., C. D. Bell, A. B. Boehm, T. S. Hogue, and R. G. Luthy. 2018. “Multiple Pathways to Bacterial Load Reduction by Stormwater Best Management Practices: Trade-Offs in Performance, Volume, and Treated Area.” *Environ. Sci. Technol*. 52(11): 6370-6379. doi.org/10.1021/acs.est.8b00408

Wright, T. J., Y. Liu, N. J. Carroll, L. M. Ahiablame, and B. A. Engel. 2016. “Retrofitting LID Practices into Existing Neighborhoods: Is It Worth It?” *Environ. Manage*. 57 (4): 856-867. doi.org/10.1007/s00267-015-0651-5

Zahmatkesh, Z., S. J. Burian, M. Karamouz, H. Tavakol-Davani, and E. Goharian. 2014. “Low-Impact Development Practices to Mitigate Climate Change Effects on Urban Stormwater Runoff: Case Study of New York City. *J. Irrig. Drain Eng*. 141(1): 04014043. doi.org/10.1061/(ASCE)IR.1943-4774.0000770.

CHAPTER 5

CONCLUSIONS

5.1 Summary of Findings

The following is a summary of main findings and contributions of the research in each chapter of this dissertation. Each hypothesis is presented with related research findings.

5.1.1 Objective 1: Quantify Stormwater Runoff in a Redeveloping Neighborhood

Chapter 2 makes significant contributions to understanding the impacts of infill development, or redevelopment, on stormwater dynamics in semi-arid regions, utilizing the Berkeley neighborhood in Denver, Colorado as a case study. This research is the first to quantify the volume and spatial distribution of stormwater runoff caused by infill development using a high-resolution, calibrated hydrologic model as well as realistic predictions of redevelopment. The increase in infill-type development in cities across the U.S. and around the globe gives this research a current and global context. Simulations of design storms for multiple redevelopment scenarios predict that an increase of 1% in impervious area will increase surface runoff by 1.63% for the 2-yr, 24-hr design storm and by 0.91% for the 100-yr, 24-hr design storm resulting in greater relative flood risks for smaller storm events – a result that is key for urban planners. In addition, results demonstrate the limitations of existing storm sewer networks by quantifying the impacts of increasing infill development on local flooding potential. Finally, we investigated harnessing potential increases in runoff volumes for water supply through beneficial use – a novel strategy for reinventing stormwater management in Denver. This research is the first to address the knowledge gap regarding the future implications of infill development on the hydrology of local urbanized areas. Overall, these results have significant implications for informing current and future stormwater regulations regarding redevelopment. The hypotheses and findings of this study are:

Hypothesis 1 – The existing storm sewer network in the Berkeley neighborhood will reach capacity and flood due to increased runoff volume from a moderate redevelopment scenario (increase in impervious area of 4.7%) during mid-sized storm events (e.g., 10-yr, 24-hr).

Finding: The existing storm sewer network in the Berkeley neighborhood reaches capacity and floods due to increased runoff volume from the *lowest* redevelopment scenario (increase in impervious area of 1.2%) during *smaller* storm events (e.g., 2-yr, 24-hr).

Hypothesis 2 – Increases in stormwater runoff volume from baseline will be highest in subcatchments experiencing the most redevelopment and lowest in subcatchments with existing LID infrastructure. Redevelopment will impact all design storms similarly.

Finding: The subcatchments with the largest increases in runoff volume are located throughout the basin in various proximity and connection with existing LID infrastructure showing that the impacts of redevelopment on runoff volume occur regardless of existing management systems. Redevelopment impacts the *small* storm event hydrographs more significantly than larger storms, where larger storm hydrographs have nearly identical peaks and receding limbs, but higher rising limbs.

5.1.2 Objective 2: Evaluate Model Sensitivity to LID Siting and Routing Parameters

Chapter 3 makes significant contributions to understanding Stormwater Management Model (SWMM) sensitivity to low impact development (LID) siting and routing parameters. Few studies have investigated the siting and routing parameters of LID modeling within hydrologic models such as SWMM, particularly in the context of redevelopment. This research investigates how LID might be implemented to manage increases in runoff volumes and flood events from redevelopment. The specific parameters we investigated are routing of outflow from LID units, LID placement in the SWMM model, and area treated by LID units. Simulating 32 configurations of these parameters reveal that impervious area treated by LID has the greatest impact on runoff and flood volumes.

We found that depending on which assumptions are made in the model regarding the LID siting and routing parameters, potential stormwater regulatory compliance, such as returning runoff to a “baseline” condition, may not be met. Relative sensitivity of runoff volume output to area treated and LID placement was found to be on average 3.0 and 11.2 times higher than the seven most sensitive physical LID and subcatchment parameters. These results demonstrate the limitations of considering only the physical parameters of LID, such as hydraulic conductivity, in LID modeling. Misunderstandings of model sensitivities can lead to costly decisions that are made based on watershed-scale modeling studies.

Finally, we investigated a common misconception of SWMM modeling: that impervious area within SWMM models does not need be adjusted with LID placement. Our results show that the model is highly sensitive to this adjustment, and we therefore created an area adjustment Excel tool for use by modelers. Overall, our results have significant implications for modelers using LID modeling to inform decisions regarding stormwater regulatory compliance. The hypotheses and findings of this study are:

Hypothesis 3 – All three siting and routing parameters will be sensitive and affect model runoff volume and flood volume outputs, but area treated will be the most affect model output followed by LID placement.

> ***Finding:*** All three siting and routing parameters do affect model runoff volume and flood volume outputs with some parameter configurations that meet baseline (pre-redevelopment) conditions and some that do not. When evaluating absolute differences in runoff and flood volumes, area treated does have the largest impact followed by outflow routing, then LID placement.

Hypothesis 4 – Adjusting LID siting and routing parameters has a greater impact on SWMM runoff and flood volume outputs than physical LID parameters (such as soil conductivity and soil thickness), but subcatchment parameters (such as depression storage and infiltration rates) have a greater impact on SWMM runoff and flood volume outputs than any LID parameter.

> ***Finding:*** When comparing the relative sensitivities of 28 total parameters, LID placement has the highest relative sensitivity for both runoff and flood volumes followed by area treated by LID. The three most sensitive subcatchment parameters had similar sensitivities to the four most sensitive physical LID parameters.

5.1.3 Objective 3: Assess Resilience to Land Use and Climate Changes

Chapter 4 makes significant contributions to understanding the impacts of both redevelopment land use change and climate change on stormwater runoff, utilizing the redeveloping Berkeley neighborhood in Denver, Colorado as a case study. While many studies have investigated the impacts of land use change or climate change on stormwater runoff separately, few have evaluated these impacts together, particularly in urban areas. Our work uses a "tipping point" resilience assessment to determine at what changes in rainfall (tipping points) the dual drainage system of a redeveloping urban neighborhood exceeds regulatory standards for flooding. We also added adaptation options in the form of distributed and regional low impact development (LID) and assessed which options most improved system resilience. The resilience assessment is novel because rather than taking a "predict-then-adapt" approach that relies heavily on uncertain climate predictions, it takes a "bottom-up" approach that focuses on local constraints and priorities. This approach is critical in a context of redevelopment when both land use change and climate change are drivers of hydrologic disturbance. The resilience assessment is also more effective in areas of particularly uncertain climate change projections.

Using this assessment, we found that the pre-redevelopment system reaches a tipping point (exceeds flooding standards) at a 7% increase in rainfall, and that redevelopment can add additional impervious areas up to about 8% before exceeding the standards at current rainfall. These results suggest that there are similar stormwater quantity impacts from both climate and land use changes from redevelopment. Results also imply that existing stormwater systems in redeveloping neighborhoods may be able to handle increases in runoff and flooding from redevelopment land use change or climate changes alone, but likely not both. Multiple LID options can improve the resilience of a redeveloping urban system facing climate change by increasing tipping points up to 12-13%. However, distributed LID provides more system resilience compared to regional LID due to the capture of more impervious areas. The implications of this work are that redevelopment presents a unique opportunity to install LID in tandem with redevelopment and increase the resilience of cities to changes in precipitation due to climate change. The hypotheses and findings of this study are:

Hypothesis 5 – The stormwater system of the Berkeley neighborhood will reach a tipping point at a 20% and 30% increase in rainfall, for the minor and major storm event regulatory requirements, respectively, at baseline conditions. Redevelopment will decrease/worsen these tipping points with greater impact on the minor storm event than the major storm event.

> ***Finding:*** The system reaches a tipping point at a 7% increase in rainfall for the minor storm event and a 27.5% decrease in rainfall for the major storm event at baseline. Redevelopment does decrease/worsen these tipping points. However, the minor and major storm event tipping points were impacted similarly by redevelopment.

Hypothesis 6 – While both distributed and regional LID options will increase/improve tipping points, distributed LID will provide greater improvements than regional LID, and the minor storm event tipping point will be impacted more than the major storm event tipping point.

Finding: LID implementation with redevelopment does increase/improve the tipping points of the system, and distributed bioretention implementation does provide greater improvements than regional LID. The minor event tipping points were impacted more with distributed LID, but regional LID had greater impacts on major event tipping points than minor event.

5.2 Broader Impacts and Contribution to the Science Community

Previous urban hydrology studies have generally focused on the changes to stormwater dynamics caused by a direct conversion from undeveloped to developed land uses. Few studies have investigated redevelopment, or "infill" development, and there has been substantial debate on the impact of this type of growth on runoff behavior, peak flows, flood events, and water quality. This research makes significant contributions to understanding the impacts of infill development on stormwater dynamics in semi-arid cities, utilizing the Berkeley neighborhood in Denver, Colorado as a case study. Key to this work is the use of a high-resolution PCSWMM model, calibrated and validated to the area of interest, rather than an un-calibrated model that applies more general hydrologic equations. This work is the first to quantify the volume and spatial distribution of stormwater runoff caused by infill development using a high-resolution, calibrated hydrologic model as well as realistic predictions of redevelopment. This research has the potential to advance the state of prediction of redevelopment impacts on stormwater runoff for the western U.S. and semi-arid watersheds across the globe. Overall, these research results have significant implications for informing current and future stormwater criteria regarding redevelopment.

In addition, this research advances scientific understanding of "to what extent and in what ways LID can and needs to be implemented in a redeveloping urban neighborhood in order to achieve environmental benefits under shifting, revised stormwater criteria policies." This work will directly benefit the Colorado Front Range by providing the knowledge necessary to adequately model and evaluate LID options to capture and treat stormwater for areas facing rapid redevelopment, population influx, and future climate conditions. In addition, this research has the potential to transform the current Denver redevelopment stormwater management requirements by providing a quantitative basis for influencing regulation. Results of this research can also be used to inform similar stormwater criteria in other redeveloping cities across the nation, particularly those of semi-arid climates similar to Colorado.

5.3 Recommendations for Revised Stormwater Management Criteria

Current Denver stormwater criteria state that flood control detention practices such as LID, including bioretention basins or permeable pavements, are exempt from redevelopments that occur on 0.2 ha (1/2 acre) or less (DPW, 2013). These criteria were adopted in 2006; however, the writers of the original criteria recognized the non-stationary nature of the field of urban hydrology and acknowledge that, "these criteria will be revised and updated as necessary to reflect advances in the field of urban drainage engineering and water resources management" (DPW, 2013, Section 3.3.2). Based on the results of this dissertation research, revision of current stormwater management criteria is necessary to counter the negative impacts of increased impervious area from redevelopment on runoff and flood volumes and to build system resilience in the face of climate change.

Based on results in this dissertation, it is recommended that distributed LID options are implemented with redevelopment, and that 100% of redeveloped impervious area runoff is routed to the LID. This recommendation would include changing the current criteria threshold of 0.2 ha (1/2 acre) to require stormwater detention for redevelopments of any size, or at least those 0.05 ha (1/8 acre) and larger. Note that 99% of redeveloped parcels modeled in this research are less than 0.2 ha, and 38% are less than 0.05 ha, on average. Implementing distributed LID adaptation options in redeveloping areas can increase the tipping points of the system (increases in rainfall under which flooding standards are failed) by up to 12.5% and 12.9% from pre-LID conditions for a higher redevelopment scenario for the minor and major storm events, respectively. This presents redevelopment as a unique opportunity for implementing LID and building resilience.

5.4 Recommendations for Future Work

Validate predictions of redevelopment impervious cover change.

It has been five years since the start of this research, and significant land cover change has occurred in the Berkeley neighborhood since that time. Future research should include using updated impervious cover data to determine the impervious cover change in that time, and these changes should be compared to estimates of redevelopment. Results should be used to either validate predictions or update/improve redevelopment prediction methodology.

Quantify redevelopment impacts on water quality.

The scope of this research was constrained to investigations of water quantity. Due to the links between water quantity and quality, it is expected that redevelopment has significant impacts on water quality as well. These impacts should be studied as an area of future research.

Assess the impacts of LID implementation with redevelopment on water quality.

This research highlights the benefits to water quantity problems (i.e., flooding) of LID implementation with redevelopment; however, ongoing work indicates that the opposite may be true for water quality. If LID implementation is focused purely on redeveloped land uses, which are primarily multi-family residential, then high-polluting land uses such as commercial and industrial may be overlooked. This could lead to decreases in water quality rather than increases and represents a needed area of future research.

Investigate the social and economic feasibility of implementing LID in tandem with redevelopment.

While this research studied the technical application of LID with redevelopment, there are social and economic aspects to consider as well. Future work can investigate the feasibility of revising stormwater criteria as suggested in this thesis in terms of developer attitudes and policy barriers. Additional research could also evaluate the co-benefits that are achievable with LID implementation in redeveloping urban areas such as aesthetics or improvements to the urban heat island effect.

5.5 References

Denver Department of Public Works (DPW), Wastewater Management Division, Engineering Division. 2013. “City and County of Denver Storm Drainage Design & Technical Criteria Manual.” denvergov.org

APPENDIX A

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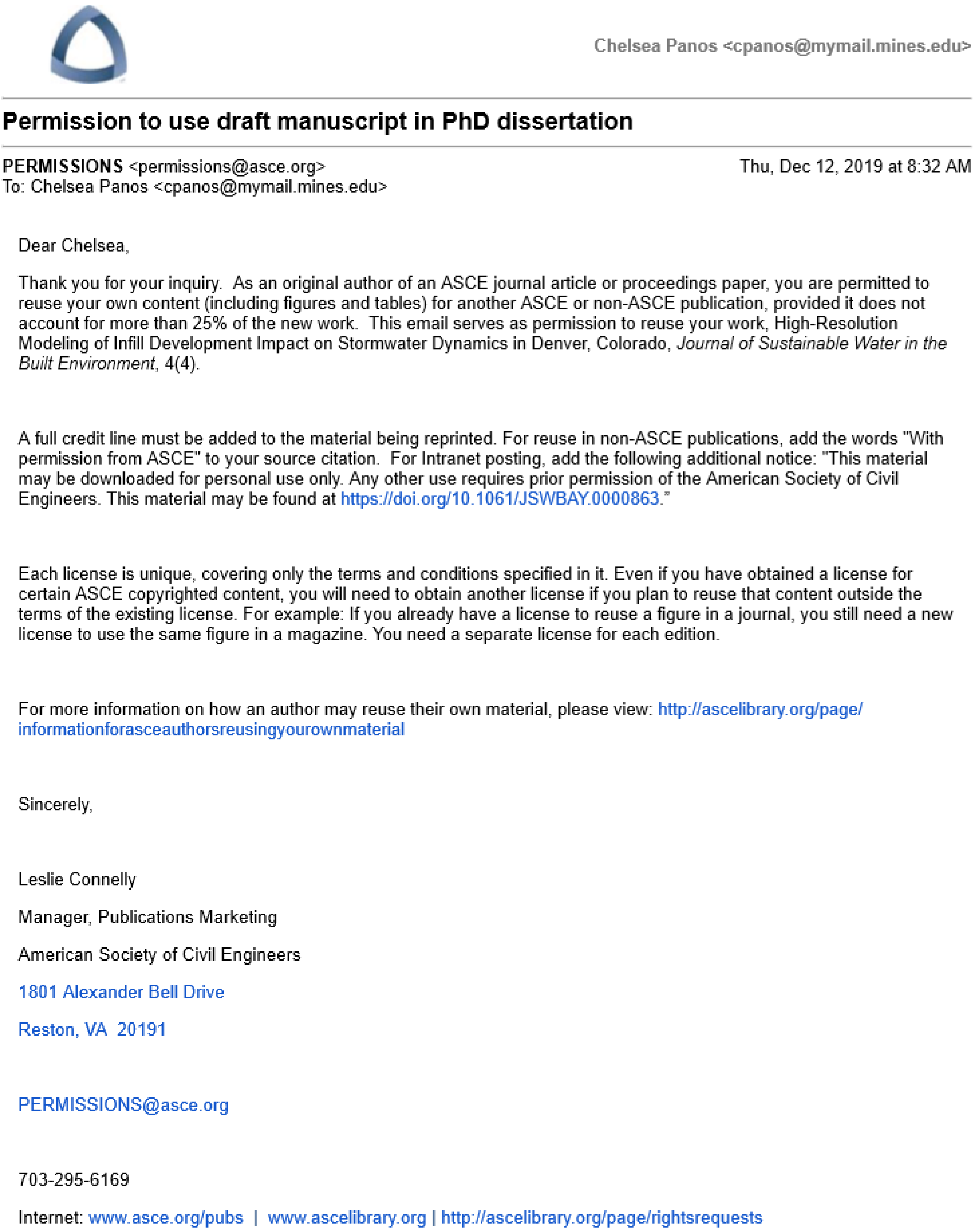

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Chelsea Panos <cpanos@mymail.mines.edu>

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2 messages

Chelsea Panos <cpanos@mymail.mines.edu> Wed, Jan 15, 2020 at 9:44 AM

To: Ryan Gilliom <ryan.gilliom@gmail.com>

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Because you are a co-author of the paper titled "High-Resolution Moedling of Infill Development Impact on Stormwater Dynamics in Denver, Colorado" published in the *Journal of Sustainable Water in the Built Environment* in 2018, I need your permission to include this paper within my dissertation.

Will you please give me your permission to include this paper in my dissertation? If so, please respond to this email, and I will use your email response as documentation of your permission and include it with my dissertation submission.

Thank you,

Chelsea

--

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Ryan Gilliom <ryan.gilliom@gmail.com> Wed, Jan 15, 2020 at 10:08 AM

To: Chelsea Panos <cpanos@mymail.mines.edu>

Hi Chelsea,
You have my permission to include this paper in your dissertation.
Regards,
Ryan Gilliom (she/her/hers)
PhD Candidate, Hydrologic Science and Engineering
Colorado School of Mines | ReNUWIt Engineering Research Center

Chelsea Panos <cpanos@mymail.mines.edu>

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2 messages

Chelsea Panos <cpanos@mymail.mines.edu> Mon, Feb 17, 2020 at 4:18 PM
To: Jordy Wolfand <wolfand@up.edu>

Hi Jordy,

Because you are a co-author of the paper titled "SWMM Sensitivity to LID Siting and Routing Parameters: Implications for Stormwater Regulatory Compliance" submitted for publication to the *Journal of the American Water Resources Association*, I need your permission to include this paper within my dissertation.

Will you please give me your permission to include this paper in my dissertation? If so, please respond to this email, and I will use your email response as documentation of your permission and include it with my dissertation submission.

Thank you,

Chelsea

--
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Wolfand, Jordyn <wolfand@up.edu> Mon, Feb 17, 2020 at 5:02 PM
To: Chelsea Panos <cpanos@mymail.mines.edu>

Hi Chelsea,

You have my permission to publish the paper in your dissertation. Please include a disclaimer noting that it has been submitted for publication.

Jordy

--

Jordyn Wolfand, Ph.D.

Assistant Professor | Civil Engineering

University of Portland

APPENDIX B

CHAPTER 3 SUPPLEMENTAL INFORMATION

Table B.1. Bioretention (BR) unit PCSWMM parameters.

Parameter (units)	Value	Source
Surface		
Berm Height (mm)	305	Fry and Maxwell (2017); UDFCD (2018)
Vegetative Volume (fraction)	0.2	Gülbaz and Kazezyılmaz-Alhan (2017)
Soil*		**Assumed loamy sand mix*
Thickness (mm)	533	Rossman and Huber (2016)
Porosity (volume fraction)	0.44	Fry and Maxwell (2017); Rossman and Huber (2016)
Field Capacity (volume fraction)	0.1	Fry and Maxwell (2017); Rossman and Huber (2016)
Wilting Point (volume fraction)	0.095	Fry and Maxwell (2017)
Conductivity (mm/hr)	145	Rossman and Huber (2016)
Conductivity Slope (-)	5.0	Gülbaz and Kazezyılmaz-Alhan (2017)
Suction Head (mm)	110	Fry and Maxwell (2017)
Storage		
Thickness (mm)	457	Rossman and Huber (2016)
Void Ratio (voids/solids)	0.3	Rossman and Huber (2016)
Seepage Rate (mm/hr)	15	NRCS Soil Survey Data (soils.usda.gov/survey)
Clogging Factor	0	Assumed no clogging
Underdrain		
Drain Exponent	0.5	Rossman (2015) (modeled as an orifice)
Drain Offset Height (mm)	76	Rossman (2015)

APPENDIX C

SUPPLEMENTAL ELECTRONIC FILES

The Excel-based SWMM Impervious Area Adjustment Tool described in Chapter 3 of this thesis is available in the supplemental electronic files. This file may be used by modelers to aid in the adjustment of impervious area parameters when implementing low impact development (LID) in a SWMM model.

SWMM_Impervious_Area_Adjustment_Tool.xlsx	Excel file containing the SWMM Impervious Area Adjustment Tool developed based on research conducted in Chapter 3 of this thesis.

APPENDIX D

CHAPTER 4 SUPPLEMENTAL INFORMATION

Table C.1. Bioretention unit PCSWMM parameters.

Parameter (units)	Value	Source
Surface		
Berm height (mm)	305.0	Fry and Maxwell (2017); UDFCD (2018)
Vegetative volume (fraction)	0.2	Gülbaz and Kazezyılmaz-Alhan (2017)
Soil*		**Assumed loamy sand mix*
Thickness (mm)	533.0	Rossman and Huber (2016)
Porosity (volume fraction)	0.44	Fry and Maxwell (2017); Rossman and Huber (2016)
Field capacity (volume fraction)	0.1	Fry and Maxwell (2017); Rossman and Huber (2016)
Wilting point (volume fraction)	0.095	Fry and Maxwell (2017)
Conductivity (mm/hr)	145	Rossman and Huber (2016)
Conductivity slope (-)	5.0	Gülbaz and Kazezyılmaz-Alhan (2017)
Suction head (mm)	110	Fry and Maxwell (2017)
Storage		
Thickness (mm)	457	Rossman and Huber (2016)
Void ratio (voids/solids)	0.3	Rossman and Huber (2016)
Seepage rate (mm/hr)	15	NRCS Soil Survey Data (soils.usda.gov/survey)
Clogging factor	0	Assumed no clogging
Underdrain		
Drain exponent	0.5	Rossman (2015) (modeled as an orifice)
Drain offset height (mm)	76	Rossman (2015)

Table C.2. Permeable pavement unit PCSWMM parameters.

Parameter (units)	Value	Source
Surface		
Berm height (mm)	1.5	Zhang and Guo (2015)
Vegetative volume (fraction)	0.0	Zhang and Guo (2015); Zhu et al. (2019)
Surface roughness (Manning's n)	0.015	Zhang and Guo (2015); Zhu et al. (2019)
Surface slope (percent)	1.0	Zhang and Guo (2015)
Pavement		
Thickness (mm)	152.4	Rossman and Huber (2016)
Void ratio (voids/solids)	0.2	Zhu et al. (2019)
Impervious surface (fraction)	0.0	Zhang and Guo (2015); Zhu et al. (2019)
Permeability (mm/hr)	1270.0	Rossman and Huber (2016)
Clogging factor	0.0	Assumed no clogging
Soil		
Thickness (mm)	228.6	Rossman and Huber (2016)
Porosity (volume fraction)	0.3	Rossman and Huber (2016)
Field capacity (volume fraction)	0.2	Rossman and Huber (2016)
Wilting point (volume fraction)	0.05	Rossman and Huber (2016)
Conductivity (mm/hr)	508.0	Rossman and Huber (2016)
Conductivity slope (-)	30.0	Rossman and Huber (2016)
Suction head (mm)	76.2	Rossman and Huber (2016)
Storage		
Thickness (mm)	450.0	Zhang and Guo (2015)
Void ratio (voids/solids)	0.3	Rossman and Huber (2016)
Seepage rate (mm/hr)	15	NRCS Soil Survey Data (soils.usda.gov/survey)
Clogging factor	0	Assumed no clogging
Underdrain		
Drain exponent	0.5	Rossman (2015) (modeled as an orifice)
Drain offset height (mm)	76.2	Rossman (2015)