Groundwater Recharge Sensitivity To Low Impact Development Design And Future Climate Change

By

Jessica Rodriguez

San Francisco State University

Internship time period: 03/2018-03/2019

Advisor: Jason Gurdak

San Francisco State University

Date submitted: 05/25/2019

Table of Contents

List of Figures

List of Tables

1.0 Acknowledgements

This project was supported by the Water Resources Institute at California State University San Bernardino and the USDA NIFA AWARD No. 2015-38422-24058, award title: Water Resources Experiential Learning for USDA Careers. This award was supported through the lead agency Cal State San Bernardino University Enterprises Corporation (FF20717). Additional funding was provided by the Doris and David Dawdy Hydrology Research Grant at San Francisco State University. I would like to thank my advisor, Dr. Jason Gurdak for selecting me for this opportunity. Lastly, I would like to acknowledge my research partner, Lawrence Fujiwara, and Melanie Pon for assisting with fieldwork.

2.0 Executive Summary

Groundwater sustainability is at the forefront of resource management. In light of climate change and growing populations, meeting future water needs must be met with planning and innovation. This is particularly challenging in cities where recharge is often limited by impervious surfaces and runoff is contaminated by urban pollutants. Low Impact Development (LID) is a design strategy that mimics the natural hydrologic cycle and is usually implemented as an alternative to the traditional stormwater system. Examples of LID best management practices (BMPs) include rain gardens, bioswales, infiltration trenches, rooftop gardens, and permeable pavement. LID BMPs delay and decrease peak runoff flows and improve water quality, and there is a growing number of studies investigating LID's effect on groundwater. Understanding potential recharge under LID BMPs and identifying the design features influencing recharge can serve an important role in the move toward groundwater sustainability and management. In this study, I used HYDRUS-1D to model five LID BMPs (two rain gardens, two bioswales, one infiltration trench) from 1948-2099 with observed historic climate data and 9 global climate models (GCMs) at representative concentration pathways (RCP) of 4.5 and 8.5. Mean recharge ranged from 1725-3458 mm/yr under the LID BMPs, with the highest recharge rates occurring under the infiltration trench. Though simulated recharge from historic, 4.5 and 8.5 RCP showed no statistically significant changes in recharge over time, runoff is predicted to increase significantly, indicating that current LID BMPs should be redesigned to store increased inflow expected from climate change. Recharge efficiency during heavy rainfall events such as El Niño can be improved by increasing the loading ratio of a BMP. Results of the one-at a time (OAT) method sensitivity analysis showed that the hydraulic conductivity of the soil underlying LID BMPs has the most influence on recharge and suggested that location is critical for optimizing or minimizing recharge.

3.0 Project Objectives

The goal of this project was to explore how low impact development can contribute to groundwater recharge and subsequently, increase groundwater availability for urban farming. Broadly speaking, I am interested in resource management and finding new avenues to achieve sustainability. The USDA covers many diverse and complex topics revolving around agriculture. This project supplies real world solutions to the challenges faced by urban watersheds and could be expanded and explored more at the USDA. The original goals of this project remained the same throughout the duration of the internship. The following contains the motivation and aims of the study.

3.1 Background

The 2014 passage of the Sustainable Groundwater Management Act (SGMA) in California marks a movement, both locally and globally, towards groundwater sustainability (CA DWR, 2017). Likewise, statewide targets of urban stormwater runoff for direct use and to recharge groundwater have been set statewide (CA DWR, 2019). A variety of approaches such as water conservation, recycled water, managed aquifer recharge (MAR), and stormwater capture and reuse will be used to meet sustainability goals. Due to the diversity of California cities, there is not a one-size-fits-all solution and innovative ways of achieving groundwater sustainability, including enhancing recharge to urban aquifers, must be investigated. MAR systems are typically large-scale (several hectares) and not appropriate in many urban settings because of the lack of available space and limited surface-water availability from rivers. Here, I explore the use and effectiveness of stormwater capture in low impact development (LID) Best Management Practices (BMPs) as a form or distributed-MAR to enhance recharge to urban aquifers.

The urban watershed is dominated by impervious surfaces that restrict stormwater from infiltrating into the soil. Traditional stormwater management employs curbs, gutters, and sewers systems designed to collect, convey and discharge stormwater into surface bodies of water as quickly and efficiently as possible (Prince George, 1999). However, this method has proven to be inadequate in many instances. Consequently, runoff volumes are increased, sewer systems are overwhelmed, and water quality is degraded (Burns et al., 2012). To address these issues, LID emerged as a small scale, decentralized alternative to traditional stormwater management (Chen et al., 2016). LID aims at mimicking natural hydrologic processes by locally retaining, detaining, and infiltrating stormwater. Examples of LID BMPs include rain gardens, bioswales, permeable pavement, infiltration trenches, detention/retention ponds and rooftop gardens.

LID BMPs are commonly designed with either an underdrain that delivers the collected stormwater into stormwater/sewage pipes or without underdrains that enable infiltration of the stormwater and recharge to underlying aquifers. Therefore, understanding groundwater recharge beneath LID BMPs and the factors that determine their recharge performance becomes increasingly important as urban watersheds and sustainability demands grow. Likewise, assessing the future recharge performance of LID BMPs is necessary as cities face intensifying weather events and climate change (Baede, 2001). Knowledge of recharge beneath LID BMPs provides practical value for water agencies and groundwater sustainability plans mandated by SGMA.

3.2 Project Goals

The purpose of this project is threefold:

1. Quantify recharge beneath different types of LID BMPs.
2. Evaluate changes recharge and runoff at LID BMPs under future climate projections and climate events, mainly El Niño.
3. Conduct a sensitivity analysis to determine LID BMP design parameters that most affect recharge, runoff, and evapotranspiration rates.

4.0 Project Approach

For the most part, the project went according to plan. The only thing that changed were the study sites. Originally, I planned to have study sites throughout the San Francisco, San Bruno, and San Mateo area. However, contacting city officials to gain permission to test those sites was difficult and time consuming. Luckily, there were five potential LID BMP study sites on the San Francisco State University (SFSU) campus. Therefore, I ended up testing and modeling these sites instead. The following section discusses the approach used throughout this internship.

4.1 Study Sites

There are five commonly used LID BMP's (one infiltration trench, two rain gardens, and two bioswales) that are part of the San Francisco State University LID Research Network. Table 1. Shows the dimensions of the study sites. The infiltration trench is about 11-m long and 1-m wide trench filled with highly permeable gravel and receives runoff from walkways and rooftops. Rain gardens are depressions in the ground with a top layer of engineered soil, generally a mixture of sand and organic material. Dry bioswales are similar to rain gardens except that the whole system is built on a about 2-degree slope and is shaped like a channel. The rain gardens and bioswales are covered in dense, drought-resistant local plants to slow and treat urban runoff from roofs and sidewalks.

Table 1. Dimensions of low impact development (LID) best management practice (BMP) study sites. Loading ratio is area/contributing area.

Site	Area (m^2)	Contributing area (m^2)	Loading ratio (%)	Design capture volume (m^3)	Vegetation
Infiltration trench	11	430	2.5	8	no
Rain garden #1	18	600	3.0	11	yes
Rain garden #2	21	576	3.6	10	yes
Bioswale #1	10	110	9	2	yes
Bioswale #2	13	370	3.5	7	yes

4.2 Models

I used HYDRUS-1D to simulate recharge under the LID BMP study sites. HYDRUS-1D is a computer program that numerically solves the Richards equation for water flux in saturated and unsaturated media (Richards, 1931). Models were run at a daily time interval from 1948 to 2099 for all 5 LID BMPs, and steady state was achieved by completing one full model spin-up run with an initial pressure head of 10 mm at the surface. I calibrated the models with field measurements taken with the SATURO dual pressure head infiltrometer which measures permeability and field saturated hydraulic conductivity using a two-ponding head approach (METER Group, 2017). Multiple tests were performed at each study site, and model output values for infiltration and recharge were compared to previous studies (Newcomer et al., 2014).

I used daily precipitation and temperature data from the Downtown San Francisco weather station (USW00023272) from the National Oceanic and Atmospheric Administration (NOAA) online portal for the time period of 1948-2017. I used climate projections from an ensemble of nine global climate models (GCMs) recommended by California Department of Water Recourses (DWR) for use in California (Lynn et al., 2015). at representative concentration pathways (RCPs) of 4.5 and 8.5. Runon to the LID BMPs were calculated using the SCS Runoff Curve Number approach (CN) (USDA, 1986).

4.3 Sensitivity Analysis

Design requirements for LID BMPs vary according to local guidelines and regulations, but are generally determined based on precipitation, soil properties, and groundwater usage of an area. For this sensitivity analysis, I tested the following nine design parameters using the one-at-a-time (OAT) method, which analyzes how the output varies when one input variable is changed at a time (Devak and Dhanya, 2017). The variables can be categorized by vegetation, native soil, engineered soil, and water, Table 2. I tested five values for each variable.

Table 2. Variables for sensitivity analysis.

Vegetation	Engineered Soil	Native Soil	Water
Interception	Layer thickness	Layer thickness	Loading ratio
Plant height	Hydraulic conductivity (K)	Hydraulic conductivity (K)	Ponding depth
Root depth			

4.4 Statistical Analysis

I focused my analysis to include only winter months (December, January, and February) because in the cold-summer Mediterranean climate of San Francisco, typically 60% or more of annual precipitation and storm systems occurs during winter months. I summed daily values to get cumulative precipitation, recharge, runoff, and transpiration, as well as recharge efficiency, which is simply the percentage of water entering the system that becomes recharge for each year.

A preliminary assessment of the results showed a non-normal distribution for all variables. Therefore, I used the Kruskall-Wallis non-parametric test with an alpha level of 0.05 to determine differences between the non-parametric groups of data (Helsel and Hirsch, 1992). Subsequently, I used the Steel-Dwass All Pairs test, which is equivalent to the non-parametric version of the Tukey test to determine differences among the groups of data (JMP, 2009). I used these statistical tests to analyze the differences between historical and future rates, differences between the five LID BMP sites, and differences among GCM datasets.

5.0 Project Outcomes

I learned a lot during the course of this internship such as planning, meeting deadlines, model building, and analysis. One surprising outcome was that increases in recharge under the LID BMP over time were not statistically significant while increases in runoff from the LID BMPs were statistically significant. This highlights the limitations of the LID BMP design standards (addressed in more detail in the following section).

5.1 Historic Recharge beneath LID BMP Study Sites

I simulated recharge under the five LID BMP study sites using historic data and evaluated if each site produced a unique recharge rate. For context, the average diffuse recharge rates for the Westside Basin aquifer have been estimated to be 200 mm/yr (Phillips et al., 1993) with urban recharge under an irrigated lawn reported to be 130-730 mm/yr (Newcomer et al., 2014). Recharge under the five LID BMPs were an order-of-magnitude larger than these previously reported diffuse and irrigated lawn recharge rates, and were 1725, 2382, 2431, 2481, and 3458 mm/yr for each of the five LID BMPs (Figure 1).

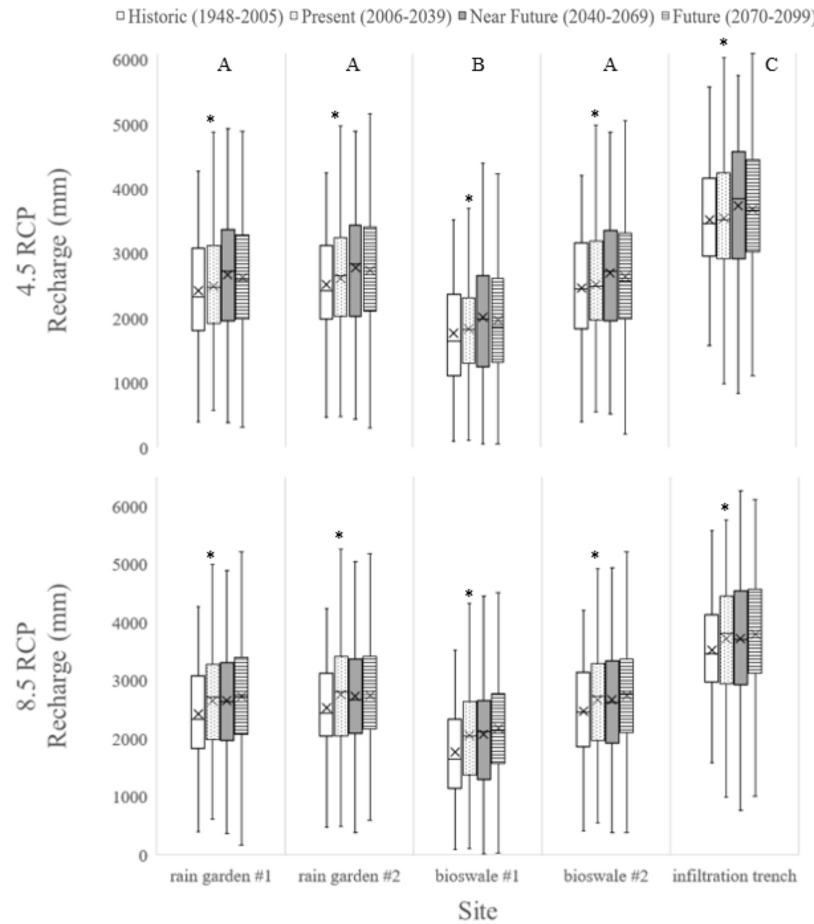

Figure 1. Cumulative annual winter recharge under low impact development (LID) best management practice (BMP) study sites by time period. Results from Steele-Dwass tests are shown with letters denoting statistical differences in recharge from historic, and asterisks denoting differences between 4.5 and corresponding 8.5 representative concentration pathway (RCP) datasets.

The infiltration trench and bioswale #1 have significantly different recharge rates, while rain garden #1 and #2, and bioswale #2 have similar recharge rates (Figure 1). The trench had statistically greater recharge values than the other LID BMPs with a mean of 3458 mm. Larger recharge rates under the infiltration trench is most likely due to the larger storage capacity of the gravel trench and thus the design of the trench to capture and infiltrate greater amounts of stormwater runon.

Bioswale #1 had statistically lower recharge rates than the four other LID BMP study sites (Figure 1). Mean cumulative winter recharge was 1725 mm and recharge efficiency was 68% (Figure 1). The lower recharge rates under bioswale #1 could be due to the swale's relatively small contributing area (110 m^2) compared to the other LID BMPs (Table 1). A smaller contributing area, and thus larger loading ratio, results in less stormwater runon available for infiltration.

Recharge under rain garden #1, rain garden #2, and bioswale #2 had similar values for recharge (Figure 1). Rain garden #1 had a mean recharge of 2383 mm, rain garden #2 had 2481 mm, and bioswale #2 had an average of 2431 mm of recharge. The loading ratio at these three sites were very similar (3.0, 3.6, and 3.5 %) and is most likely the reason that recharge rates are indistinguishable at these sites.

5.2 Recharge by Time Period

I evaluated recharge under the LID BMP study sites over four time periods: historic (1948-2005), present day (2006-2039), near future (2040-2069), and future (2070-2099) using both 4.5 and 8.5 RCP climate projections. The 4.5 RCP models show recharge increases from historic to present, from present to near future, and then decreases from near future to future for the five LID BMPs (Figure 1). Lowest recharge rates are seen in the historic time period, and the highest rates in the near future time period ranging from 2013 mm at bioswale #1 and 3735 mm at the infiltration trench, which is an increase of 200-300 mm from the historic time period. Although there are fluctuations in recharge over time, there are no statistically significant differences in average recharge between the time periods.

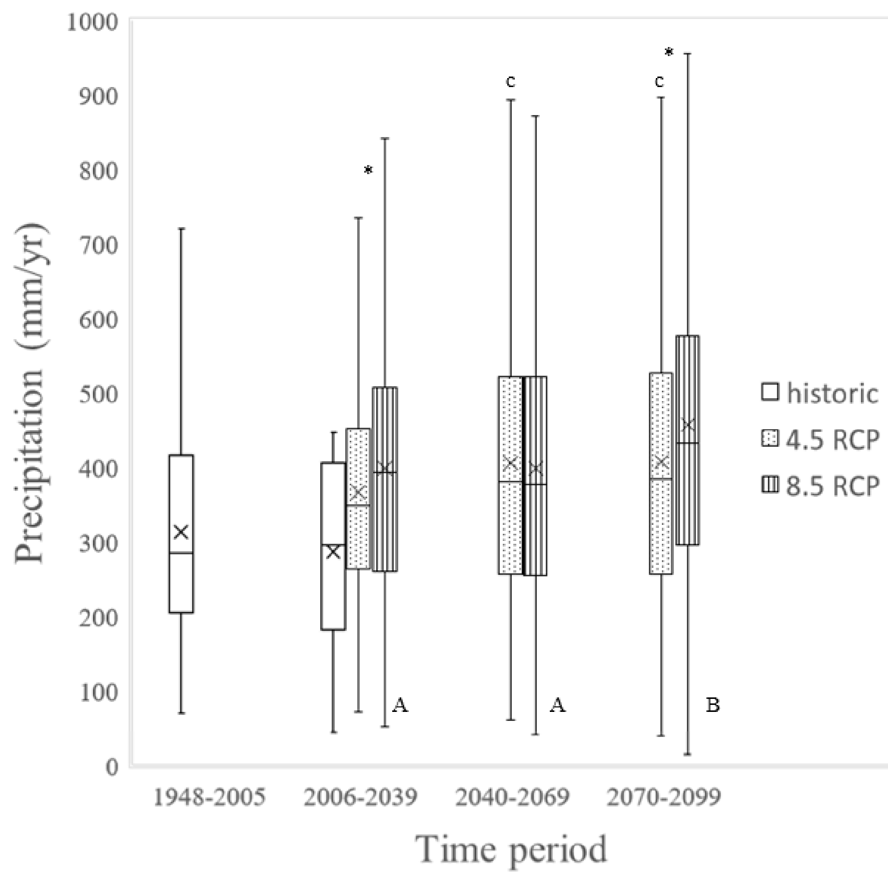

Figure 2. Winter precipitation over four time periods: historic (1948-2005), present (2006-2039), near future (2040-2069), and future (2070-2099). Results from Steele-Dwass tests are shown with letters denoting statistical differences in precipitation from historic, and asterisks denoting differences between 4.5 and corresponding 8.5 representative concentration pathway (RCP) datasets.

Significant increases in precipitation are reflected in runoff values rather than recharge rates under the LID BMP study sites (Figure 2 and 3). The 4.5 RCP projections predict a continuous increase in precipitation over the four time periods, with statistically significant increases in precipitation from historic to near future, and historic to future time period (Figure 2). Runoff values show the same temporal trend as precipitation while maintaining the statistically significant increases from the historic to near future and historic to future that are observed in precipitation, but not in simulated recharge (Figure 3). Overall decreases in precipitation, recharge, and runoff from near future to future can be explained by the 4.5 RCP model itself. From the historic to the future time periods, runoff increases by about 200 and 1000 mm at bioswale #1 and the infiltration trench, respectively.

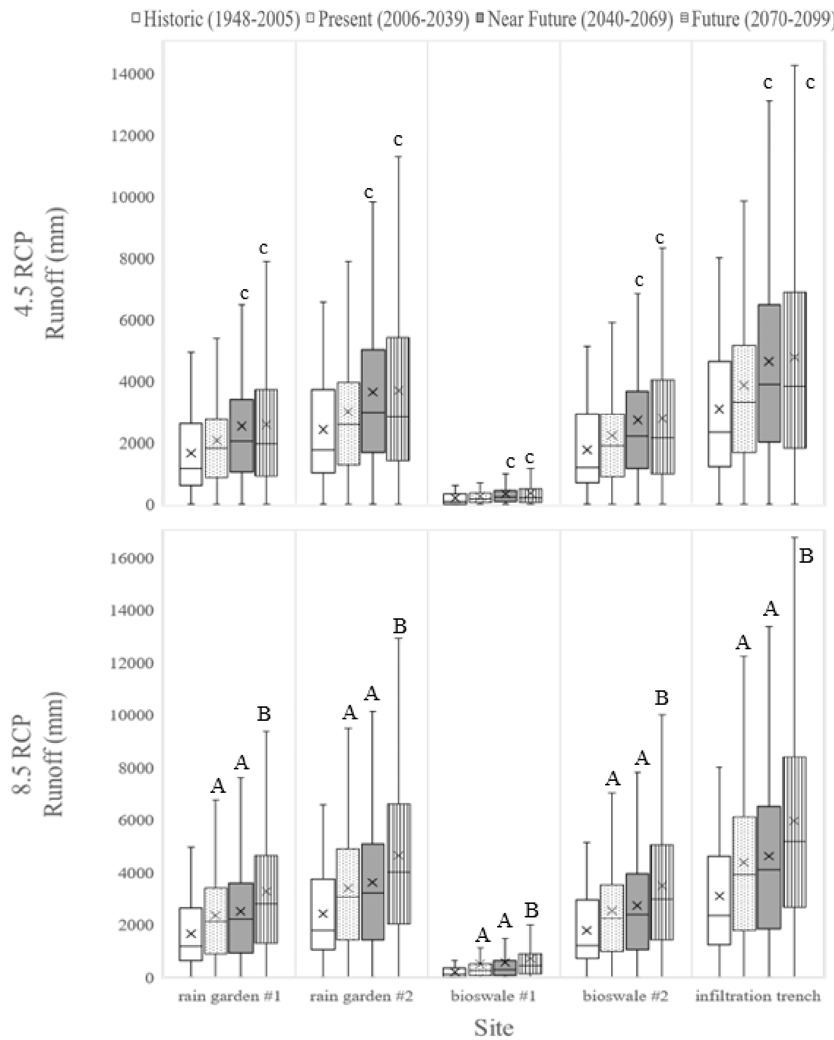

Figure 3. Runoff from low impact development (LID) best management practice (BMP) study sites over four time periods: historic (1948-2005), present (2006-2039), near future (2040-2069), and future (2070-2099). Results from Steele-Dwass tests are shown with letters denoting statistical differences in runoff from historic, and asterisks denoting differences between 4.5 and corresponding 8.5 representative concentration pathway (RCP) datasets.

Precipitation, recharge and runoff have a similar relationship in the 8.5 RCP models as in the 4.5 RCP models. Recharge under the LID BMP study sites modeled with 8.5 RCP show an overall increase in recharge over the four time periods (Figure 1). There is a large initial increase in recharge from the historic to present time period and then smaller increases in recharge from present to near future to future (Figure 1). Over the course of the entire time span (historic to future), the mean recharge rates increased by 200 to 400 mm among the LID BMP study sites (Figure 1). Unlike the 4.5 RCP models, the 8.5 RCP models show the largest recharge rates occurring in the future time period, with 2,172 mm at the bioswale #1 and 3,791 mm at the infiltration trench. Bioswale #1 was the only LID BMP to show a statistically significant increase in recharge among any of the time periods with an increase of 1,768 mm during the historic time period to 2,172 mm during the future time period.

Similar to the 4.5 RCP models, when modeled with 8.5 RCP, temporal changes in average recharge rates do not reflect the same temporal changes in precipitation. Under the 8.5 RCP projections, there is an increase in precipitation from 1948-2099 with all time periods being statistically significantly different except for the present and near future, which have similar rainfall values (Figure 2). Runoff from the 8.5 RCP models show the same statistically significant increases over time as precipitation (Figure 2). All LID BMPs show a statistically significant increase in runoff across the four time periods with the exception of present to near future (Figure 3).

LID BMPs design standards are based on historic storm events, therefore there is a need to reconfigure these systems to account for the intensifying weather of climate change. Models show that under future climate conditions, current LID BMP designs do not effectively capture the increased stormwater and efficiently promote recharge. Instead, more stormwater overflow is produced from the LID BMPs, which leads to flooding, erosion, and water quality degradation. LID BMPs must be redesigned in order to protect infrastructure and receiving bodies of water, as well as treat stormwater runon as a valued resource capable of recharging urban aquifers.

5.3 Recharge During El Niño, La Niña, and Neutral Events and Recharge Efficiency

I evaluated recharge under the LID BMPs during El Niño, La Niña, and neutral years. Overall, recharge rates beneath all LID BMPs are higher during El Niño years compared to neutral years (Table 3). Bioswale #1 and rain garden #1 had the highest percent increase (22%) in recharge from the neutral years to the El Niño years, while the infiltration trench had the least increase of 13% (Table 3). Bioswale #2, and rain garden #2 had 20 and 21% increases (Table 3). There was no statistical difference in recharge between the El Niño years and the La Niña years, as well as between La Niña years and the neutral years (Table 3).

Table 3.Recharge and percent increase during El Niño, La Niña, and neutral winter months under low impact development (LID) best management practice (BMP) study sites.

Site	El Niño Recharge (mm)	La Niña Recharge (mm)	Neutral Recharge (mm)	Percent increase from Neutral to El Niño
Rain garden #1	2634	2398	2152	22%
Rain garden #2	2704	2553	2234	21%
Bioswale #1	1954	1655	1596	22%
Bioswale #2	2668	2449	2215	20%
Infiltration trench	3698	3443	3275	13%

Recharge efficiency was analyzed during the strong and very strong El Niño and La Niña years. Rain garden #1, #2, bioswale #2 and the infiltration trench have an inverse relationship between precipitation and recharge efficiency (Figure). El Niño years had more rain and smaller recharge efficiency, while La Niña years had less rain and larger recharge efficiencies. The r-squared values range from 0.4-0.6 indicating that about half of the variance in recharge efficiency can be explained by precipitation. Bioswale #1 did not show a statistically significant relationship between precipitation and recharge efficiency

(Figure 4). Recharge efficiency fluctuated between 47-78% during both El Niño and La Niña years. Bioswale #1 had a large p-value of 0.82 and a small r-squared vale of 0.04. Bioswale #1's maintains a constant recharge efficiency during these climate events most likely because of its large loading ratio. Design standards of BMPs should consider the changes in precipitation and runoff associated with climate events. Due to the predictability of El Niño, preparations should be made by groundwater sustainability plans to safeguard infrastructures and water supplies during these climate events.

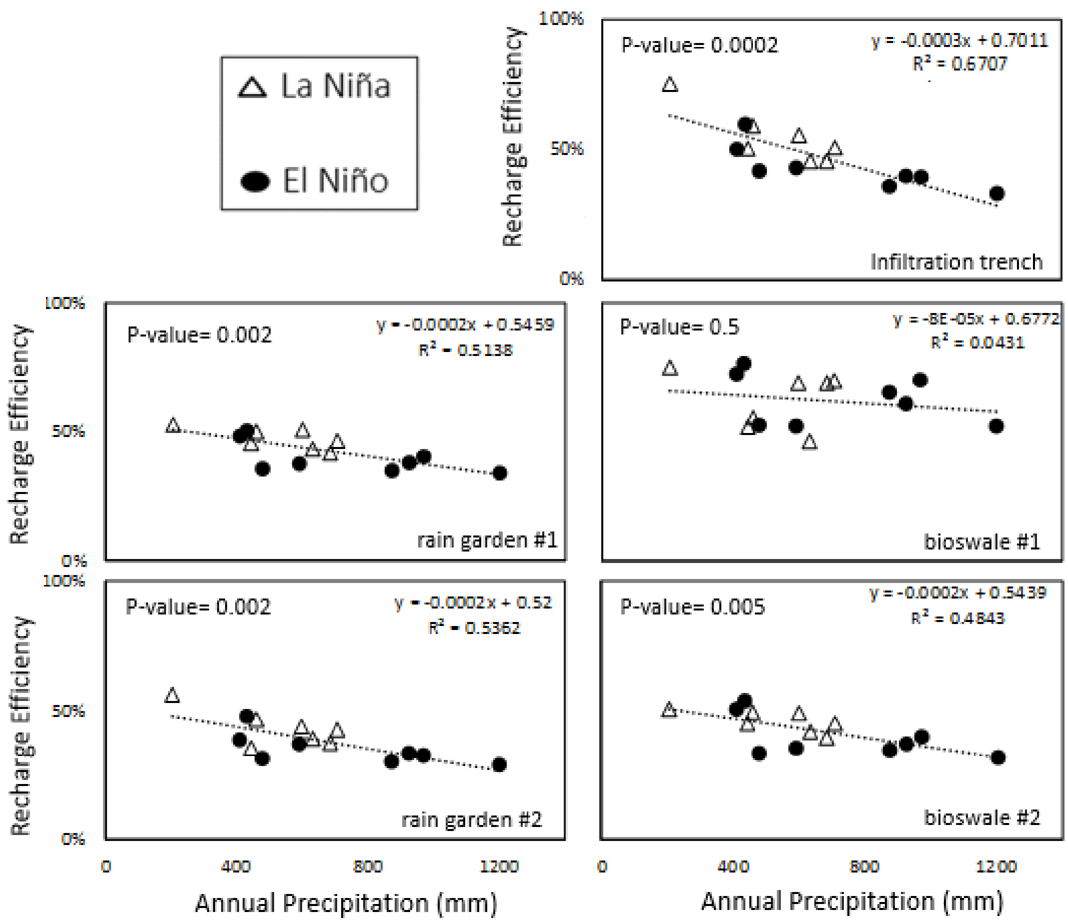

Figure 4. Recharge efficiency of low impact development (LID) best management practices (BMPs) study sites during El Niño and La Niña years. Triangles are La Niña years and circles are El Niño years.

Bioswale #1 shows a more gradual decline in recharge efficiency with increased precipitation when all years are considered (Figure 5). Rain garden #1, #2, bioswale #2, and the infiltration trench have high recharge efficiency when there is less rainfall while bioswale #1 had a smaller recharge efficiency with smaller rainfall and maintained a larger recharge efficiency as annual precipitation increased. BMPs with larger loading ratios can retain and infiltrate more inflow before runoff is initiated. Based on these findings, designing LID BMPs with relatively larger loading ratio is one way to increase recharge efficiency.

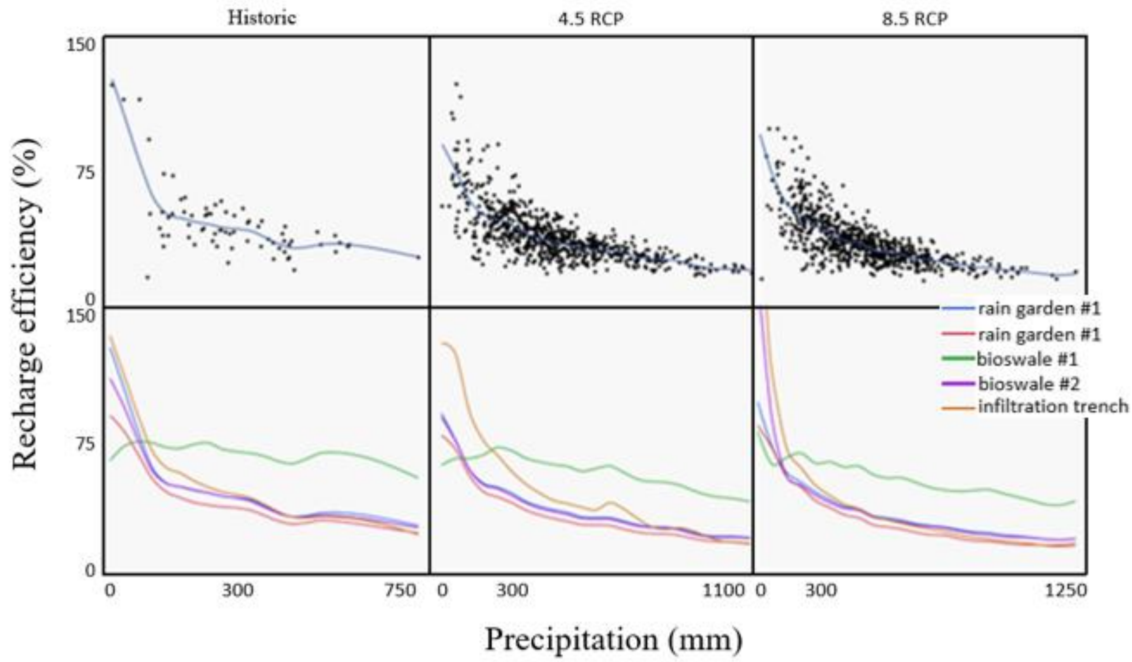

Figure 5. Recharge efficiency of low impact development (LID) best management practice (BMP) study sites versus precipitaiton. Top row is rain garden #1 with points and kernel smoother. Bottom row is kernal smoother without points for the five LID BMP study sites.

5.4 Sensitivity Analysis

LID BMP design parameters were assessed to determine a parameters sensitivity to recharge, runoff, and evapotranspiration. Of the 10 parameters tests, recharge was most sensitive to the hydraulic conductivity of the native soil (Table 4). Standard deviation of the hydraulic conductivity of native soil was 5,010 mm, which is about five times greater than the standard deviation of the other parameters (Table 4). The greater the hydraulic conductivity of the native soil, the more recharge will take place under the LID BMP. If recharge is desired, locating areas where the native soil has a high hydraulic conductivity will optimize recharge rates.

Table 4. Standard deviation of low impact development (LID) best management practice (BMP) design parameters for sensitivity analysis to recharge, runoff, and evapotranspiration. K is hydraulic conductivity and loading ratio is LID BMP area divided by contributing area.

Parameter	Recharge Standard Deviation (mm)	Runoff Standard Deviation (mm)	Evapotranspiration Standard Deviation (mm)
Baseline	1051	3041	39
Native Soil K (*mm/dy*)	5010	2272	39
Thickness of native soil (mm)	880	3024	37
Engineered soil K (*mm/dy*)	1042	3028	38

Thickness of engineered soil layer (mm)	1179	3049	38
Loading ratio (%)	1102	4448	38
Ponding depth (*mm*)	1121	3598	40
Interception (*mm*)	1053	3021	48
Plant height (*mm*)	1059	3005	95
Plant root depth (*mm*)	1050	3030	38

Loading ratio, ponding depth, and the thickness of the engineered soil layer showed less of an influence on recharge with standard deviation of about 1,100 mm (Table 4). More water in the system is not as critical as how quickly the native soil can infiltrate that water. Overall, plants had the smallest effect on recharge rates. Interception, plant height, and root depth all had a standard error of about 35 mm (Table 4). Instead, plant height and root depth limited recharge. When plant height was increased from 76 to 456 mm, recharge reduced by 251 mm. To a lesser extent, as root depth increased from 76 to 900 mm, recharge decreased by 20 mm. While plants are useful in slowing and treating urban runon, they are not needed to enhance recharge and instead vegetation can reduce recharge beneath LID BMPs.

Stormwater retention is an essential feature of most LID BMPs and becomes more important as runoff volumes are expected to increase due to climate change, as shown above. Results of the sensitivity analysis indicate that loading ratio had the biggest impact on runoff rates with a standard deviation of 4,448 mm (Table 4). Small loading ratios (or relatively large contributing areas) mean a larger amount of water entering the LID BMP and overwhelming the system and producing more runoff, whereas a larger loading ratio (or relatively smaller contributing areas) translates to less runon and increases the capability of the LID BMP to retain more stormwater. After the loading ratio, ponding depth were next most influential on runoff with a standard deviation of 3,598 mm (Table 4). Allowing deeper ponding depths by raising retention walls or situating bioswales in a deeper depression in the ground will decrease the amount of runoff.

LID BMP design parameters were also evaluated for their sensitivity to evapotranspiration. While plants had the least effect on recharge, plant height and interception were the biggest drivers of evapotranspiration (Table 4). Plant height had a standard deviation of 95 mm, which is two to three times more than the other parameters.

6.0 Conclusions

I used HYDRUS-1D to model five LID BMPs (two rain gardens, two bioswales, one infiltration trench) from 1948-2099 with observed historic climate data and nine GCMs at RCP of 4.5 and 8.5. I simulated recharge rates for the LID BMP study sites and quantified recharge during historic, present, near future, and future, to assess whether recharge will change over time as a function of future climate change. Recharge during EL Niño, La Niña, and neutral years was assessed to understand how these climate events impact recharge rates under LID BMPs. I used the OAT method to perform a sensitivity analysis to determine the design parameters of LID BMPs that most influence recharge.

Overall, the infiltration trench had the largest recharge values of 3,458 mm/yr during the winter months due to the greater ability of the gravel trench to infiltrate water. Bioswale #1 had the smallest recharge rates, averaging 1,725 mm/yr due to the small contributing area that supplies stormwater runon. Rain garden #1 and #2, and bioswale #3 showed statistically similar rates of about 2,400 mm/yr. All LID

BMPs show recharge rates larger than other sources of urban recharge by an order of magnitude and are comparable to other estimations of recharge under LID BMPs (Newcomer et al., 2014).

Both 4.5 and 8.5 RCP simulations showed no statistically significant increases in recharge from historic to future time periods. Instead, statistically significant increases were simulated in runoff values that more closely reflect the future precipitation patterns predicted by both the 4.5 and 8.5 RCP models. The 8.5 RCP models show statistically more precipitation and runoff from historic to all time periods, while the 4.5 RCP models show increases from historic to near future and historic to future. The 8.5 RCP simulations have statistically more precipitation, recharge, and runoff during the present and future time periods than the 4.5 RCP models. Future design of LID BMPs need to account for increased precipitation and stormwater runon caused by climate change. Altering design guidelines to promote more recharge and less runoff under intensifying weather is critical to avoid flooding and degradation of water quality at receiving bodies of water.

Weather events that typically bring more rainfall like El Niño produce increased runoff volumes and decreased recharge efficiencies at LID BMPs. BMPs with larger loading ratios maintain higher recharge efficiencies with increased precipitation. Consideration and preparations for El Niño events in groundwater management plans is necessary to protect infrastructure and bodies of water. Results of the runoff sensitivity analysis also identified loading ratio as the primary design parameter controlling runoff rates. Increasing BMP loading ratio standards can be an effective way to handle increased precipitation and runoff during climate events and climate change.

Results of the recharge sensitivity analysis identified the hydraulic conductivity of the underlying soil as the most important design parameter that influences recharge. The standard deviation of 5,010 mm is about five times greater than the other nine parameters tested. Therefore, locating areas that have high hydraulic soil conductivity to maximize recharge before building BMPs can be a valuable first step in the design process. Loading ratio and ponding depth, and thickness of engineering soil had a lesser impact, while plant height, root depth, and interception showed the least control on recharge.

The findings from this study can be used to help inform groundwater management agencies, and points to the need to reevaluate LID BMP design guidelines to account for future climate change. Current guidelines of LID BMPs are based on historic storm events, and when modeled under future climate, increases in inflow do not directly translate to increases in recharge. Instead, findings indicate that runoff is expected to increase significantly. By locating areas with higher hydraulic conductivity, increasing loading ratios, and ponding depths, LID BMPs can be designed to collect and infiltrate more stormwater runon and enhance aquifer recharge.

The Experimental Learning Internship has given me practical experience conducting a study that can be applied to career opportunities at the USDA. I learned all the aspects of planning, executing, and reporting that goes in to a research project.

7.0 References

Baede, A.P.M., editor. 2001. Climate Change 2001: The Scientific Basis, Appendix I. IPCC Third Assessment Report. Cambridge University Press, Cambridge, U.K. p. 787–881

Burns, M.J., T.D. Fletcher, C.J. Walsh, A.R. Ladson, and B.E. Hatt. 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landsc. Urban Plan. 105(3): 230–240. doi: 10.1016/j.landurbplan.2011.12.012.

CA DWR. 2017. Best Management Practices for the Sustainable Management of Groundwater; Sustainable Management Criteria. California Department of Water Resources Sustainable Groundwater Management Program.

CA DWR, 2019. Stormwater Targets for Groundwater Recharge and Direct Use in Urban California. California Department of Water Resources Water Use and Efficiency Branch.

Chen, Y., H.W. Samuelson, and Z. Tong. 2016. Integrated design workflow and a new tool for urban rainwater management. J. Environ. Manage. 180: 45–51. doi: 10.1016/j.jenvman.2016.04.059.

Devak, M., and C.T. Dhanya. 2017. Sensitivity analysis of hydrological models: review and way forward. J. Water Clim. Change 8(4): 557–575. doi: 10.2166/wcc.2017.149.

Helsel, D.R., and R.M. Hirsch. 1992. Statistical methods in water resources. Elsevier.

JMP: release 8. 2009. 2nd ed. SAS Institute Inc, Cary, N.C.

Lynn, E., C. Chair, D. Division, W. O'Daly, F. Keeley, et al. California Department of Water Resources (DWR) Climate Change Technical Advisory Group (CCTAG). : 142.

Newcomer, M.E., J.J. Gurdak, L.S. Sklar, and L. Nanus. 2014. Urban recharge beneath low impact development and effects of climate variability and change. Water Resour. Res. 50(2): 1716–1734. doi: 10.1002/2013WR014282.

Phillips, S. P., S. N. Hamlin, and E. B. Yates (1993), Geohydrology, water quality, and estimation of ground-water recharge in San Francisco, California, 1987–1992, WRIR 93-4019, 69 pp., U.S. Geol. Surv., Reston, Va.

Prince George's County Maryland, 1999. Low-impact development hydrological analysis. Prince George's County, Maryland, Department of Environmental Resources Program and Planning Division.

Richards, L. 1931. Capillary conduction of liquids in porous mediums. Physics 1: 318–333.