GROUNDWATER RECHARGE SENSITIVITY TO LOW IMPACT DEVELOPMENT DESIGN AND FUTURE CLIMATE VARIABILITY

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by
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San Francisco, California
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CERTIFICATION OF APPROVAL

I certify that I have read Groundwater Sensitivity To Low Impact Development Design and Future Climate Variability by Jessica Rodriguez, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Science in Geosciences at San Francisco State University.

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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 a one-at a time (OAT) method sensitivity analysis showed that the hydraulic conductivity of the soil underlying a LID BMP has the most influence on recharge and suggested that location is critical for optimizing or minimizing recharge.

I certify that the Abstract is a correct representation of the content of this thesis.

_______________________________ 5-21-2019

Chair, Thesis Committee Date

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1.0 INTRODUCTION

Groundwater is a fundamental component of the hydrologic cycle, sustains many rivers, lakes, wetlands, and other groundwater dependent ecosystems, and is a significant source of freshwater for human consumption. Groundwater is also the foundation for irrigated agroecosystems and global food production, particularly in semi-arid and arid regions. As a result, over-abstraction of groundwater, particularly in many of the largest and most important aquifer systems has resulted in rapidly declining water levels and substantial loss of storage, often referred to as the global groundwater crisis (Famiglietti, 2012). Unsustainable groundwater use is becoming a recognized problem and many local to regional policy and management actions are being implemented to achieve sustainability (Gurdak et al., 2019).

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.

1.1. Background

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 has shown much success as a stormwater management tool. Studies indicate that LID is extremely good at filtering and removing heavy metals and nutrients present in urban runoff with 50%-95% removal rates (Davis et al., 2003; Allen P. Davis et al., 2006). LIDs are capable of capturing large amounts of stormwater and thus decreasing urban runoff to sewers by 48-97% (Dietz and Clausen, 2008). Due to versatility of type and size, LID may be 15-80% cheaper than traditional stormwater management systems (USEPA, 2007). Ecosystem services such as adding wildlife and pollination habitats, improving aesthetics, increased green and recreational spaces, better air quality, and raising property value should be considered as well (Schifman et al., 2017).

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.

Recent LID usage in urban watersheds has given rise to a growing number of studies investigating the interaction between LID and groundwater. Previous studies at the San Francisco State University (SFSU) LID Research Network showed that recharge beneath an infiltration trench was an order of magnitude larger than recharge beneath an irrigated lawn (Newcomer et al., 2014). Recharge efficiencies for the infiltration trench were 58-79% compared to 8.0-33% at the irrigated lawn (Newcomer et al., 2014). Catchment-scale studies using a mass balance approach estimated that implementation of 5,700 drywells resulted in 48-75% of precipitation becoming recharge (Edwards et al., 2016). Placement of LID BMPs along critical flow paths has been shown to be more important than the number of BMPs in capturing and infiltrating stormwater (Fry and Maxwell, 2017). Spacing and size of LIDs in areas with a shallow water table can cause structural damage due to groundwater mounding beneath LIDs (Endreny and Collins, 2009). Beyond this relatively few number of studies, recharge rates beneath different types of LID is still largely unknown.

Furthermore, understanding how recharge beneath LID BMPs will respond to climate variability and climate change is critical to groundwater management as well as protecting infrastructure. Rainfall events are expected to increase in frequency and intensity due to climate change (Baede, 2001), and over the time periods of 1860-2010, the San Francisco Bay Area has seen an increase in the frequency of large storm events (Russo et al., 2013). Interannual and multidecadal climate variability like El Niño-Southern Oscillation (ENSO) partially control groundwater recharge (Kuss and Gurdak, 2014). The El Niño phase of ENSO is characterized by increased rainfall in the eastern Pacific and has a recurrence time of 2-7 years (Ghil, 2002), and El Niño generally results in above average winter precipitation for much of California. Evaluating the efficiency of LID BMPs to capture stormwater and promote groundwater recharge under climate change and climatic events may show these systems to be inadequate and thus call for a redesign of these systems.

1.2. Research Goals

The purpose of this thesis is threefold. First, I will quantify recharge beneath different types of LID BMPs. Second, I will evaluate changes recharge and runoff at LID BMPs under future climate projections and climate events, mainly El Niño. Lastly, I will conduct a sensitivity analysis to determine LID BMP design parameters that most affect recharge, runoff, and evapotranspiration rates. The following sections contain the methodology, results and discussion, and a conclusion for this study.

2.0 METHODOLOGY

I built models with HYDRUS-1D to quantify recharge under five LID BMP study sites. Models were created with historic and future climate scenarios predicted by nine global climate models (GCMs) with representative concentration pathways (RCP) of 4.5 and 8.5, and calibrated with field-based measurements of infiltration rates and hydraulic conductivity. I used the one-at-a-time (OAT) method to do a sensitivity analysis of LID BMP design parameters that most influence recharge, runoff, and evapotranspiration.

2.1. Study Sites

The LID BMPs that I evaluated are situated within the Lake Merced watershed in San Francisco, California, and any potential recharge would contribute to the Westside Basin aquifer. The Westside Basin covers about 117 km^2 of land surface spanning from west San Francisco to San Mateo, California (SFPUC, 2017). There are three known aquifer units: shallow, primary production, and deep aquifer. Aquifers are made of sand and gravel and are divided by clay units (City of San Bruno et al., 2012). Groundwater levels range in value from 1.5 to 91 meters below land surface. San Francisco, South San Francisco, Daly City, and San Bruno are actively pumping the aquifer for municipal and domestic usage. Approximately 5,107 acre-feet was pumped from the Westside Basin aquifer in 2016, and in 2017, San Francisco began pumping the Westside Basin aquifer for drinking water.

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, Figure 1. 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.

The area of the LID BMPs range from 10-21 m^2 with a loading ratio, defined as the LID BMP area to contributing area, of 2.5-9.0%. The SFSU LID Research Network is in the separate sewer system area of the city and is under the jurisdiction of the San Francisco Public Utilities Commission (SFPUC). The SFPUC requires a capture volume greater than or equal to 90% of annual runoff, which is equivalent to a 0.75-inch design storm. Table 1 lists the characteristics of the LID BMPs used in this study.

2.2. HYDRUS-1D Models

HYDRUS-1D is a computer program that numerically solves the Richards (Richards, 1931) equation of water flow in saturated and unsaturated media:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right]$$

Equation 1

where θ is the volumetric water content [$L^3 L^{-3}$], t is the time [T], z is the spatial coordinate, K is the unsaturated hydraulic conductivity [L/T], h is the water pressure head [L], (Šimůnek, 2009).

Models were run at a daily time interval from 1948 to 2099 for all 5 LID BMPs. Steady state was achieved by completing one full model spin-up run with an initial pressure head of 10 mm at the surface. Soil profiles were 1,880 mm deep with 4 soil layers: an engineered soil layer (0-996 mm bls) and 3 native soil layers (997-1,880 mm bls). Parameters for the gravel layer of the infiltration trench and the native soil layers were obtained from a core sample analysis by Newcomer et al. (2014). Engineered soil parameters for the bioswales and rain gardens were obtained from experiments done by Liu and Fassman-Beck (2018). Table 2 Shows the HYDRUS-1D input values for all soil layers used in the models. The rain garden and bioswale models had a maximum ponding depth of 152 mm, an interception constant of 2 mm, a rooting depth of 300 mm, and a plant height 152 mm.

2.3. Climate and Runoff

Daily precipitation and temperature data were obtained 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) at representative concentration pathways (RCPs) of 4.5 and 8.5: ACCESS-1.0, CanESM2, CESM1-BGC, CMCC-CMS, CNRM-CN5, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, and MIROC5. The California Department of Water Recourses (DWR) recommends the use of these nine GCMs for water related planning and management in California (Lynn et al., 2015).The GCM output has been biased correlated spatially downscaled (BCSD) using the latest CMIP5 framework for California (Brekke et al., 2017). These data sets are at a daily timestep and span from 2018 to 2099.

El Niño, La Niña, and neutral years are identified and listed in Table 3. Future daily wind speeds were approximated from historical monthly wind normals using a random number generator function. Due to the absence of future wind data, I created one year of wind speeds at a daily timestep and used the dataset for each year of the models.

Runoff was estimated using the SCS Runoff Curve Number (CN) (USDA, 1986):

$$Q = \frac{(P - I)^2}{(P - \mathrm{I_a}) + S}$$

Equation 2

where Q is the runoff, P is the rainfall, S is the potential maximum retention after runoff is initiated, I_a is the initial abstraction. Since the contributing area of the LID BMPs in this study were dominated by impervious services (rooftops and paved walkways), I used a CN of 98 to calculate runoff. Total runoff volumes from contributing area were then divided by the LID BMP area to give a depth of runon to LID BMPs. Runon values were then added to precipitation values for HYDRUS-1D models.

2.4. 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 tested include loading ratio, hydraulic conductivity of native soil, hydraulic conductivity of the engineered soil, thickness of engineered soil, thickness of native soil, ponding depth, interception constant, root depth, and plant height. The range of values chosen for each parameter are typical of LID BMPs within the study site, Table 4 shows the values tested for each parameter. I used bioswale #2 as the baseline model because it has the median loading ratio, 3.5%. The model was run with the CanESM2 RCP 8.5 dataset because it predicts the greatest annual winter rainfall, 536 mm.

Altering the drainage area effectively changes the loading ratio of the system. I chose 2-10% because it encompasses the ratio recommended by the SFPUC (SFPUC, 2016). Interception ranges from 1-6 mm because Soulis et al. (2017) found interception constants of 0.5-6.8 mm for two types of plants commonly used in green infrastructure. Plant height and root depth are within the range of plants in the system estimated from study sites. Hydraulic conductivity values of native soil were within the range of values found in the area(SFPUC, 2016). Engineered soil hydraulic conductivity, layer thickness, and ponding depths were taken from recommendations made by various city requirements

(SFPUC, 2016, 2017). Rosetta, a built-in feature of HYDRUS-1D, provide alternate soil parameters for this test.

2.5. Model Calibration

The SATURO dual pressure head infiltrometer measures permeability and field saturated hydraulic conductivity using a two-ponding head approach (METER Group, 2017):

$$K_{fs} = \frac{\Delta(i_1 - i_2)}{(D_1 - D_2)}$$

Equation 3

where K_{fs} is the field hydraulic conductivity [L^3 L^{-3}], Δ is a constant based on the size and shape of the infiltrometer [L], i_1 is the rate of infiltration at the high-pressure head [L/T], i_2 is the rate of infiltration at the low-pressure head [L/T], D_1 is the high-pressure head [L], and D_2 is the low-pressure head [L]. Multiple tests were performed at each LID BMP and measurements were used to calibrate the HYDRUS-1D models. Model output values for infiltration and recharge were compared to previous studies (Newcomer et al., 2014)

2.6. 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.

3.0 RESULTS AND DISCUSSION

I analyzed recharge under the five LID BMP study sites in three ways. First, I quantified historic recharge under each LID BMP, and then I evaluated how recharge under LID BMPs varies over four time periods (historic, present, near future, and future). I also evaluated how recharge under LID BMPs respond to climate variability events (El Niño, La Niña, neutral years). Lastly, I provide the results of the sensitivity analysis of LID BMP design parameters to recharge, runoff, and evapotranspiration.

3.1. 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 2).

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 2). The trench had statistically greater recharge values than the other LID BMPs with a mean of 3458 mm and a recharge efficiency of 49% (Table 5). 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 2). Mean cumulative winter recharge was 1725 mm and recharge efficiency was 68% (Table 5 or Figure 2). 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 2). 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 with a recharge efficiency of 39-45%. 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.

3.2. 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 2). 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.

Significant increases in precipitation are reflected in runoff values rather than recharge rates under the LID BMP study sites (Figure 3 and 4). 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 3). 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 4). Overall decreases in precipitation, recharge, and runoff from near future to future can be explained by the 4.5 RCP model itself. The 4.5 GCMs predicts a global temperature to peak and stabilize within the near future time period. This can be seen in temperature and precipitation values (Figure 3 and 5). From the historic to the future time periods, runoff increases by about 200 and 1000 mm at bioswale #1 and the infiltration trench, respectively.

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 3). 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 3). 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 2). 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 3). Runoff from the 8.5 RCP models show the same statistically significant increases over time as precipitation (Figure 4). All LID BMPs show a statistically significant increase in runoff across the four time periods with the exception of present to near future (Figure 4).

Two time periods have statistically significant differences between the 4.5 and 8.5 RCP simulations: the present and future (Figure 2). During the present time period, the 8.5 RCP models predict 32 mm more rainfall, 133-221 mm more recharge, and 232-501 mm more runoff than with the 4.5 RCP models. The 8.5 RCP models also show 51 mm more precipitation, 0-196 mm more recharge, and 360-1199 mm more runoff in the future time period than the 4.5 RCP models. More emphasis on the 8.5 RCP models will be more valuable for planning and designing LID BMPs to handle the effects of climate change.

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.

3.3. 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 6). 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 6). Bioswale #2, and rain garden #2 had 20 and 21% increases (Table 6). 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 6).

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 6). 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 6). 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.

Bioswale #1 shows a more gradual decline in recharge efficiency with increased precipitation when all years are considered (Figure 7). 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.

3.4. 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 (Figure 7). 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 (Figure 7)**Error! Reference source not found.**. 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.

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 (Figure 7). 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 7). 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 7). 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 7). 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 7). Plant height had a standard deviation of 95 mm, which is two to three times more than the other parameters.

4.0 CONCLUSION

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.

5.0 REFERENCES

Allen P. Davis, Mohammad Shokouhian, Himanshu Sharma, and Christie Minami. 2006. Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal. Water Environ. Res. 78(3): 284–293.

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

City of San Bruno, California Water Service Co., Daly City, California, Hetch Hetchy Regional Water Systems, WRIME. South Westside Basin Groundwater Management Plan. 2012: 310.

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.

Davis, A.P., M. Shokouhian, H. Sharma, C. Minami, and D. Winogradoff. 2003. Water quality improvement through bioretention: Lead, copper, and zinc removal. Water Environ. Res. 75(1): 73–82.

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.

Dietz, M.E., and J.C. Clausen. 2008. Stormwater runoff and export changes with development in a traditional and low impact subdivision. J. Environ. Manage. 87(4): 560–566. doi: 10.1016/j.jenvman.2007.03.026.

Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections. 2017. https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html (accessed 20 October 2017).

Edwards, E.C., T. Harter, G.E. Fogg, B. Washburn, and H. Hamad. 2016. Assessing the effectiveness of drywells as tools for stormwater management and aquifer recharge and their groundwater contamination potential. J. Hydrol. 539: 539–553. doi: 10.1016/j.jhydrol.2016.05.059.

Endreny, T., and V. Collins. 2009. Implications of bioretention basin spatial arrangements on stormwater recharge and groundwater mounding. Ecol. Eng. 35(5): 670–677. doi: 10.1016/j.ecoleng.2008.10.017.

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: 10.1002/hyp.11177.

Ghil, M. 2002. Natural Climate Variability. Encyclopedia of Global Environmental Change, The Earth System: physical and chemical dimensions of global environmental change. Wiley, Chichester ; New York. p. 6

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.

Kuss, A.J.M., and J.J. Gurdak. 2014. Groundwater level response in U.S. principal aquifers to ENSO, NAO, PDO, and AMO. J. Hydrol. 519: 1939–1952. doi: 10.1016/j.jhydrol.2014.09.069.

Liu, R., and E. Fassman-Beck. 2018. Pore Structure and Unsaturated Hydraulic Conductivity of Engineered Media for Living Roofs and Bioretention Based on Water Retention Data. J. Hydrol. Eng. 23(3): 04017065. doi: 10.1061/(ASCE)HE.1943-5584.0001621.

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.

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

Russo, T.A., A.T. Fisher, and D.M. Winslow. 2013. Regional and local increases in storm intensity in the San Francisco Bay Area, USA, between 1890 and 2010: STORM INTENSITY IN THE SFBA. J. Geophys. Res. Atmospheres 118(8): 3392–3401. doi: 10.1002/jgrd.50225.

Schifman, L.A., D.L. Herrmann, W.D. Shuster, A. Ossola, A. Garmestani, et al. 2017. Situating Green Infrastructure in Context: A Framework for Adaptive Socio-Hydrology in Cities: SITUATING GREEN INFRASTRUCTURE. Water Resour. Res. 53(12): 10139–10154. doi: 10.1002/2017WR020926.

SFPUC. 2016. San Francisco Stormwater Management Requirements and Design Guidelines. San Francisco Public Utilities Commission, San Francisco, CA.

SFPUC. 2017. San Francisco Public Utilities Commission: What is Green Infrastructure? http://sfwater.org/index.aspx?page=667 (accessed 19 October 2017).

Soulis, K.X., J.D. Valiantzas, N. Ntoulas, G. Kargas, and P.A. Nektarios. 2017. Simulation of green roof runoff under different substrate depths and vegetation covers by coupling a simple conceptual and a physically based hydrological model. J. Environ. Manage. 200: 434–445. doi: 10.1016/j.jenvman.2017.06.012.

USEPA. 2007. Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices. United States Environmental Protection Agency.

6.0 FIGURES

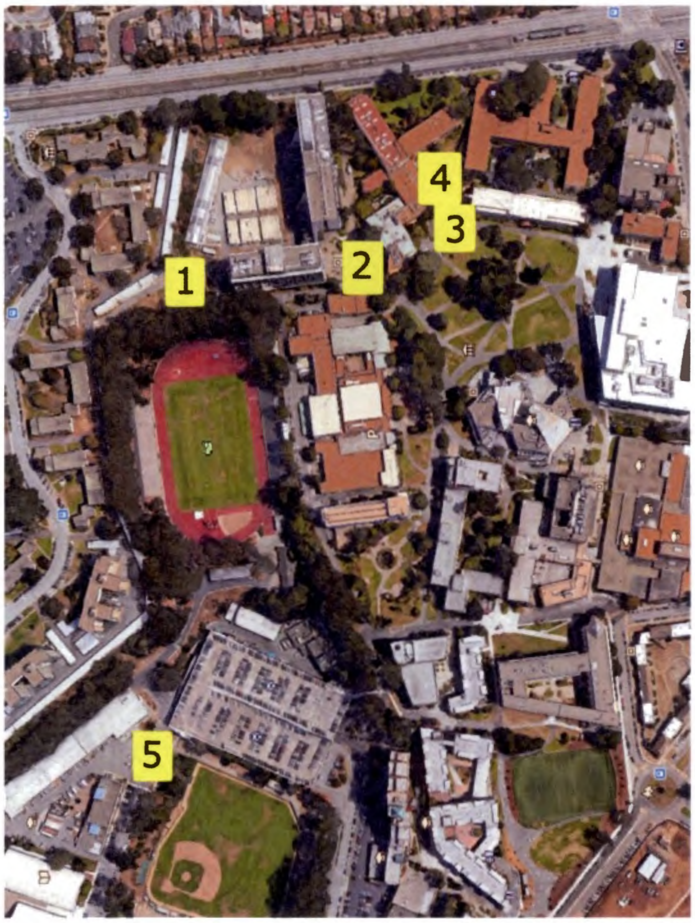

Figure 1. Location of low impact development (LID) best management practices (BMPs) at the San Francisco State University LID Research Network.

1. Infiltration trench
2. Bioswale #1
3. Rain garden #2
4. Bioswale #2
5. Rain garden #1

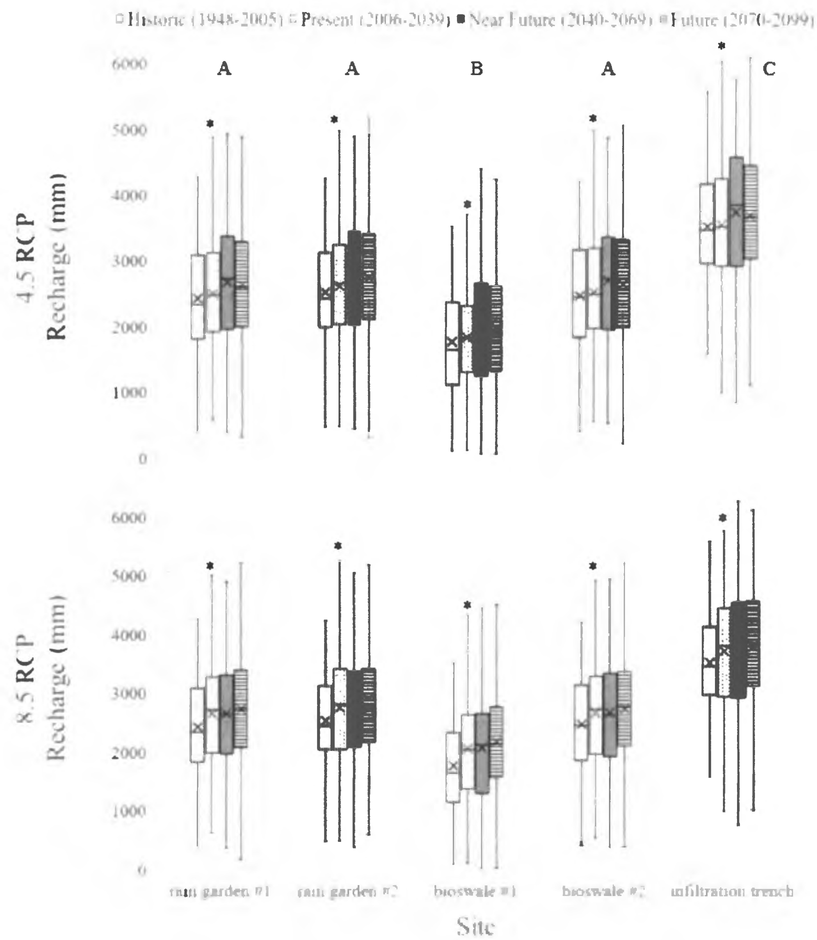

Figure 2. Cumulative annual winter recharge under low impact development (LID) best management practice (BMP) study sites by time period. Results from Steele-Dwass tests are shown with letters denoting statistical differences in recharge from historic, and asterisks denoting differences between 4.5 and corresponding 8.5 representative concentration pathway (RCP) datasets.

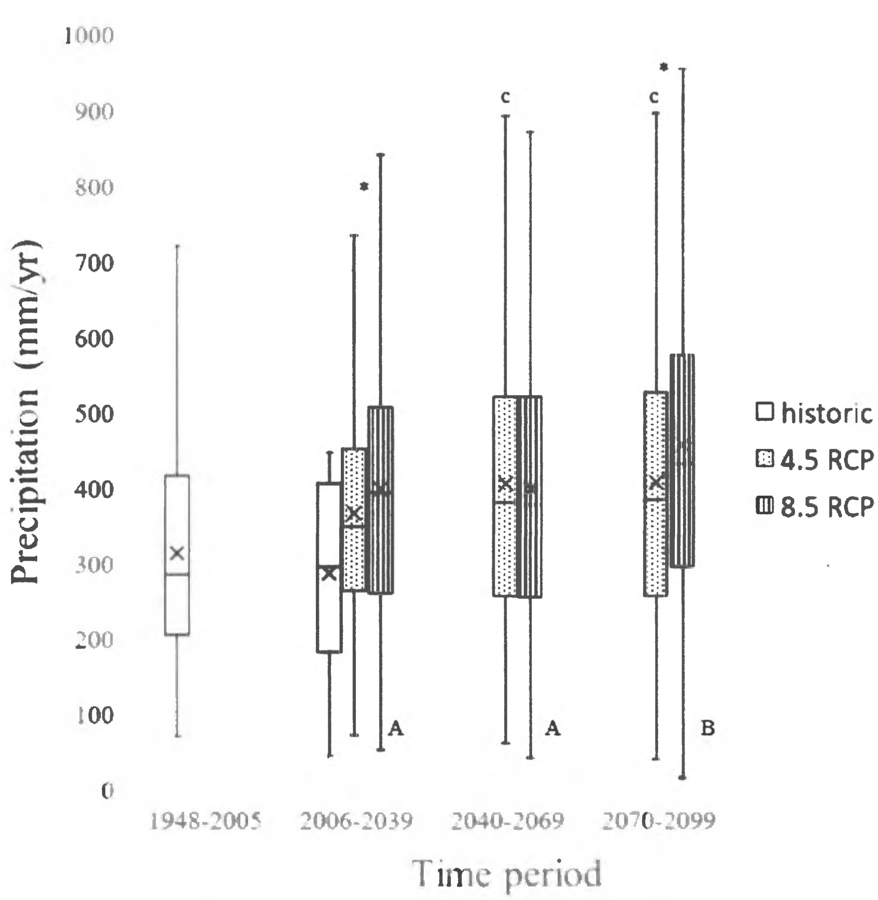

Figure 3. Winter precipitation over four time periods: historic (1948-2005), present (2006-2039), near future (2040-2069), and future (2070-2099). Results from Steele-Dwass tests are shown with letters denoting statistical differences in precipitation from historic, and asterisks denoting differences between 4.5 and corresponding 8.5 representative concentration pathway (RCP) datasets.

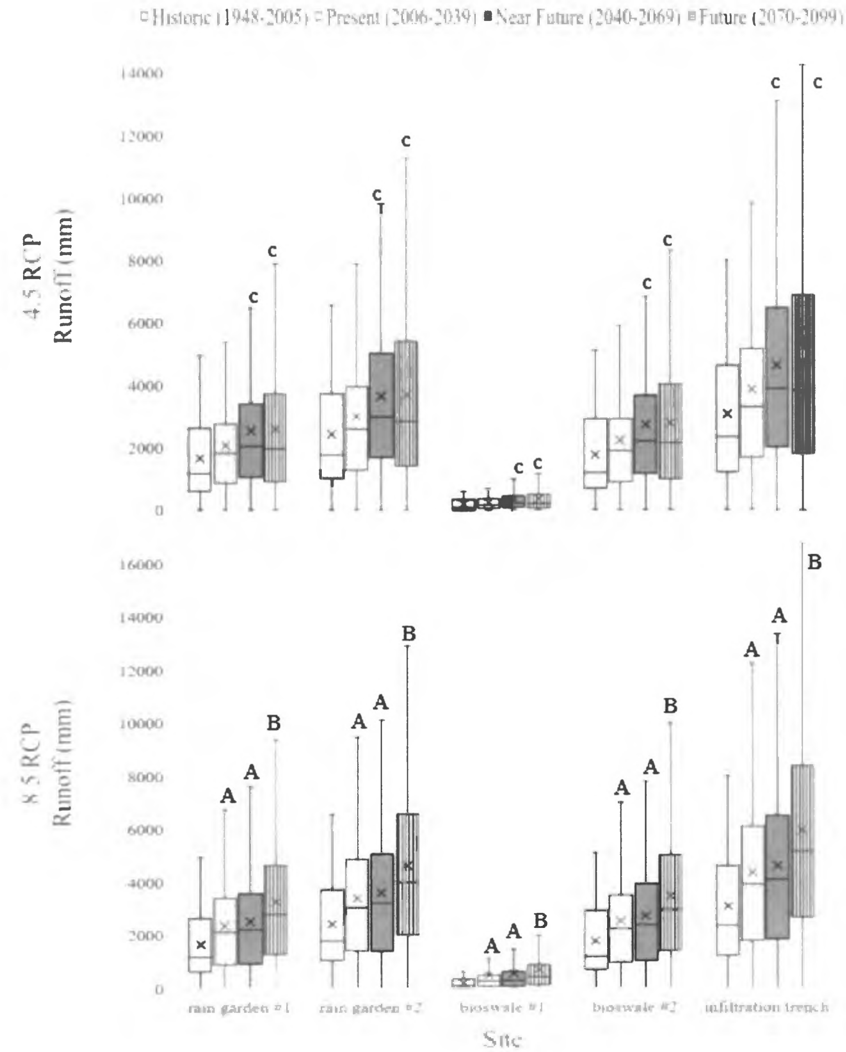

Figure 4. Runoff from low impact development (LID) best management practice (BMP) study sites over four time periods: historic (1948-2005), present (2006-2039), near future (2040-2069), and future (2070-2099). Results from Steele-Dwass tests are shown with letters denoting statistical differences in runoff from historic, and asterisks denoting differences between 4.5 and corresponding 8.5 representative concentration pathway (RCP) datasets.

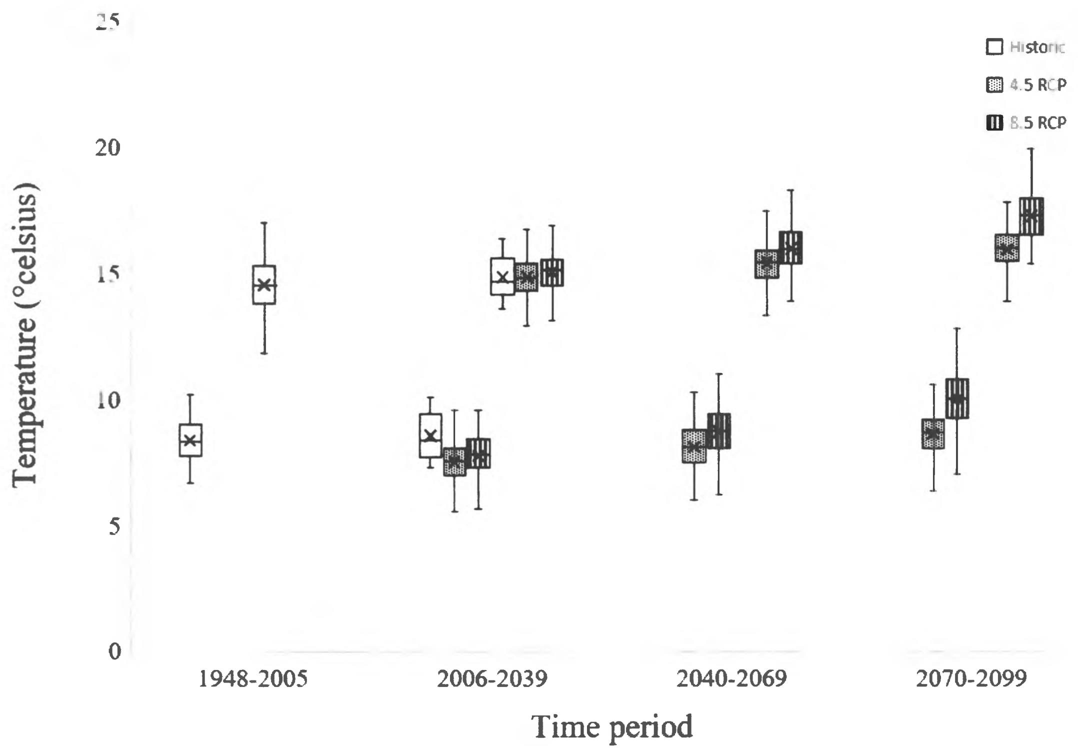

Figure 5. Temperature by time period with observed historic, and future projections from global climate models (GCMs) with 4.5 and 8.5 representative concentration pathways (RCPs). Each dataset has two boxplots per time period for temperature maximums and minimums. Lower values are temperature minimums and higher values are temperature maximums.

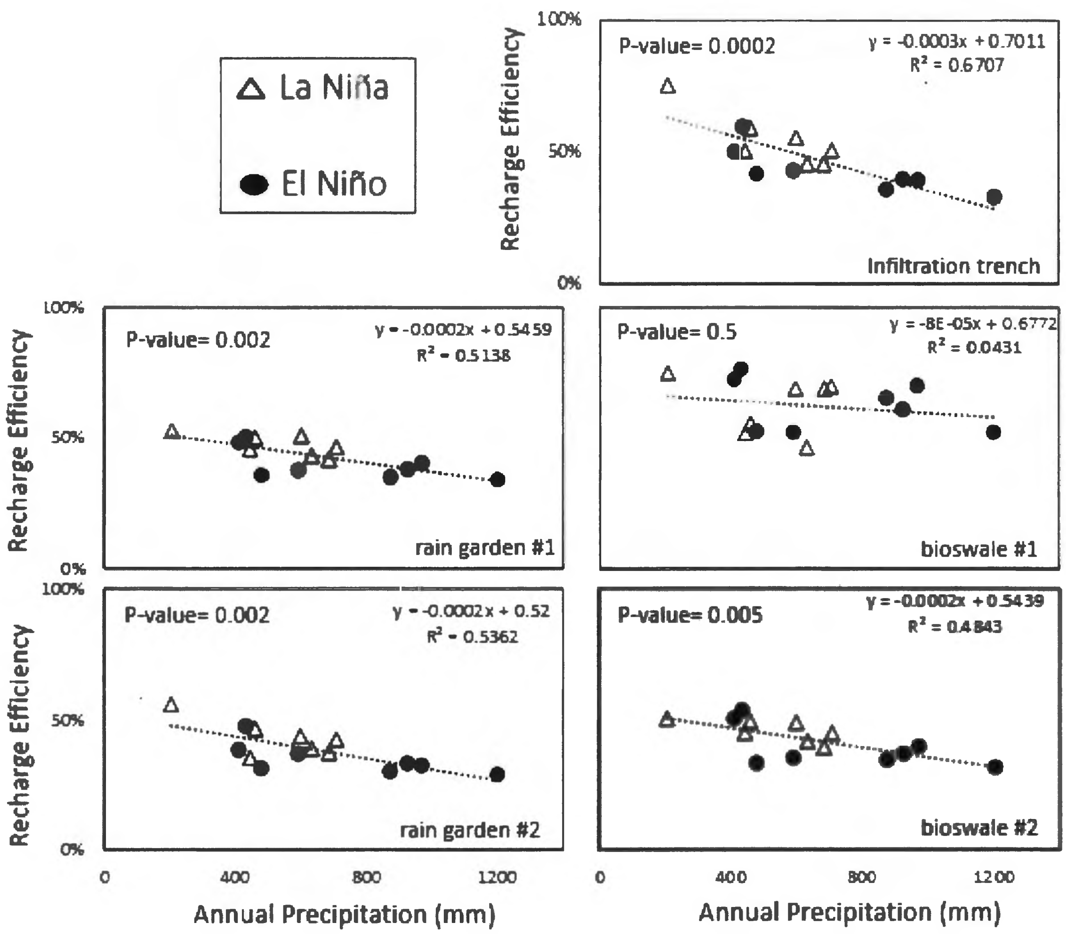

Figure 6. Recharge efficiency of low impact development (LID) best management practices (BMPs) study sites during El Niño and La Niña years. Triangles are La Niña years and circles are El Niño years.

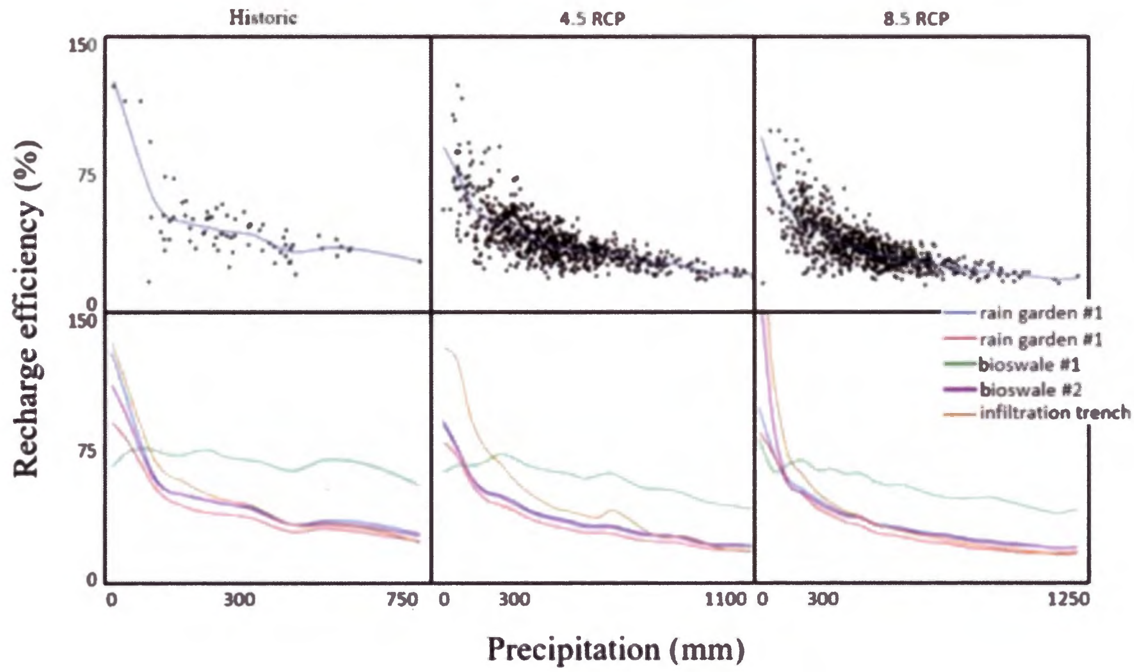

Figure 7. Recharge efficiency of low impact development (LID) best management practice (BMP) study sites versus precipitaiton. Top row is rain garden #1 with points and kernel smoother. Bottom row is kernal smoother without points for the five LID BMP study sites.

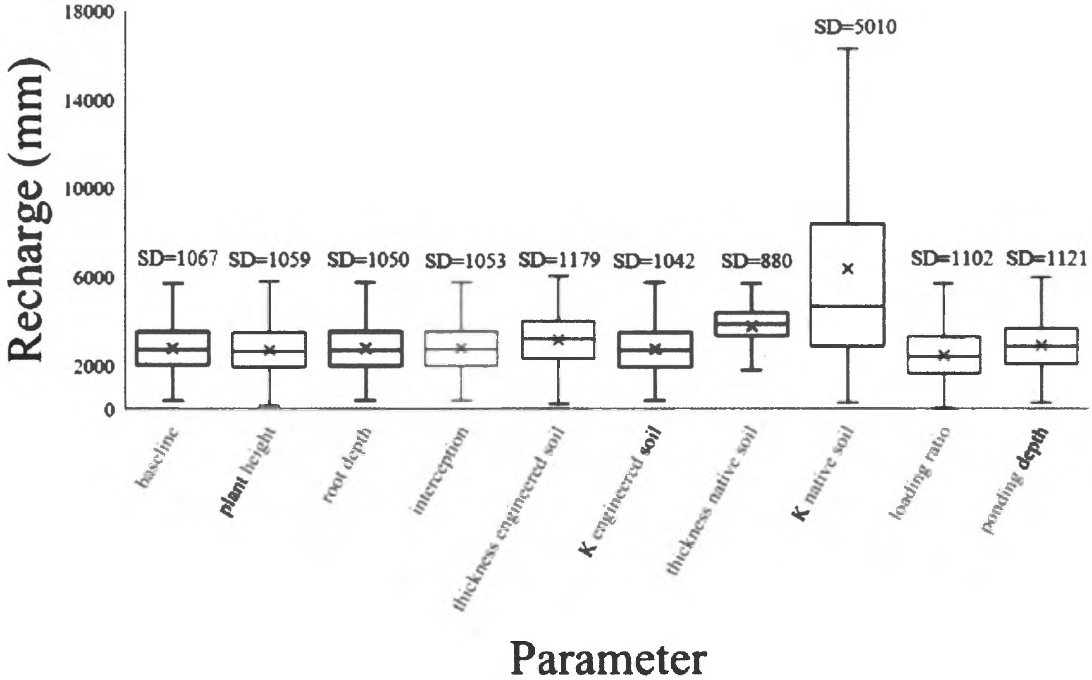

Figure 8. Sensitivity analysis of recharge to low impact development (LID) best management practice (BMP) design parameters. Parameters were assessed under historical conditions and future conditions predicted by the CanESM2.1 global climate model (GCM) a representative concertation pathway (RCP) of 8.5. Standard deviation (SD) is in mm.

7.0 TABLES

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

Table 2. Soil properties of engineered soils and native soils used as HYDRUS-1D input [θ_r, residual volumetric water content; θ_s, saturated volumetric water content; α and n, parameters in the soil water retention function; K_s, saturated hydraulic conductivity; and l, tortuosity parameter in the conductivity function].

Material	**θ_r (m^3 m^{-3})**	**θ_s (m^3 m^{-3})**	**α (mm^{-1})**	**n**	**K_s (mm day^{-1})**	**l**
Engineered soil (infiltration trench)	0.0	0.51	0.011	1.7	840,000	0.5
Engineered soil (rain garden/bioswale)	0.01	0.511	0.0032	1.3	11,232	0.5
Native soil layer 1	0.06	0.4	0.00266	1.9055	1700	0.5
Native soil layer 2	0.5	0.34	0.00286	1.7861	730	0.5
Native soil layer 3	0.06	0.32	0.00266	1.2904	70	0.5

Table 3. List of El Niño, La Niña, and neutral years and subcategorized by strength. Weak is ±0.5-0.9 sea surface temperature (SST) anomaly, moderate is ±1.0-1.4, strong is ±1.5-1.9, and very strong is ≥± 2.0.

El Niño Years				La Niña Years		
Weak	Moderate	Strong	Very strong	Weak	Moderate	Strong
1952-53	1951-52	1957-58	1982-83	1954-55	1955-56	1973-74
1953-54	1963-64	1965-66	1997-98	1964-65	1970-71	1975-76
1958-59	1968-69	1972-73	2015-16	1971-72	1995-96	1988-89
1969-70	1986-87	1987-88		1974-75	2011-12	1998-99
1976-77	1994-95	1991-92		1983-84		1999-00
1977-78	2002-03			1984-85		2007-08
1979-80	2009-10			2000-01		2010-11
2004-05				2005-06		
2006-07				2008-09		
2014-15				2016-17		

Neutral Years			
1948-49	1961-62	1981-82	1996-97
1949-50	1962-63	1985-86	2001-02
1950-51	1966-67	1989-90	2003-04
1956-57	1967-68	1990-91	2012-13
1959-60	1978-79	1992-93	2013-14
1960-61	1980-81	1993-94	

Table 4. Low impact development (LID) best management practices (BMPs) design parameters tested for sensitivity analysis. Asterisks denote values of baseline case.

Parameter	**Value 1**	**Value 2**	**Value 3**	**Value 4**	**Value 5**
Native Soil K (*mm/dy*)	70 (sandy clay loam)*	120.4 (loam)	382.5 (sandy loam)	1051 (loamy sand)	3502 (loamy sand)
Thickness of native soil (mm)	2000*	12000	22000	32000	42000
Engineered soil K (*mm/dy*)	3502	7803	9517	11,232	14,630*
Thickness of engineered soil layer (mm)	500	1000*	1500	2000	2500
Loading ratio (%)	2	4*	6	8	10
Ponding depth (*mm*)	0	152*	304.8	457.2	609.6
Interception (*mm*)	2*	3	4	5	6
Plant height (*mm*)	152*	228	304	380	456
Plant root depth (*mm*)	0	152*	304	457	600

Table 5. Mean cumulative annual winter recharge, recharge volume, runoff, and evapotranspiration for low impact development (LID) best management practice (BMP) study sites. Values are based models run with historic observed climate data.

Site	Recharge (mm)	Recharge Volume (acre feet)	Runoff (mm)	Evapotranspiration (mm)
Rain garden #1	2382	3.48×10^{-2}	1661	168
Rain garden #2	2481	4.22×10^{-2}	2423	171
Bioswale #1	1725	1.40×10^{-2}	199	171
Bioswale #2	2431	2.56×10^{-2}	1774	185
Infiltration trench	3458	3.08×10^{-2}	3086	26

Table 6. 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%

Table 7. 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