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Stormwater to Groundwater: How California can increase groundwater storage and build climate resilience.

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This Master's Project

Stormwater to Groundwater: How California can increase groundwater storage and build climate resilience.

By

Emily Perales

is submitted in partial fulfillment of the requirements
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Your Name Date

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List of Acronyms

BMP	Best Management Practice
CASEGEM	California Statewide Groundwater Elevation Monitoring
CWA	Clean Water Act
DWR	California Department of Water Resources
EAR	Enhanced Aquifer Recharge
EPA	United State Environmental Protection Agency
FY	Fiscal Year
GI	Green Infrastructure
GIS	Geospatial Information System
GSA	Groundwater Sustainability Agency
LACWD	Los Angeles County Waterworks District
MAF	Million Acre Feet
NBI	Nature Based Infrastructure
NLCD	National Land Cover Database
NPDES	National Pollutant Discharge Elimination System
NRC	National Resource Council
O&M	Operations and Management
SFPUC	San Francisco Public Utility Commission
SGMA	Sustainable Groundwater Management Act
SMO	Stormwater Management Ordinance
SMR	Stormwater Management Requirements and Design Guidelines
SSIP	Sewer System Improvement Program
SWC	National Stormwater Calculator
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USRCS	U.S. Resource Conservation Services

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Acknowledgements

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Thank you to all my friends and family who supported me through this process. Thank you for the countless proofreads and for letting me ramble on about my thesis. Thank you for giving me the space and time I needed to complete this project.

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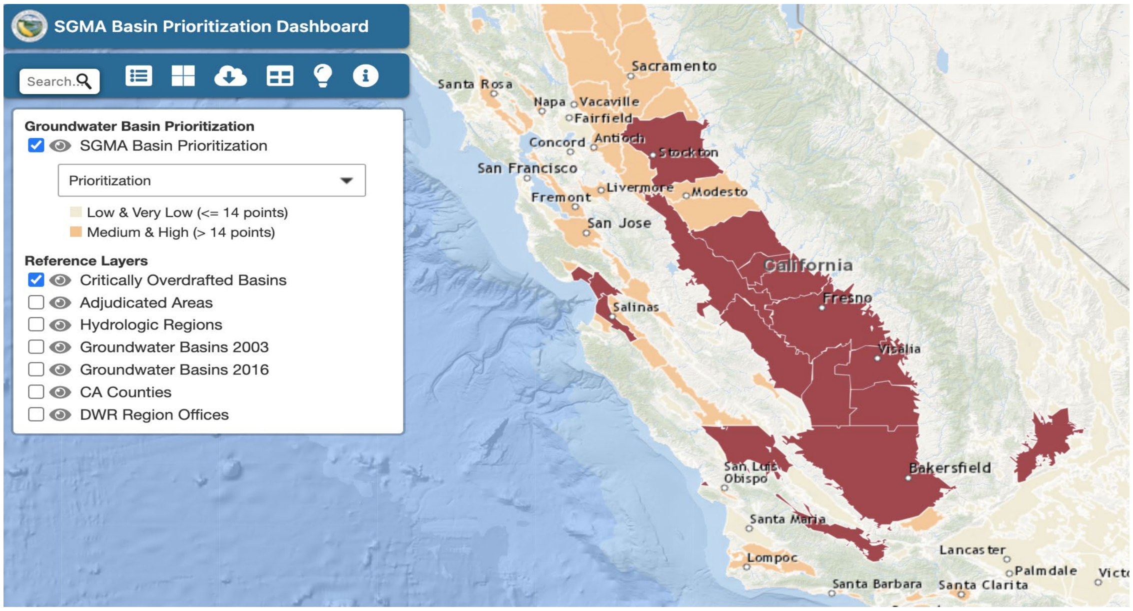
Abstract

California is predicted to have more intense and frequent changes in weather patterns within the next 50 years. Historical and current groundwater use for residential and agricultural use is unsustainable and is creating significant deficits in groundwater aquifers throughout the state. To better adapt to potential damages caused by atmospheric rivers (e.g. flooding), better stormwater management and capture could increase California's Climate adaptability. This study is focused on the means and methods to capture stormwater and increase groundwater recharge. Nature-based infrastructure (NBI), or Green Infrastructure (GI), has been used in urban areas throughout the country to mitigate harmful stormwater effects by replicating the natural hydrological cycle for groundwater recharge. This study analyzes known NBI methods to best apply them to California's unique soils. A suitability analysis was conducted to identify the "Most Suitable" areas throughout the state based on percent of impervious surfaces, hydrological soil type and known locations of aquifers. A cost analysis and policy analysis of NBI implementation was also conducted. A GIS analysis revealed roughly 5,000 square miles of groundwater potential areas were identified for NBI implementation. Further adaptation of the GIS model could target critically low aquifers. Six NBI methods were identified as means to retain and filter stormwater for groundwater recharge. The noted NBI methods were also found to be a substantially cheaper alternative to standard stormwater management utilizing gray infrastructure. This study also found a varying degree of municipal data regarding NBI/GI. Of the 3 California cities analyzed, each city heavily invested in more expensive gray infrastructure projects over NBI/GI projects in FY22. The state of California would greatly benefit from adapting the model created for this project (or something similar) to better manage urban stormwater and recharge critically low groundwater aquifers. Doing so could considerably increase the state's groundwater storage and sustain California's water needs in dry/drought years.

Introduction and Background

According to the California Department of Water Resources (DWR), groundwater makes up 36% of the state's water supply (DWR. August, 2022). During dry and drought years, groundwater can contribute up to 48% of the state's supply (DWR, 2022). In Southern California, water consumption often outpaces the amount of water replenished by imported and groundwater sources (Parker, et al., 2022). As climate change plays a dominant role in our environment, the California Natural Resources Control Board continues to invest more money in sustaining California's water supply by expanding the state's water portfolio (DWR. August, 2022). Since one third to nearly half of California's annual water supply comes from groundwater, it is imperative that the state take steps to increase groundwater recharge from stormwater capture in order to sustain aquifer recharge. Several climate change models predict drier conditions as well as changes in precipitation patterns (Cayan, et al., 2007). While some models show that overall precipitation levels may not change in the next 30 years (Cayan, et al., 2007), annual rainy seasons may shorten in time thus compacting rain/snowfall into shorter and more intense storms. Urban stormwater infrastructure needs robust adaptation to compensate for increasing water flow after major rain events. More importantly, newer infrastructure needs to be implemented with the goal of capturing stormwater to replenish groundwater storage to keep up with water demand during dry years.

Groundwater basins in California are underground reservoirs that have the potential to store more water for human and ecological use in dry years. There are over 500 identified water basins within that state that have the potential to hold 8-12 times more water than that of current surface water capacity throughout the state (DWR, 2023). In 2014, the California Sustainable Groundwater Management Act (SGMA) was passed, establishing a framework for groundwater sustainability agencies (GSAs) to plan and implement best management practices (BMPs) for medium to high priority basins that have critically low levels of water. The GSAs plan to avoid undesirable results, such as overdraft and land subsidence. Since passing SGMA, California has been able to collect data regarding the water levels in various basins within the state; the Water Data Library and the California Statewide Groundwater Elevation Monitoring (CASGEM) is the database that houses information on basin characteristics, conditions, and use of groundwater as well as current critical overdraft levels of California’s groundwater (Bulletin 118, 2020, Figure 1). Analysis of the above metrics are critical in helping California state and local officials develop sustainable solutions and better BMPs for maintaining the groundwater supply.



Groundwater Basin Prioritization
☑ SGMA Basin Prioritization
Prioritization
Low & Very Low (<= 14 points)
Medium & High (> 14 points)

Reference Layers
☑ Critically Overdrafted Basins
☐ Adjudicated Areas
☐ Hydrologic Regions
☐ Groundwater Basins 2003
☐ Groundwater Basins 2016
☐ CA Counties
☐ DWR Region Offices

Figure 1: A snapshot of the CASGEM aquifer prioritization tool. The areas in red are the critically over drafted aquifers. The areas in orange have been identified as basins of Medium to High Priority based on current groundwater levels. Much of the California Coastal Basin Aquifers identified earlier are Medium to High Priority with some sections of the basin at critically over drafted levels.

Climate and Water Concerns

California has a typical Mediterranean climate characterized by hot, dry summers and cool, wet winters. As such, floods and droughts are not new or unusual occurrences. However, climate and atmospheric modeling predict the advent of “precipitation whiplash” where there is a rapid transition between wet and dry conditions (Swain, et al., 2018). The rapid transition intensifies stream flow and flood-damage potential. At least half the state is predicted to have a 50% relative change in dry seasons and wet seasons within our lifetime. A compounding factor is the extended dry periods between precipitation events; longer periods between events means both a decrease in snow accumulation and decrease in soil and plant saturation (le Roux, et al., 2013). With the snowpack decreasing in California, it can no longer be a reliable source of stored water during the dry seasons (Cayan, et at., 2008). While surface water sources, such as dams and reservoirs, have been a dominant means of water storage, California’s aquifers are an underutilized natural means of water storage. Water scarcity from prolonged drought conditions could be mitigated by capturing stormwater from intensifying storms and storing it in existing underground reservoirs.

Hydrological Cycle

The hydrological cycle is one of the key elements that helps maintain the global climate. Among other things, the cyclical flow of water content in the atmosphere regulates global temperatures and salinity levels in our oceans (NRC, 2012). Generally speaking, water evaporates from land and oceans, condenses in the atmosphere as clouds and then precipitates, as seen in Figure 1. On permeable surfaces, water will infiltrate into soils and recharge subsurface aquifers. Groundwater from aquifers contribute to soil saturation and, at mass capacity, will release water to the surface via natural springs and rivers (also known as baseline flow). The resulting delayed release of water prolongs the availability of water within an ecosystem, providing fresh water sources to human and ecological life over a longer period of time. However, anthropogenic changes to the earth's surface have resulted in more impermeable surfaces or land cover, resulting in a decrease of groundwater recharge.

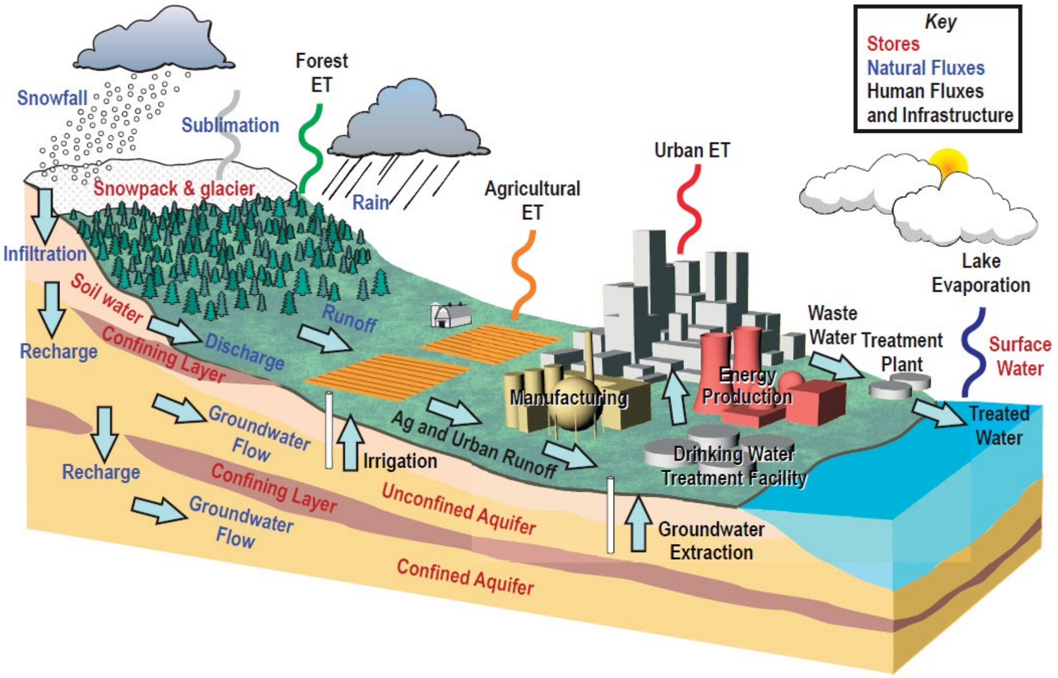


Figure 2: The hydrological cycle or process of water moving through the atmosphere, condensing, precipitating, evaporating (also known as evapotranspiration) and condensing again. Precipitation as rain or snow fall releases freshwater that can infiltrate into groundwater or run-off and discharge into surface water bodies such as rivers, lakes, or oceans. Water is then extracted from groundwater for human use. Source: National Academies of Science, 2018.

Incorporating different land cover types and breaking up continuous impervious surfaces in developed/urbanized areas can restore the natural hydrological cycle and replenish groundwater storage. Stormwater is generated by water run-off from precipitation and snowmelt. The run-off flows over developed land cover and impervious surfaces (e.g., farmland, concrete pavement, etc.) collecting pollutants (such as oils, chemicals, and sediments), 23 discharging them into waterways such as rivers, lakes, and oceans (EPA, 2022). Impermeable surfaces like concrete parking lots, rooftops, roads, and highways—predominant structures in urban landscapes—instead collect water on surfaces and increase the velocity of stormwater as it passes over hard surfaces and into waterways (NLCD, 2023). Continuous impervious surfaces do not allow stormwater run-off to penetrate soil and infiltrate into the groundwater table thus disrupting baseline flow (NCLD, 2021). Impervious cover within a watershed has a 55% run-off rate versus a 10% run-off rate over natural land cover (FISRWG, 1998). Increased water velocity within waterways can damage infrastructure and increase flood risks in urban areas (especially those in floodplains). According to DWR, increasing stormwater capture has the potential to add .25-1 million acre feet (MAF) or 81.5-326 billion gallons of water to groundwater by 2030 (California's Water Supply Strategy, 2022). For scale, .25 MAF is roughly 6 years of water supply for San Francisco residents. Capturing more stormwater will require more intentional infrastructure projects. An increase of stormwater management techniques in modern infrastructure could increase groundwater recharge and reduce risks associated with run-off. Leveraging stormwater throughout the state has great potential to augment groundwater storage in anticipation of state needs during dry years.

Groundwater Overdraft and Land subsidence

Land subsidence is the compaction of subsurface sediments in the absence of groundwater pressure–a measured result of over drafting groundwater aquifers (Faunt, et al., 2016). Without sufficient groundwater to recharge and maintain water pressure within an aquifer, land will continue to subside (i.e. sink) until the aquifer ultimately collapses from compaction thereby rendering it unable to hold water in the future. Excessive groundwater usage (over drafting) has been an ongoing concern in California; California's Central Valley has utilized large amounts of groundwater to maintain irrigation demands for agricultural production since the 1920's (Faunt, 2009), with more excessive drawdowns and over drafting often occurring during drought years. As such, hydrologists have studied ways to mitigate land subsidence and maintain aquifers in the

Central Valley utilizing tools like CASGEM. The intensifying dry conditions and water supply shortages throughout the state generate concern for increased need of groundwater supply. While water usage continues to be an issue throughout the state, intentional NBI implementation could help recharge the water supply and maintain groundwater aquifers for later ecological and human use.

Current Stormwater Practices

Urban stormwater runoff and capture is a growing field of study as emerging research is finding more degraded waterways from stormwater pollution (Sadeghi, et al., 2019). In the past century, stormwater infrastructure was designed to quickly remove stormwater from urban areas, routing flows toward waterways and eliminating flood risk (Garrison, et al., 2011; Gaines, 2016). The historical methods, also known as gray infrastructure, consist of constructed levees, cement channels, and tunnels that diverted rainwater to waterways with little to no treatment (Rauscher, et al., 2010). The man-made transformation of streams and rivers throughout urban areas, like the Los Angeles River, are effective storm water removal methods. However, with increasing drought conditions in California and changing precipitation patterns, it is more crucial that the stormwater be captured rather than removed (California State Water Board, 2022). During the atmospheric river events from late 2022 and early 2023, the Bureau of Reclamation estimated that nearly 80% of the stormwater in Los Angeles drained into the Pacific Ocean. That is an estimated 5-10 billion gallons of much needed water that could have been added to the aquifers in Los Angeles County (Smith, 2023). Constructed waterways and controlled stormwater/sewage drainage pipes disrupt the hydrological process by disrupting the downward mobility of water (see Figure 3). Redesigning urban landscapes to allow for more stormwater infiltration could restore that process and help rebuild the water table.

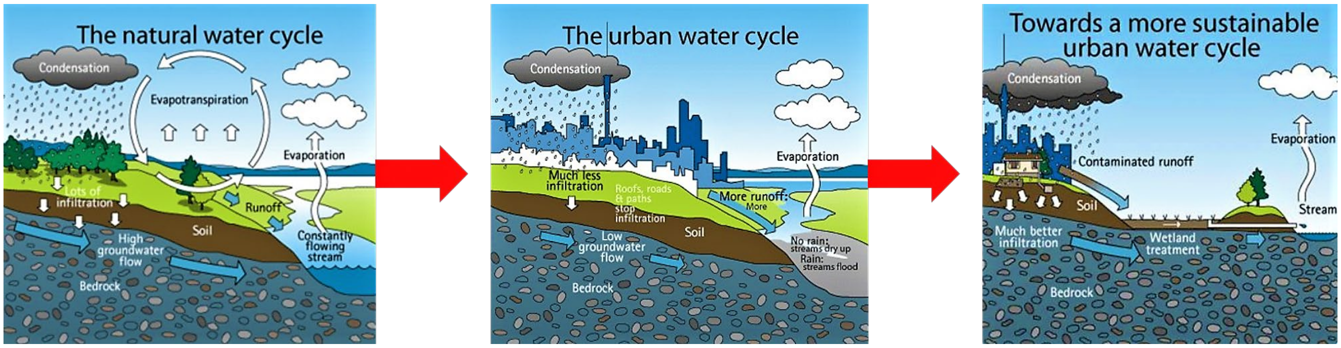


Figure 3: The panel on the left is the hydrological cycle where precipitation can infiltrate into groundwater or streams, evaporate, condense, and precipitate again. The middle panel shows the disruption of urban and impervious landscapes where there is less infiltration and stream flow and higher stormwater run-off. The right panel demonstrates integrated filtration techniques and infrastructure (such as constructed wetlands) that manage run-off and encourage infiltration. Source: Auckland Council (2010).

Nature Based Infrastructure

Nature-Based Solutions (NBS) are an emerging methodology for better stormwater management and treatment (Kabisch, et al., 2016). Implementing stormwater treatment technologies require careful considerations and BMPs to decrease contamination of surface and groundwater (Brumley, et al., 2018). Enhanced Aquifer Recharge (EAR) is one such practice that has shown to be a cost-effective means to increase groundwater supply and purify water. EAR is an umbrella term that incorporates both anthropogenic and natural methods, including but not limited to injection wells, dry wells and trenches, infiltration basins, and permeable pavements (EPA, 2021). Similarly, several nature-based infrastructure (NBI) methods have been developed and designed based on the naturally occurring hydrological and biological cycles. NBI, also commonly referred to as Green Infrastructure or GI, incorporates built and natural processes for capturing and treating stormwater. Capturing water with NBI allows for both infiltration into the subsurface soils and uptake by plants and microbiology (McMahon, 2000). Stormwater capture with NBI, while studied in-depth in controlled settings, is still in the early days of mass utilization in modern infrastructure (Hatt, et al., 2009). The recent rain events of Winter 2023 in the state of California demonstrated both how current gray infrastructure has fallen short of capturing stormwater and ways in which small-scale NBI has successfully restored hydrological processes.

Effective application of NBI requires special considerations for location and method of NBI in relation to soil type. Non-porous subsurface soil compositions like rock or clay would nullify the infrastructure while well-drained, grainy soils could maximize infiltration (USDA, 2022). National data from the U.S. Geological Survey and Geographic Information System (GIS) mapping can identify "groundwater potential zones" or areas where groundwater recharge is most viable (Ashwini, et al., 2023). Geological data is not only important for understanding infiltration but also necessary to monitor groundwater quality and potential geochemical reactions in aquifers (McQuiggan et al., 2022). While California has several geological mapping tools and accompanying aquifer data, there needs to be a comprehensive tool for the purpose of groundwater recharge. Initial literature review indicates that NBI is a useful means of stormwater retention, but there is little information about groundwater quality of aquifers in areas that have implemented NBI. Furthermore, there was a lack of discussion in the literature surrounding NBI implementation on a regional scale for greater aquifer recharge. Further analysis for identifying the areas with high potential for groundwater recharge in urban areas could bolster stormwater infiltration techniques at a potentially lower cost.

Permitting and Costs

Under the Clean Water Act (CWA), stormwater is considered a non-point source and is generally difficult to regulate under the National Pollutant Discharge Elimination System (NPDES). However, NPDES permits regulate municipal wastewater treatment systems and stormwater quality before it is returned to waterways. The cost of the treatment system can vary by the size of municipality, the treatment technology(ies) required for treatment and cost of labor. Low-end implementation costs (a.k.a. capital costs) can range from \$2-\$10 million per project (Los Angeles County Waterworks District, 2022). These calculations do not include regular operation and management (O&M) costs, treatment, conveyance, nor the cost of acquiring NPDES permits per regulatory requirements (23 CCR 220). For example, the Los Angeles County Waterworks District (LACWD) estimates that planned retrofits and updates to the Los Angeles River will likely cost upward of \$10 billion (LACWD, 2022). Other (i.e. NBI) stormwater treatment methods are more cost-effective, can filter stormwater naturally with fewer O&M requirements, and can meet NPDES regulations (EPA, 2007). Initial research shows that there are few comprehensive financial tools for municipalities and private land developers to plan funding allocations for NBI/GI BMPs. More analysis of NBI capital costs and current NBI/GI spending is necessary to understand where there are opportunities for California's urban centers to expand NBI/GI implementation and allocate the necessary funds.

Scope of Study

The main focus of this study will be on urban stormwater practices in densely populated and highly impervious areas in California. This paper infers that areas with more dense populations will likely have more impervious surfaces that characterize urban spaces. For the purposes of this study, we focus on California's top 20 most densely populated counties. The counties with the highest densities account for 79% of California's population and 20% of the total land cover (Census Bureau, 2020), as noted in Table 1 and seen in Figure 4 (below). The counties with the most people could also be an indicator of counties with the greatest water usage (outside of agricultural lands). It should also be noted that a large portion of the state is open agriculture land with more opportunities for larger water collection and storage projects. However, California has a contentious history with water rights for farmers and the agriculture industry (Faunt, 2009). While the use of groundwater for agriculture plays a large role in the state's water budget, addressing those issues fall outside the scope of this work and will only be discussed in brief. This study will also focus on 3 major urban centers within the most populated counties: Sacramento, San Francisco, and Los Angeles. This paper posits that aquifer recharge under urban areas can be used to supplement drinking water and decrease water demands and drawdowns from rural/alpine sources. This study will focus on studying geological factors for infiltration, the best nature-based solutions for infiltration and city centers in California that may be utilizing nature-based solutions already.

Table 1: Comparison of California's top 20 most densely populated counties (population per mi^2) versus California's 20 most populated counties, overall. Many highly populated counties included protected spaces like the Mojave Desert, where stormwater infrastructure cannot be implemented (See Figure 4).

	CA State Total (58 counties)	20 most populated counties	% of CA total population	20 most densely populated	% of CA total pop
Population (2020)	39,538,223	35,065,015	88.69%	31,336,469	79.26%
Mean population density	707.48	1,878.76	265.56%	1,934.475	273.43%
Area (mi^2)	158,036.9	69,766.05	44.15%	32,181.84	20.36%

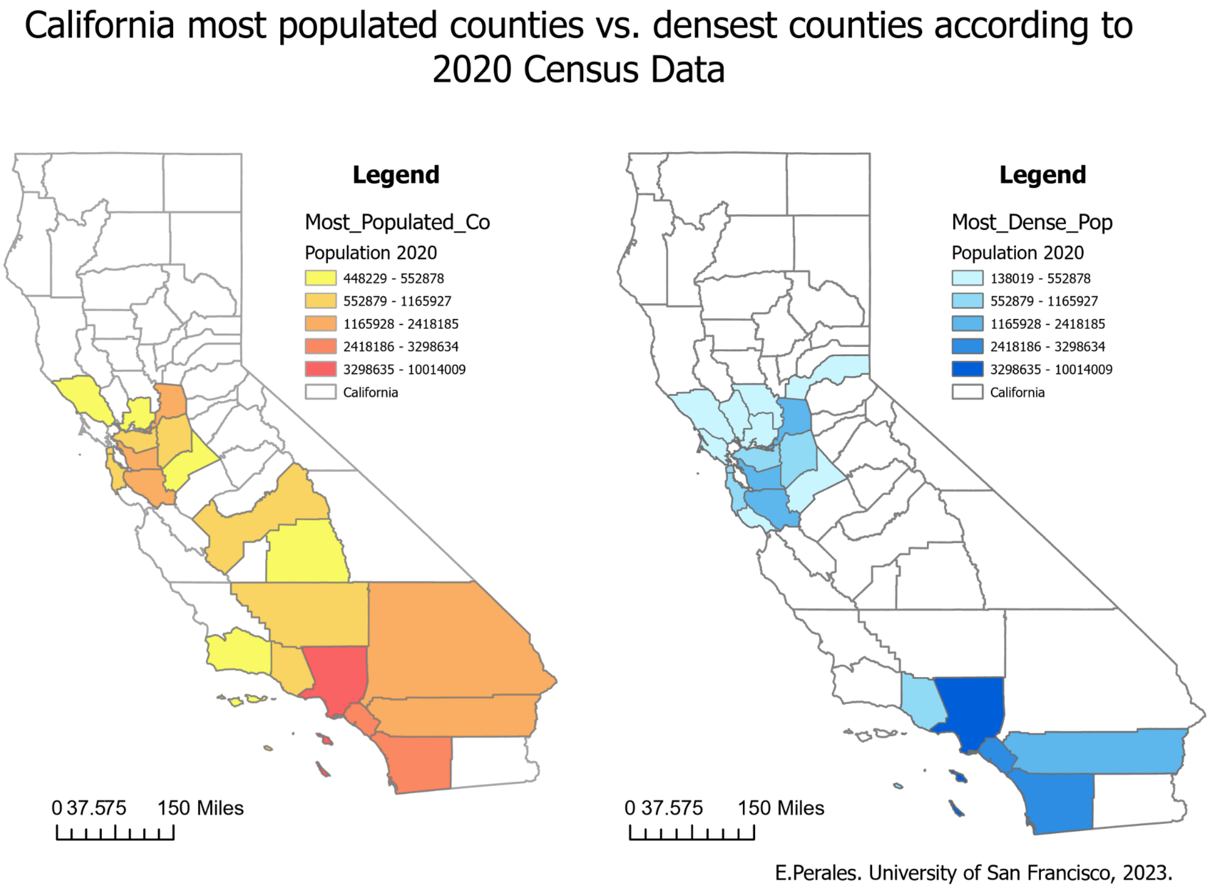


Figure 4: Comparison of California's 20 most populated counties (left) versus California's 20 most densely populated counties (right). The densest counties are in the darker shades and the less dense counties are in the lighter shades. This study will focus on the densest counties that will likely have more development and impervious areas. The areas with the desist populated counties include Los Angeles, San Diego, Alameda, and Santa Clara counties.

Objectives

To build resilience to drought, clean water scarcity, and flooding due to climate change, the main objective of this study is to understand which NBI methods will decrease stormwater pollution in waterways while simultaneously increasing stormwater infiltration after major rain events in California. The goal is to understand where California can tactically apply NBI methods to meet the groundwater retention goals set forth in the 2022 Water Supply Strategy. To meet these objectives the following sections aims to answer the following questions:

1. Are there areas in California where aquifer recharge can be maximized (where are California's "groundwater potential zones")?

2. Which NBI methods could best be applied within California municipalities to purify and store more water and what are their associated costs?
3. What is the current state of NBI implementation in California's urban areas? Where are opportunities for increasing NBI implementation?

This study will also look for additional metrics regarding groundwater quality in relation to NBI and the quantity of groundwater recharge possible from NBI methods. Additionally, this study aims to analyze current costs associated with implementation of NBI methods compared to conventional stormwater infrastructure (gray infrastructure) and make recommendations as to how California can implement future stormwater projects.

Methods

To answer the questions listed above, this paper utilizes three types of analysis. First, a GIS analysis in ArcGIS Pro was conducted to identify "groundwater potential zones" in California. Second, a literature review of the SCOPUS database revealed studies of 6 primary NBI methods. Last, policy and cost analysis of municipal stormwater treatment plans were evaluated for 3 major cities in California; Los Angeles, San Francisco, and Sacramento. The 3 cities were selected based on their varying population size, location to waterways, and varying stormwater/wastewater infrastructure. By comparing the costs of implementation, practical recommendations for NBI implementation can be made for other municipalities in California. Furthermore, understanding current NBI activities in cities throughout the state could contribute to state-wide aquifer recharge and future water budgeting for dry/drought years.

Identifying groundwater potential zones

Using GIS, a suitability analysis was conducted utilizing California-focused datasets, including aquifer data, land cover data, and soil composition data. Compiling these data, this study will perform a weighted suitability analysis to find which aquifers in California have the highest percentage of developed land cover, the areas with soil composition are better suited for water infiltration, and any potential overlap and/or ideal areas for implementing NBI.

The first data layer is the U.S. Geological Survey (USGS) Aquifer layer which shows aquifers throughout the continental United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands from the USGS's Ground Water Atlas of the United States. The layer delineates the aerial extent of the principal aquifers of the US but does not show the depth of each aquifer. Per the DWR water supply strategy and CASGEM, we can infer that most aquifers are in need of recharge so their geological location, rather than their depth/capacity, will suffice for our purposes. For this study, we focus on the 141 major aquifers in California. The second data layer is from the National Land Cover Database (NLCD). NLCD compiled a raster data layer of the impervious surfaces that characterize urban areas as a percentage of developed surface (per 30-meter pixel) in the U.S. The land cover layer visualizes cumulative data from 2001-2019. As urban areas have increased with population size so have the percent impervious surface area–causing the high stormwater volume. A third layer from the Natural Resources Conservation Service (NRCS) displays hydrologic soil grouping which provides an index of the rate that water infiltrates a soil. The soil groupings can be utilized in rainfall-runoff models to predict potential stream flow (United States Department of Agriculture, Technical Release–55). All three layers were clipped by a California boundary and enhanced to include the U.S. Census Bureau to focus on densely populated areas as another measure of urbanization as well as potential water use.

Identify Types of Nature Based Infrastructure

Drawing from NBI studies globally and nationally, this paper conducts a comparative analysis on NBI technologies in developed landscapes. A search was conducted in the SCOPUS database using the following keywords, "Stormwater", "Groundwater", "California", "Green Infrastructure", and "Nature Based Infrastructure". Ninety-five documents were identified as relevant to this study. The publications were evaluated for metrics on water infiltration, water quality, best soil type for application, and any subsequent groundwater sampling. For the sake of time, this paper focused on studies from 2000 to present as that is when more stormwater research was conducted. Twenty of the ninety-five publications were analyzed for their reviews of NBI methods. Initial review of the literature revealed the need for further research into applied vegetation to some NBI methods and geochemical processes that take place in aquifers. The scope of this study will not fully address vegetative and geochemical elements and it should be noted that they can contribute to the NBI' capacity for stormwater purification and should be considered for further research. This analysis, instead, will focus on the rates of infiltration and the overall filtration of anthropogenic (inorganic) pollutants that may decrease water quality and how NBI methods can promote or increase either.

Cost of Implementation

By analyzing publicly accessible information from the Cities of Sacramento, San Francisco, and Los Angeles, a policy and spending analysis was conducted to understand current decision-making and application of NBI in California. This included Fiscal Year (FY) 2022 spending on stormwater infrastructure. The main indicators that were evaluated included implementation of a Stormwater Management Plan (SWMP); any planned investments for conventional stormwater (gray) infrastructure compared to NBI projects; capital costs and O&M costs of stormwater treatment projects via NBI/GI versus gray infrastructure; and any EAR metrics, including groundwater monitoring and NBI placement. This study aims to understand where and how California cities are currently spending money for stormwater management and if there are opportunities to implement more NBI. If available, the data may be used as a framework to guide future NBI implementation throughout the state. If the financial data is unavailable, then a gap analysis will be necessary.

Results

Suitability Analysis

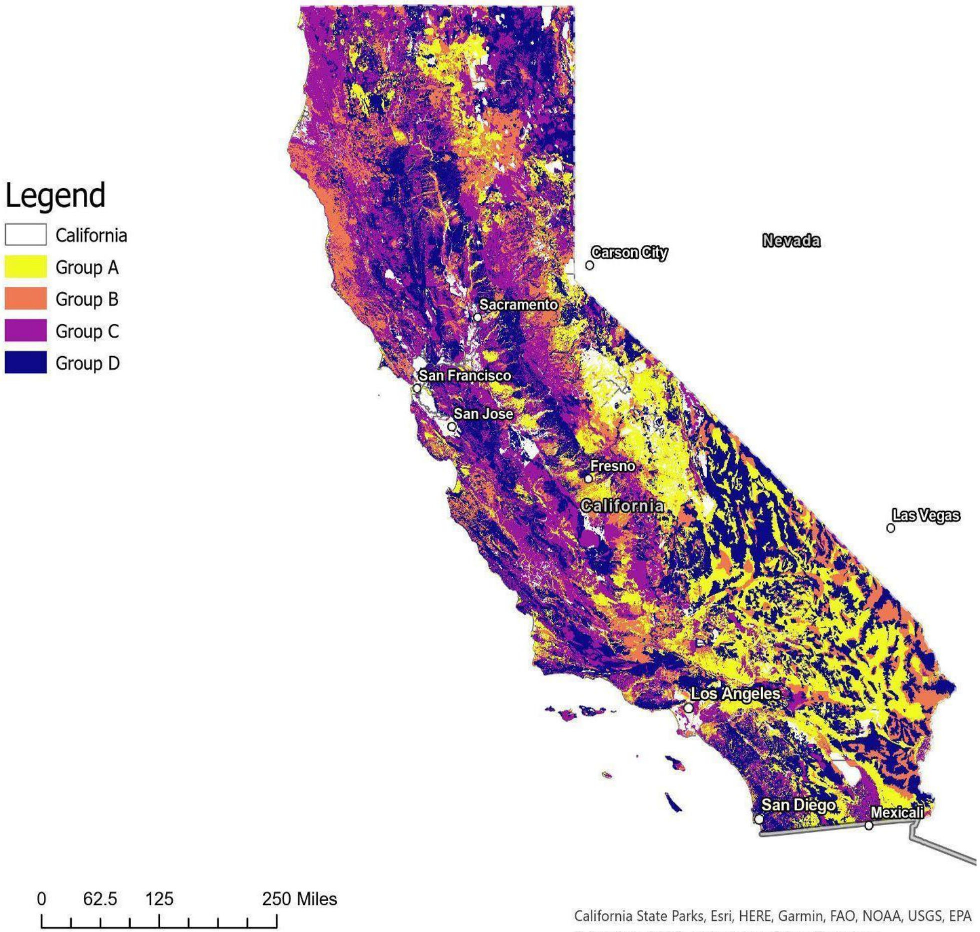
The literature revealed the importance of soil type on the infiltration rates and recharge potential. The U.S Department of Agriculture's Natural Resource Conservation Service classified soils based on their physical properties. There are four main groupings of these properties as they relate to soil run-off potential (USDA, NRCS, 2012). The USGS Hydrologic Soil data layer, provided by Esri and ArcGIS Pro, includes the four main groups along with 3 additional groups that account for the water table. The 7 identified soil types are as follows:

1. Group A - Soils consisting of deep, well drained sands, gravelly sands or aggregated silts with high infiltration and low runoff rates.
2. Group B -Soils consisting of deep well drained soils with a moderately fine to moderately coarse texture (sandy loam) and a moderate rate of infiltration and runoff.
3. Group C - Soils with a layer that impedes the downward movement of water or fine textured soils and a slow rate of infiltration. These are clay loams and soils with low organic content.
4. Group D - Soils with a very slow infiltration rate and high runoff potential. Group D is composed of clays that have a high shrink-swell potential, soils with a high-water table, soils that have a clay pan or clay layer at or near the surface, and soils that are shallow over nearly impervious material.
5. Group A/D - Soils with a very slow infiltration rate due to a high-water table but will have high infiltration and low runoff rates if drained.
6. Group B/D - Soils with a very slow infiltration rate due to a high-water table but will have a moderate rate of infiltration and runoff if drained.
7. Group C/D - Soils with a very slow infiltration rate due to a high-water table but will have a show rate of infiltration if drained.

Initial mapping showed that groups A/D, B/D, and C/D were a small, outlying portion of the study area–mostly in rural or undeveloped areas. These data were omitted from the analysis so as not to skew results–some of these areas appear white on the map (Figure 5) along with areas with no data. Group D (consisting of clay soils) make up 34% of the state and have an infiltration rate of less than 0.05 inches of water per hour (see Table 2). Group A and B soils are deemed the most desirable to maximize groundwater recharge and are targeted in subsequent analyses. Their infiltration rate ranges from 0.15- over 0.3 inches per hour.

Table 2: Percentage of soil types through California by group. Based on the area surveyed, Group A and B (the most ideal hydrologic soil types) make up 37% of the state, or ~84,000mi^2. Rate of infiltration data provided by US Department of Agriculture, Natural Resource Conservation Services.

Hydrological Soil Type	**Infiltration Rate (in/hr)**	**Total mi^2**	**% Of California**
Group A	> 0.30	45,963.21	20.20%
Group B	0.15-0.30	38,169.63	16.78%
Group C	0.05-0.15	64,843.91	28.50%
Group D	< 0.05	78,552.4	34.52%



California State Parks, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA
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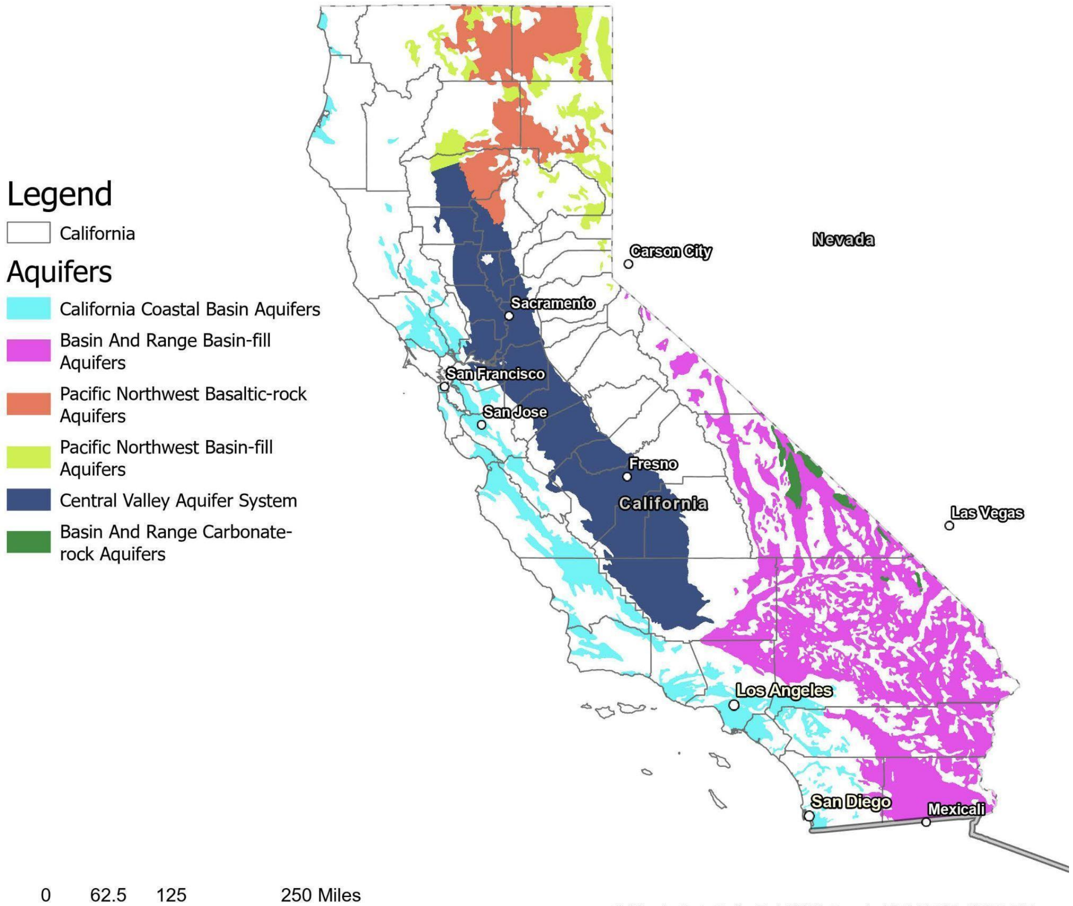
Figure 5: Hydrologic soil groups throughout California. As noted in Table 2, there is a significant amount of clay soils (Group D), symbolized in dark purple, that are prevalent throughout the state. Significant amounts of Group D Soil are seen in the San Francisco Bay Area, and into Northern California. Group and A and B soil types are scattered around California with a significant amount of Group A soil in the Southeast, predominantly in dry, arid desert regions.

As mentioned previously, California's aquifers have the potential to hold 8-12 times more water than current surface water storage (DWR, 2022). This study targets the state's basin aquifers as locations where NBI could provide a direct line for recharge. The USGS Aquifer data layer, also provided by Esri and ArcGIS Pro, identified 6 major groupings of aquifers or groundwater basins, throughout the state (Figure 6). Each of these basin groupings contain dozens of smaller aquifers or subbasins at varying depths.

1. California Coastal Basin Aquifers
2. Basin and Range Basin-fill Aquifers
3. Pacific Northwest Basaltic-rock Aquifers
4. Pacific Northwest Basin-fill Aquifers
5. Central Valley Aquifer System
6. Basin and Range Carbonate-rock Aquifers



California State Parks, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA
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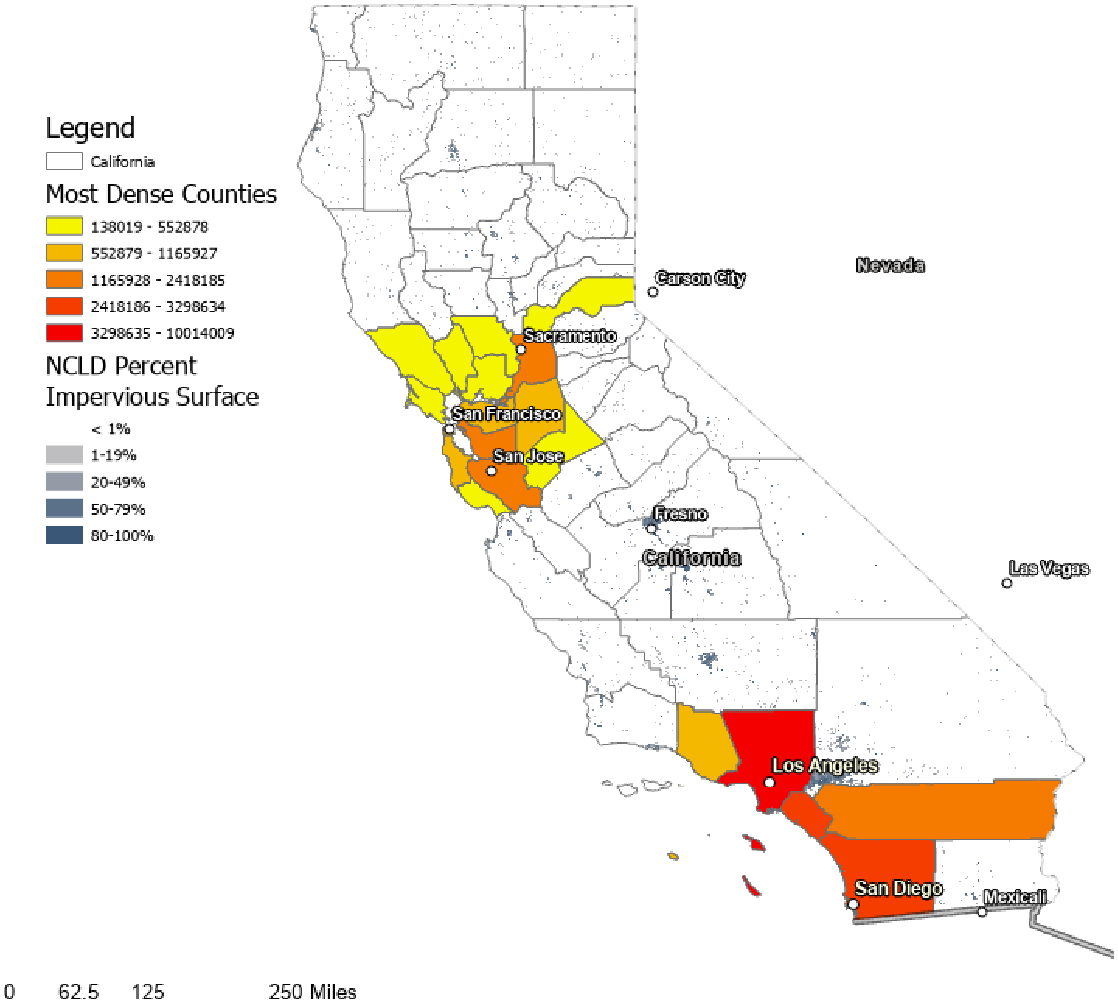
Figure 6: Map of Aquifers by type in California. The largest continuous aquifers are in the inland areas. There is also a considerable amount of smaller coastal aquifers that, including the Salinas Valley that could be targeted for aquifer recharge. Coastal aquifers also lie underneath many of California's most populated cities/counties such as San Diego, Los Angeles, San Jose (Santa Clara County. Also note the Central Valley Aquifer system that lies below Sacramento and Fresno.

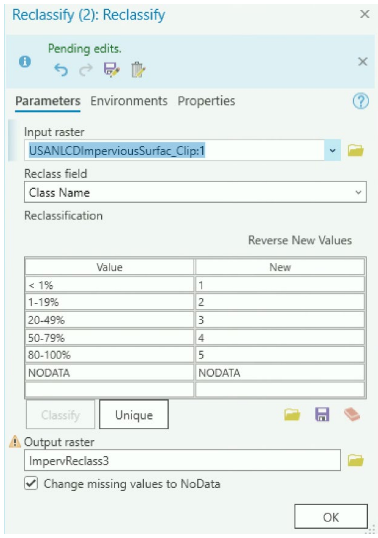
The final layer from the NLCD displays the percentage of impervious surfaces based on land cover data. The visualization clearly identifies urban and developed areas–including those that fall outside of the “most densely populated” counties that were identified earlier (Figure 7). Urban areas with high percentages of impervious surfaces included Fresno, Bakersfield, Chico, and San Bernardino. Mapped images showed several warehouse-like buildings and industrial surfaces such as parking lots and industrial business campuses.



California State Parks, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA
E.Perales, 2023. University of San Francisco

Figure 7: Map of high impervious areas compared to most densely populated counties. The areas with the highest percent impervious surfaces are shown in dark blue while areas within less than 1% are symbolized in white. In comparison the counties with the densest populations by county, symbolized in gradual colors from the yellow to red (red being the densest), there are notable clusters of highly impervious surfaces that fall outside of the highlighted counties. Those areas include Fresno, Bakersfield, and Riverside.

The NLCD impervious surfaces layer and the USGS hydrologic soil classification layer required reclassification. The reclassification tool in ArcGIS ranks elements of each soil type and percent impervious cover in order of preferred focus. This study aims to focus on highly urbanized areas and impervious surfaces, so they were ranked as shown in Figure 8. Areas with 80%-100% impervious surfaces will likely have the highest stormwater concerns at peak flow (the point of maximum flow rate during run-off). This study aims to utilize NBI in highly impervious/urbanized areas so higher percentages were given higher rankings in order to train the model. The subsequent values, 50%-79%, 20%-49%, 1%-19%, and less than 1% were given dissenting ranks of 4, 3, 2, and 1, respectively. Note that there were areas with “No data" and they are represented in white on later mapped visuals. Similarly, the Hydrologic Soil layer was ranked from 4-1 with Group A receiving the highest rank as higher infiltration rates are most preferred for groundwater recharge. Again, there is a “No data" grouping that is visualized in white. No reclassification was done to the Aquifer layer as recharge to any/all aquifers is preferred in this study. After the first two layers were reclassified, they were run through a weighted suitability model with ModelBuilder in ArcGIS Pro, as seen in Figure 8.



Reclassify (2): Reclassify

Pending edits.

Input raster: USANLCDImperviousSurfac_Clip:1

Reclass field: Class Name

Reclassification

Reverse New Values

Value	New
< 1%	1
1-19%	2
20-49%	3
50-79%	4
80-100%	5
NODATA	NODATA

Output raster: ImpervReclass3

☑ Change missing values to NoData

Figure 8: Example of ranking system in ArcGIS Pro.

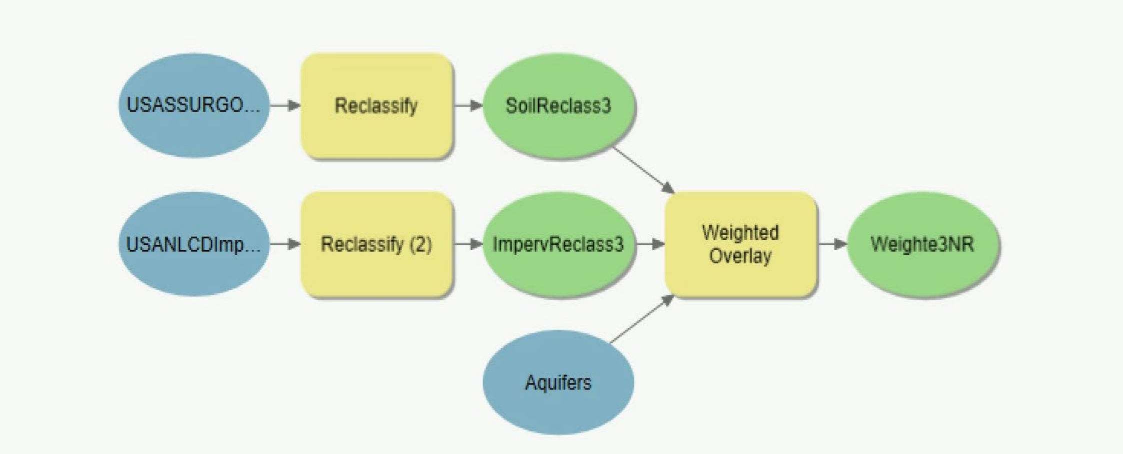
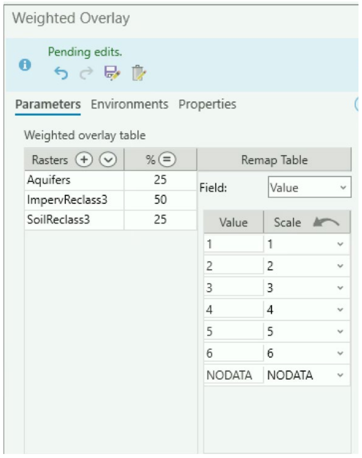


Figure 9: Model created to reclassify and perform a suitability analysis with the weighted overlay tool in ArcGIS pro. The reclassify tool was applied to USANCLD impervious layer and USASSURGO hydrologic soil layer. The aquifer layer did not require reclassification. The resulting reclassified layers were run through a weighted overlay tool along with the aquifer layer. The result is the mapped suitability analysis or groundwater recharge potential map.

The suitability model above was used to run 3 separate scenarios of a weighted suitability in order to find the best fit for groundwater potential zones. The first scenario weighted impervious surfaces at 50% (out of 100%), aquifer location at 25% and soil type at 25% (Figure 9). The map that was produced in this scenario (Scenario 1, Figure 10) was highly sensitive to impervious surfaces in urban areas. For comparative analysis, a second and third scenario were run to see if more NBI application areas could be identified. Scenario 2 weighted impervious surfaces at 40%, aquifers at 30% and soil type at 30%, prioritizing urban areas while also giving more gravity to aquifer location and preferred soil types. Scenario 3 weighted impervious surfaces at 34%, aquifers at 33% and soil type at 33%, giving all layers near equal importance. After running and comparing all scenarios, Scenario 2 was identified as the most accurate tool for NBI application. Scenario 2 not only identified more areas for NBI application, but it better accounted for soil types best suited for aquifer recharge. Scenario 3, while an overall good model, the near-equal weighting of the layers put more emphasis on aquifers that were in rural areas where there were less impervious surfaces. Once the model was run, 4 suitability categories were generated. Those categories were renamed as seen in Table 3. Over 5,000 square miles (3.23 million acres) were identified as "Most Suitable" or "Suitable" for NBI implementation and groundwater potential zones throughout California (Figure 11). The "Suitable" areas, symbolized in green and dark green respectively, are in urban areas with a higher potential for groundwater recharge. The "Suitable" areas have desirable soil types (group A and B) with high infiltration rates, and they are above known aquifers. The "Good" and "OK" areas, symbolized in yellow and orange respectively, could also benefit from NBI. However, the "Good" and "OK" areas have lower percentages of impervious surfaces and are not a priority for this study. The "Good" and "OK" areas can contain less desirable soil types (Group C and D) with low lates of infiltration. These areas would require more considerations and potentially more rigorous infrastructure interventions.



Rasters	%
Aquifers	25
ImpervReclass3	50
SoilReclass3	25

Field: Value

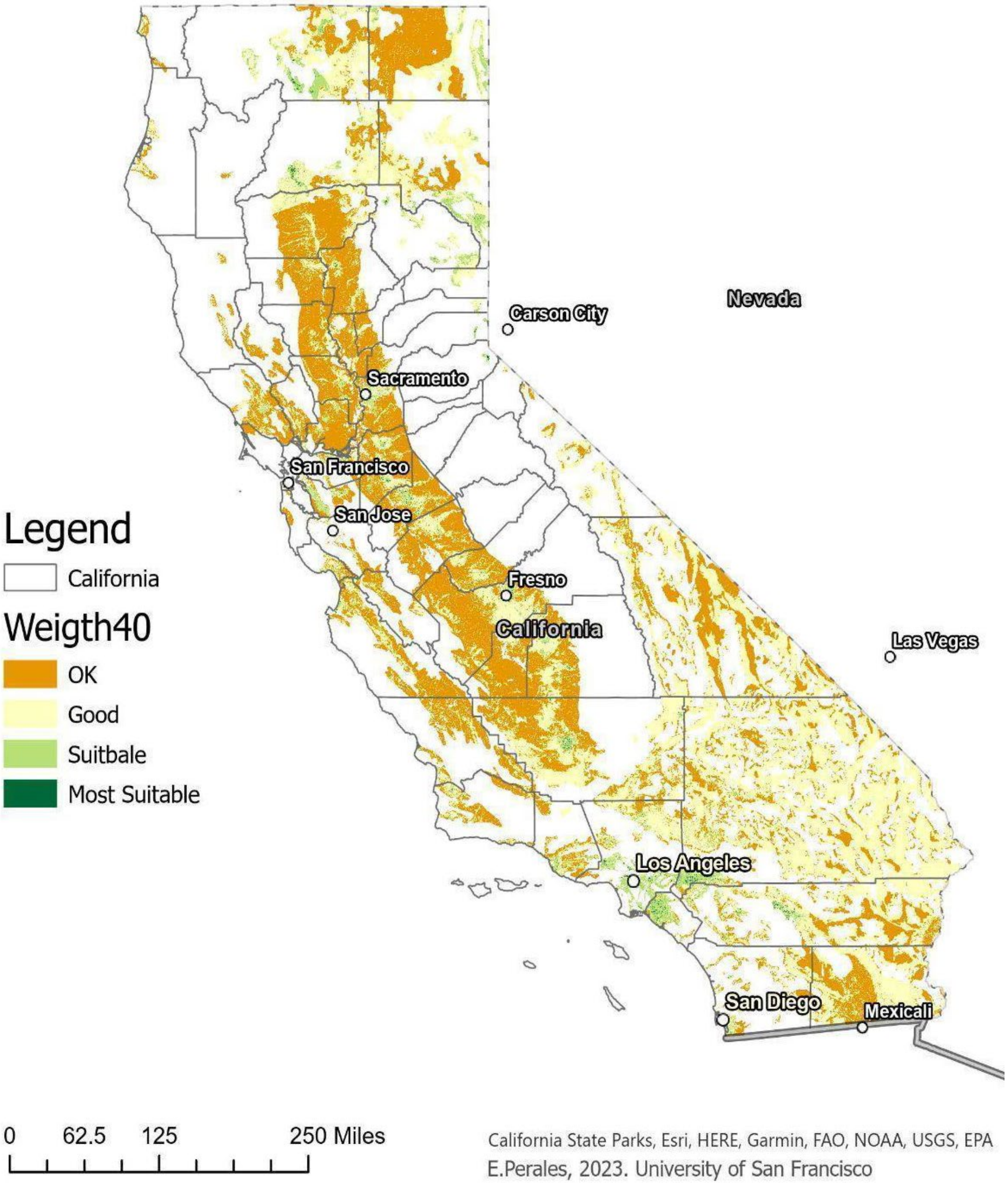
Value	Scale
1	1
2	2
3	3
4	4
5	5
6	6
NODATA	NODATA

Figure 10: Example weighted suitability analysis.

Table 3: Results of suitability analysis. The highest ranked areas (renamed “Most Suitable” and “Suitable”) total 5,063.4 mi^2. The “Ok” and “Good” areas that could benefit from applied NBI in the future total just over 90,000mi^2.

Suitability Value	Alias	Area (mi^2)	Area (Acres)
1	OK	43,861.3	28,071,244.3
2	Good	47,921.6	30,669,835
3	Suitable	4,815.3	3,081,807.4
4	Most Suitable	246	157,537.4

a.



California State Parks, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA
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b.

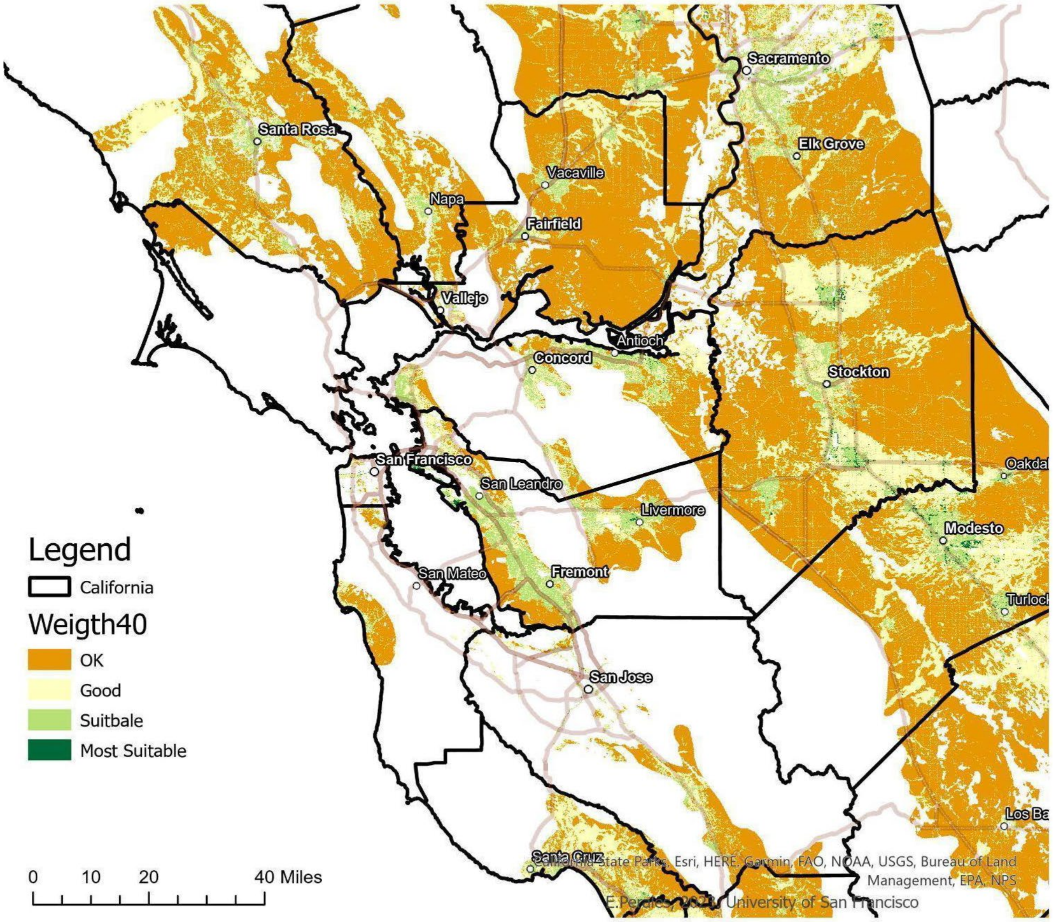

Figure 11: Mapped outcome of Scenario 2 suitability analysis. Areas in dark green show the "most suitable" areas for NBI application. "Suitable" areas are symbolized in light green, "Good" location in yellow, "OK" location orange. Unsuitable areas and areas with no data are shown in white. Image (a.) shows the groundwater potential zones throughout California. The image below (b.) is a zoomed-in screenshot of the same data in the San Francisco Bay Area. The map can zoom to 30x30m cells and can identify individual square blocks for their suitability/potential.

NBI and Recharge Methods

Using national data from the E.P.A. (2 national reports) and 18 extensive studies on NBI/GI methods, six standard NBI techniques/methods were identified as effective aquifer recharge methods. The methods and basic descriptions of each are shown, at a glance, in Table 4. With the exception of permeable pavements, all other NBI were able to significantly decrease flood risks. Of note, constructed wetlands are another prevalent NBI method to mitigate stormwater pollution. But no data was found in relation to groundwater recharge and constructed wetlands thus they have been excluded from subsequent discussion. One study in San Francisco showed that infiltration and groundwater recharge was nearly 10 times greater beneath Low Impact Development (LID) than an irrigated lawn (Newcomer, et al., 2014). LID is seen as a general term for urban landscaping strategy to replicate natural hydrologic processes that filters stormwater of debris, total suspended solids (TSS), and other pollutants. Figure 12 shows a general example of LID construction with an inflow of stormwater to a biofiltration pond.

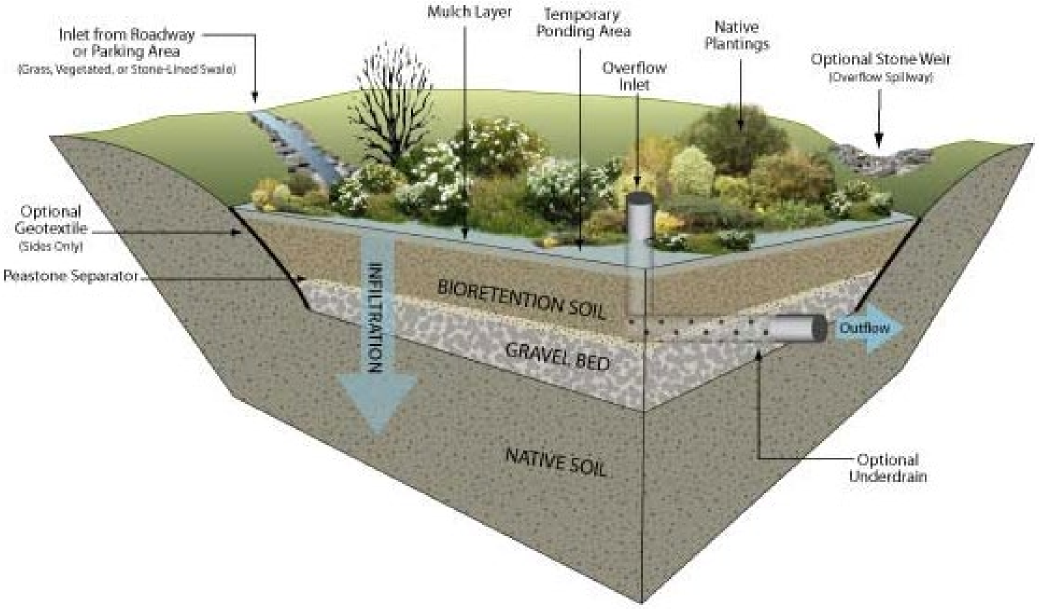

Figure 12: Example of LID. Stormwater can collect in the basin with native vegetation and layers of bioretention soil and gravel. The model above also gives the option for an “overflow inlet" that can pipe out water to a storm drain system should the water level reach critically high levels. (Source: Massachusetts Department of Environmental Protection, 2022)

In the literature, LID is generally considered the new BMP for stormwater management (Darnthamrongkul and Mozingo, 2021; Hetzel 2018, Sparkman, et al, 2017, EPA, 2021). The effectiveness of the LID methods may vary depending on the vegetation utilized and soil filtration layers applied. The vertical profile of the filtration layers may vary depending on targeted filtration needs. Additional filtration layers and media in a NBI method can increase sorption of heavy metals and other pollutants when needed (Wium-Andersen, et al., 2016). For example, adding limestone or olivine I to a filtration layer is better for filtering phosphorus (a common constituent in fertilizers). The layers can also be adapted for a spectrum of infiltration speeds.

Table 4: 6 main NBI methods found in the literature with their descriptions and best application and soil type. Dry wells are highlighted in orange as they would require more significant intervention (i.e., more heavy digging equipment). Permeable pavements highlighted in purple require the least amount of intervention but may not contribute to flood mitigation. The methods in green signify a vegetation element is included in the application. Green roofs, highlighted in blue can reduce stormwater velocity and are used in addition to any of the other methods.

Method	**Description**	**Ideal Soil Type**	**Best Application**
Dry Wells	Can range in technology requirements based on geology and stormwater pollution (EPA, 2021)	**Group D**	Especially good for clays and dense soils or areas with high peak flow levels. Can bypass vadose zones with low-permeability.
Permeable Pavements	Concrete blocks with integrated gaps for soil, gravel or sand (Brattebo and Booth 2003; EPA 2021)	**Group A & B**	Well-drained sand, gravel and moderately coarse textures.
Biofiltration ponds/basins/ gardens	Constructed water collection systems with vegetation and layered soil filtration media (Hatt et al. 2009).	**Groups A, B, & C**	Well-drained sands, gravel. Fine to coarse textures and soils with slow infiltration rates. Good for high flow areas and areas with slow infiltration. Emphasis on vegetation to maintain healthy oxygen levels. Requires more land.
"Green Streets"	Incorporates vegetated curbs, street trees, sidewalk planters, permeable pavement, and landscaped medians (EPA, 2009)	**Group A and B**	Sandy, loam soils with medium-high infiltration rates. City streets, alleys, sidewalks
Urban Green Spaces	Designated open green space like Parks and undeveloped land (Kelleher et al. 2020, Li et al. 2017). Highly variable by level and diversity of vegetation.	**Group A and B**	Sandy, grainy soils. Good for multifunctional spaces (e.g. beautification, community engagement). Higher vegetation increases porosity.
Green Roofs	Constructed "living" green spaces on roofs of buildings. Delays rainwater flow in urban areas, reducing peak flow (Luckett, 2009)	Complimentary to any group.	Addition to high percent impervious surface areas.

To apply any of the 6 methods, considerations for land use, available space, and desired outcomes would have to be undertaken. For example, dry wells do not take up significant surface area, but this method will bypass some of the vadose zone (the unsaturated soil area between the surface and groundwater aquifer) thus bypassing soils that serve as natural filters. In which case, proximity to pollution sources (such as factories/industrial areas) should be considered to mitigate pollution of underlying groundwater sources. The three methods highlighted in green are categorically considered to be LID with varying vegetation elements (e.g., trees, shrubs, grasses and groundcovers). The literature indicated that all LID listed above were shown to decrease levels of pollutants in subsoils below the implementation site. Biofiltration ponds (a.k.a. retention ponds) and rain gardens are some of the most common means for stormwater diversion and retention. They can vary in size and are often paired with the "green streets" method. Research showed additional social benefits from tree-lined streets or "green streets" by increasing urban beautification and decreasing the "heat-island-effect" in urban areas. Similarly, urban green spaces and rain gardens were shown to increase plant biodiversity and increase human health (Kondo, et al 2018, Aram, et al. 2019). Green roofs were shown to be a complementary method that is used to help slow the flow rate of stormwater by delaying the release of rainwater and giving time for the stormwater on the ground-level to infiltrate. Green roofs include opportunities for temperature regulation of buildings from reduced energy usage and implications for added structural reinforcement for added weight (Luckett, 2009). All of the above NBI methods were shown to filter stormwater from pollutants, large debris, and TSS while also contributing to groundwater recharge.

Capital costs, or costs of installation, for NBI methods can vary and estimates are loosely compiled throughout the literature. Each method contains several variables for implementation including the surface area utilized, the slope of land, filtration layers needed, surrounding pollution constituents, underlying soil conditions, and retention/filtration goals. This study has identified 2 distinguished sources that can generally account for capital cost estimates. The first is the National Stormwater Calculator (SWC) that is operated and updated by the EPA. The SWC is publicly accessible online and as well as a downloadable application that contains geographic data (including topographic data to determine slope), local rain gauge data, and LID cost estimation based on locality. A user can identify a given property by inserting an address and proceed to input current impervious surface cover. An integrated cost estimate module assesses local data and provides potential costs based on the user's desired NBI interventions. For example, when entering hypothetical information for 1 acre of land in Oakland, CA with the goal of converting the land to 20% rain gardens a cost summary is produced (Figure 12). The SWC can also account for multiple

NBI methods (as shown below) to aid decision-making. The SWC also provides estimated data on infiltration, run-off, and evaporation rates for the hypothetical project site (not shown).

Cost Summary

Estimate of Probable Capital Costs (estimates in 2020 US.$)

Maintenance Costs | Graphical View

	Drainage Area %	**Has Pre-Treatment?**	**Current Scenario (C)**		**Baseline Scenario (B)**		**Difference (C - B)**	
Cost By LID Control Type	**Current / Baseline**	**Current / Baseline**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Disconnection	0 / 0	No / No	$0.00	$0.00	$0.00	$0.00	$0	$0
Rainwater Harvesting	0 / 0	No / No	$0.00	$0.00	$0.00	$0.00	$0	$0
Rain Gardens	20 / 0	No / NA	$7,718.87	$14,640.95	$0.00	$0.00	$7,718.87	$14,640.95
Green Roofs	0 / 0	No / No	$0.00	$0.00	$0.00	$0.00	$0	$0
Street Planters	0 / 0	No / No	$0.00	$0.00	$0.00	$0.00	$0	$0
Infiltration Basins	30 / 0	No / NA	$7,786.07	$17,554.41	$0.00	$0.00	$7,786.07	$17,554.41
Permeable Pavement	10 / 0	No / NA	$39,416.97	$53,221.25	$0.00	$0.00	$39,416.97	$53,221.25
Total	**60 / 0**	**Varies**	**$54,921.91**	**$85,416.62**	**$0.00**	**$0.00**	**$54,921.91**	**$85,416.62**

Figure 13: The above hypothetical scenario provides estimates for a 1-acre parcel of land in Oakland, CA. The cost summary from the SWC provides a range of estimated costs from low to high. In this scenario, the hypothetical developer is looking for estimates to convert 20% of the land into rain gardens. 20% of 1 acre equates to roughly 8,700ft^2 or a 90 ft x 90ft section of land.

The second is the International Stormwater BMP Database that is led by research conducted by the Water Research Foundation (WRF). The BMP Database is displayed in a Microsoft Access database. It contains BMP costs and designs that date from 1989 to 2006. These data are compiled from various project sites that have reported their work to the WRF. The data reads as line-items with designated Site ID numbers, types of NBI, actual total costs of implementation and other supplementary data. Neither the SWC nor the BMP database have cost estimates for dry well construction or urban green spaces thus supplementary cost estimates were acquired from various publications. Based on the above data, the following table was compiled for each NBI method (Table 5). For dry wells and urban green spaces, projects often include a combination of methods, and the data below is best estimates for individual elements within a project. The table also includes on metrics on recommended land use types for NBI; the methods ability to mitigate flooding; improves stormwater quality; and the level of intervention required to implement each NBI type.

Table 5: Cost estimates for the 6 leading NBI methods measured in dollars per square foot. The table also includes some elements for consideration when applying to NBI, including land type, flood mitigation goals, water quality improvement goals, and how much intervention may be needed. The above costs are based on California's price market.

NBI Method	Land Use type (Urban/Rural)	Flood Mitigation	Improve water quality	Level of intervention	Capital Cost Range (Low-High)
Dry Well	Both	x	(depth dependent)	High	$1,200- $15,000.
Permeable Pavement	Both	(low, steady rain)	x	Medium	$8.68 - $11.65 per sqft
Biofiltration Basin	Urban	x	x	Medium	$0.86 - $1.91 per sqft
Green Street	Urban	x	x	Medium-Low	$0.81 - $2.38 per sqft
Urban Green Space	Both	x	x	Medium	$6-$18 (an additional $175 if includes added NBI)
Green Roof	Urban	x	x	High- Medium	$5.07 - $11.29 per sqft

The level of intervention generally accounts for additional elements needed to implement the NBI method. Dry wells, for example, can require added pretreatment measures and costly permits on top of capital costs. Green streets are shown to require less interventions and associated costs apart from resurfacing sidewalks and roads at the implementation site. To compare, this study examined the costs of 10 gray infrastructure projects in Los Angeles, utilizing Los Angeles County Water District data. The 10 sample sites were variations of completed stormwater drainage projects—including storm drainpipe retrofits and water main replacements. On average, the cost of these gray infrastructure projects costs ~$200 per linear foot.

Policy Analysis

The BMPs and stormwater management plans of Sacramento, San Francisco, and Los Angeles were evaluated to assess any common issues of NBI implementation in California cities. These three cities in California were selected based on the following criteria: varying population and size, varying water systems, perceived flood potential, and percent impervious surfaces. The policy analysis was based on information gathered from publicly accessible sources and public facing outlets such as newspapers, websites, public notices, etc. Each city was evaluated for the following metrics; implementation of a Stormwater Management Plan (SWMP), allocated funding for NBI/GI, groundwater monitoring metrics associated with NBI implementation, and any EAR metrics (i.e. measured groundwater levels). The above metrics were chosen to qualify the thoroughness of NBI application and overall stormwater planning at the city-level in relation to the state-wide plan.

To begin, the city of Sacramento's stormwater management plan is based out of Sacramento State University. There was extensive information and outreach material on LID but includes little to no financial information regarding the installation of current LID projects. Through Sacramento's Stormwater Quality Improvement Program (City Stormwater Program), the city offers grant funding for small school/education projects as well as restoration, monitoring, and neighborhood improvement projects. All projects are subject to NPDES compliance. In 2014, in a partnership between the city utility (Sacramento Department of Utilities) and California State University Sacramento, the city received $3 million from the state for LID construction. The 2021/2022 (FY22) annual city budget designated approximately $45,000 annually to the "Storm Drainage Fund" that goes toward O&M costs of the city's drainage system (City of Sacramento, 2022). The budget also contains a "Wastewater fund" for roughly $23,600 that has 6 objectives; 1 of the 6 objectives aims to implement LID and GI for run-off minimization. There was no considerable mention of stormwater retention or groundwater recharge.

The City of San Francisco's SWMP was last updated in 2016 and contains little data on completed and on-going projects. San Francisco's stormwater is overseen by San Francisco Public Utility Commission (SFPUC). The Stormwater Management Requirements and Design Guidelines (SMR) is SFPUC's stormwater management policy that was released in 2016. It is enforceable under the Stormwater Management Ordinance (SMO) (Public Works Code, Article 4.2 Sections

147-147.6). The main goals of the SMR and SMO are to reduce strain on San Francisco's combined sewer system and increase infiltration. No specifics are given for capital costs of implementation. Instead, there are various guidelines and associated principles/strategies for installation. Principle 2, "Incorporated Existing drainage patterns, soil conditions and geology into site design" contains one of the few mentions of groundwater. Contrastingly, in 2019, the city also began a Sewer System Improvement Program (SSIP). The new program aims to invest upward of one billion dollars in retrofitting San Francisco's aging combined sewer system (Abrams and Madjus 2014). As of June 2022, the program has spent $1.086 billion–including $490 million in sub-contracts (SSIP Annual Report, June 2022). The program has completed 52% of "Phase 1" and has another $1.2 billion (approx.) to spend. The 2022 SSIP includes 9 GI projects, some funded via city grants totaling about $10.4 million. San Francisco also plans on managing 1 billion gallons of wastewater with GI by 2050 (SSIP, 2022) with no mention of aquifer recharge as a part of the management.

The SWMP for The City and County of Los Angeles is governed by Los Angeles County Water Department (LACWD). LACWD lists 106 water infrastructure projects that were completed, are in development, or are in construction since 2018. In 2004, Measure O was passed which allocated nearly $55 million directly to 3 major NBI/GI projects (City of Los Angeles, 2018). More recently, the LACWD's 2021-2022 annual budget allocated roughly $10.4 million in funding from Measure W, SB1 and Stormwater Pollution abatement funding. These funds went toward 2 flood control projects and 8 water quality improvement projects (City of Los Angeles, 2020). The same 3 funding sources mentioned also allocated $436,017 for 3 engineering positions for designing and implementing GI projects as part of an Enhanced Watershed Management plan. Within the same budget year, LACWD allocated $36.3 Million to "water infrastructure" for 45 projects. The 45 projects include capital improvement plans, treatment plans, sewer repair and rehabilitation projects, as well as personnel funding for gray infrastructure. An additional $4,798,565 is set aside for on-call emergency personnel to repair damaged storm drainage facilities and protect properties from storm damage (City of Los Angeles, 2020). Los Angeles County Public Works is also in the process of implementing a revitalization of the Los Angeles River with the goal of investing $19 - 24 billion over the next 25 years on 78 project sites (Los Angeles River Master Plan, 2023). The plan incorporates both gray and green infrastructure projects to increase green space, water retention and filtration, and biodiversity along the riverfront. One of the nine goals of the plan is stormwater retention and treatment to replenish groundwater storage for dry years. Figure 14 shows the budgetary allocations of NBI/GI methods versus gray infrastructure for each city. Sacramento allocated the least amount of FY22 funding to NBI/GI projects. But based on overall percentage of gray to green infrastructure investment, San Francisco allocated the smallest percentage of stormwater management funding toward NBI/GI.

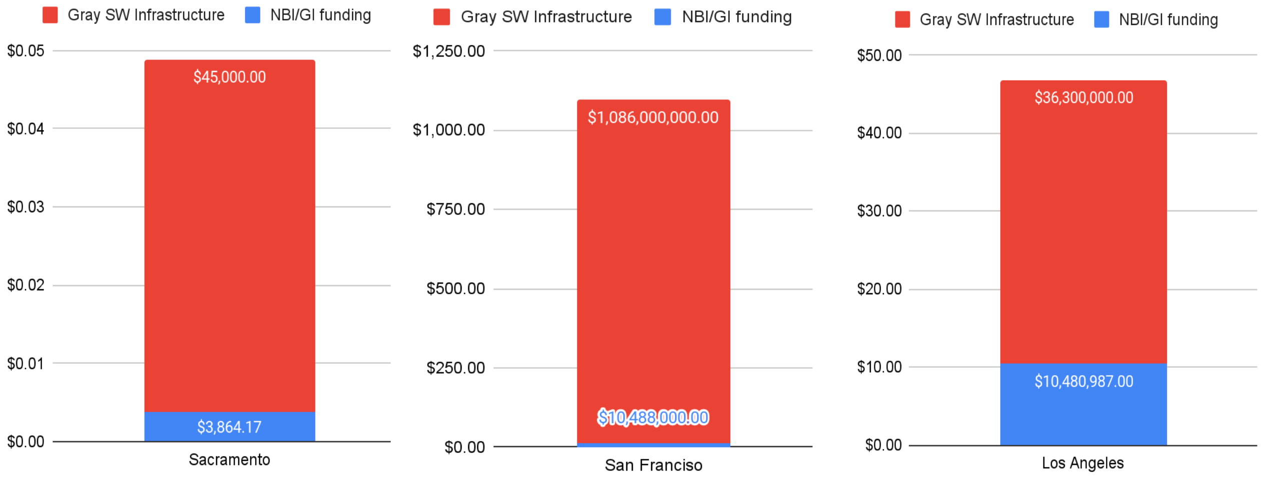

Figure 14: Comparison of gray and green infrastructure investments for Sacramento, San Francisco, and Los Angeles in 2021-2022. NBI/GI projects make up roughly 1% of San Francisco projects, 28% of Los Angeles projects and 8.6% of Sacramento. These funding include personnel and O&M costs. The level of funding/investment for each city is markedly different and could not be placed on the same graphed scale.

When comparing all the cities to the desired metrics, all cities had a SWMP (to varying degrees) and designated funding for NBI/GI projects. However, only Sacramento expressed clear surface water and groundwater monitoring measurements and results. The metrics were provided, in large part, due to studies conducted by Sacramento State University. The other cities allocated fundings for groundwater monitoring, but none were made publicly available or easily accessible for study. Further analysis revealed that while each city noted the importance of NBI/GI for stormwater management, only the LA River Master Plan mentioned the recharge of aquifers as a goal/objective for project implementation. Generally, implementation appeared more opportunistic, as small-scale project looked to relandscape an area (i.e. park, school, neighborhood, etc.) for beautification purposes. Similarly, there did not appear to be considerations made for aquifer location or current groundwater levels. Table 6 gives a simple break-down of the metrics used to assess the budgets and policies of each city. Each metric was given a simple pass/fail grade.

Table 6: Table of priority metrics for policy analysis. Sacramento, San Francisco, and Los Angeles demonstrated a straightforward SWMP and budgeted for NBI/GI projects. Sacramento reported city-sponsored groundwater monitoring metrics as a result of studies conducted by Sacramento State University. None of the city policies and publicly accessible information demonstrated EAR metrics (i.e., groundwater measurements).

City	**Has SWMP**	**Direct NBI/GI funding**	**Groundwater monitoring metrics**	**EAR metrics**
Sacramento	x	x	x	
San Francisco	x	x		
Los Angeles	x	x		

Discussion

Groundwater Potential Zones

Of the four hydrologic soil types that were identified by the USGS, Group D, the least desirable clay soils, make up one third of the topsoil in California. The clay soil, once completely swollen, equates to a near-impervious surface. It would be particularly difficult to place most NBI in these areas unless significant interventions were made to amend or bypass the vadose zones. However, Group A and Group B soils also make up nearly one third of California's topsoil. The high infiltration rate of these topsoil groups indicate that they can manage moderate to heavy rainfall (.5 mm/h to 8 mm/h or 0.02 in/hr to 0.03in/hr) without concern for pooling or flooding. With the help of the mapping model, we can identify the areas in which NBI would be best applied and infiltration can be maximized. The model is able to identify where preferable soil types are located and if they are covered by continuous impervious surfaces. The mapped aquifer data, then, could be compared to aquifers that are critically low as identified by the CASGEM (Figure 1) and prioritized for recharge. By understanding the percent of impervious surfaces within urban settings, municipalities can identify highly impervious areas and implement NBI interventions to discontinue or break-up the continuous impervious surfaces and recharge aquifers. As seen in the resulting maps (Figure 6), many of the areas with higher impervious surface, also contain the highest population in California. This could create potential issues with land-use within municipalities. However, based on available space, NBI is adaptable and can be applied in a variety of areas and circumstances.

The model created in this project identified 246 mi^2 of “most suitable” land available for NBI for application. The majority of the groundwater potential zones included highly impervious areas such as parking lots, roads, warehouses, and otherwise places with little to no vegetation. The model identified these areas for their location on top of Group A soils with high infiltration potential. The “most suitable” areas also included spaces like airport runways that are not practical for NBI application. The model revealed roughly 4800 mi^2 of “suitable” areas for NBI application. These areas generally contained more vegetation over lower quality/less ideal soil types for infiltration. Much of the area included residential spaces and parks that likely could utilize NBI implementation to enhance stormwater infiltration and groundwater recharge. Lastly, the areas identified as “good” and “OK” generally contained higher, naturally occurring, vegetation with the more desirable hydrologic soil types (Group A and Group B). While these areas may not necessarily need NBI interventions, these areas generally reside over aquifers. In the case that aquifers in the mapped areas are identified as critically low (as seen earlier in Figure 1), these areas may serve as target regions for NBI implementation.

Based on the data gleaned from the suitability analysis, potential stormwater collection from 1 inch of rain can be calculated (Table 7). From the 246 square miles of “most suitable” groundwater potential zones identified earlier 1 inch of rain would equate to 4.3 billion gallons of water. In the roughly 5,000 square miles of combined “Most Suitable” and “Suitable” areas 1 inch of rainfall would equate to roughly 87.9 billion gallons of water. Literature suggests that some water is inevitably lost due to evapotranspiration and run-off. Furthermore, it may not be practicable to assume NBI can be implemented in all groundwater potential zones due to municipal issues like private land use or zoning. However, if even 50% of stormwater is captured over the roughly 5,000 square miles, California could potentially add over 43.9 billion gallons of water to groundwater aquifers with 1 inch of rain.

Table 7: On top are the conversion factors for calculating the amount of rainwater in 1 inch of rain. Source: U.S. Geological Survey, 2019. Below is the estimated amount of rainwater that would fall in the "most suitable" and "suitable" groundwater potential zones.

Area	**Area (mi^2)**	**Gallons**	**Acre Feet**	**MAF**
40 x 70 ft Roof	0.0001	1,743	0.06	0.0000001
1 Acre	0.00156	27,154	0.99	0.0000010
1 mi^2	1	17,380,000	639.75	0.0006398

	Area (mi^2)	**Gallons**	**Acre Feet**	**MAF**
"Most Suitable"	246	4,275,480,000	157,378	0.16
"Suitable"	4815.3	83,689,914,000	3,080,610	3.08
Combined	5061	87,965,394,000	3,237,990	3.24

NBI Analysis

Research identified six main NBI techniques and methods to enhance aquifer recharge. All methods but permeable pavements mitigated flooding and all methods improved the stormwater quality but decreasing the level of pollutants in sub-surface soils. The NBI methods studied required varying degrees of intervention as most all can be adapted for large-scale projects. Dry wells are the NBI method with the highest level of interventions required since wells can require more invasive machinery for digging. They also often require the installation of more intensive pre-treatment technologies depending on the depth of the well. That said, dry wells allow more direct flow of stormwater to aquifers and bypass much of the topsoil. They are especially useful in areas with high levels of clay soils (Group C and D) and have the capability of recharging aquifers when other methods are insufficient. However, several considerations should be made in order to mitigate aquifer pollution from stormwater. Considerations include proximity to potential pollution sources, such as agricultural lands, or close to industrious areas with a high risk of contamination.

Permeable pavement includes variation of gravel, cement pavers, and porous pavement materials that allow for infiltration. Permeable pavement demonstrated significant filtration of heavy metals and TSS in sub-soils immediately underneath the pavement. By all indications, this method is particularly useful for mitigating potential groundwater pollution from stormwater infiltration. This method is also shown to be effective in areas with consistent precipitation and during smaller rain events. Research shows that more studies need to be conducted utilizing permeable pavements in relation to large rain events to assess effectiveness during higher flows and flood scenarios.

Three of the methods identified (biofiltration ponds, “green streets”, and urban green space) are considered LID. Each incorporates variations of similar soil-layering elements to filter stormwater of heavy metals, excess nutrients and TSS. Furthermore, depending on plant species selected for implementation, studies showed that vegetated NBI methods provided other social and ecological benefits. The vegetation that is incorporated into the LID generally serves two purposes; to mitigate and extract excessive nutrients, such as nitrogen and phosphorus, and to increase positive social impacts, such as beautification, human health benefits and a reduction in the urban heat island effect. LID and open green spaces can also be adapted to incorporate naturally oxidizing plant species to increase oxygen levels in water during the infiltration process and increase soil porosity from root systems. There was a significant increase in community satisfaction from the beautification effects from established NBI methods as well as an increase in biodiversity in areas with “green streets”, rain gardens and vegetated bioswales (small retention ponds). Tree-lined streets and green space with trees also showed a positive impact on urban heat island effects. The vegetative NBI methods were generally shown to be helpful over hydrological groups A, B and C and they all helped capture stormwater and decrease flooding.

Lastly, green roofs were mentioned as an NBI method that would complement others and decrease velocity of stormwater. Typical construction of green roofs include soil layers which have the potential to filter any rainwater impurities from atmospheric pollution. The filtration process both slowed the rate of stormwater and helped to alleviate stormwater pollution “downstream”. Green roofs are shown to be beneficial in most urban settings and in highly impervious areas. As mentioned above, green roofs have the added benefit of absorbing heat and decreasing energy costs for buildings. Green roofs can also increase the biodiversity and green space in highly urbanized areas.

Research showed that there are few tools available for NBI implementation planning. The SWC is a powerful tool for initial site screening by private landowners or land developers. It helps develop estimates for capital costs and maintenance based on national data collection by the EPA. But there are no other notable sources to corroborate local market costs of implementation. The BMP database that was developed by the WRF is also a helpful tool that provides historical data on BMP projects and their associated costs. But again, these data did not reflect local, current capital costs. In any case, cost estimates for dry wells and urban green spaces were harder to acquire since neither the SWC nor the BMP database displayed data for either NBI method. While digging wells and building city parks (aka urban green spaces) are not new concepts, utilizing these two methods in relation to groundwater recharge (and associated capital costs) is still growing in data and understanding. However, supplementary data sources (Oregon State University and The City of Santa Clara, respectively) were able to give a general estimate for dry wells and urban green spaces.

Overall, green streets and biofiltration ponds (including rain gardens) were the least expensive NBI method per square foot. Permeable pavement and green roofs were the next cheapest NBI methods. Both require varying levels of interventions for filtration layers and can vary in the surface area needed. Permeable pavements also showed a varying life cycle since maintenance/resurfacing is dependent on traffic and use of the paved area. For example, parking lots need to be replaced roughly every 5 years while walkways can last for considerably longer. Green roofs can vary in construct and cover-type. For example, roofs can range from mossy meadow-like cover to larger vegetable gardens for added utility. As such there may be added costs to maintain structural integrity of a building depending on the size/type of green roof. The NBI methods with the widest range of costs are dry wells and urban green spaces. Dry wells applied to Group D soil types may require more intrusive digging machinery to bypass the clay layers. As such, dry wells are often considered the "last resort" for stormwater management. The depth of the well is also an indicator of pretreatment measures required for municipal permits. The simplest of wells can cost $1,200–these are mainly smaller, residential-sized wells–while deeper wells can cost $15,000, including permitting costs and pretreatment measures. Urban green spaces can also widely vary in space and often integrate other NBI methods like bioswales and retention ponds. Low-end costs include grass lawns at roughly $6 per square foot, planting areas at roughly $10 per square foot and hard scaping (i.e., walking paths) at approximately $18 per square foot. With the exception of dry wells, the capital costs of NBI methods are shown to be significantly lower than capital costs of the gray infrastructure methods sampled from LACWD stormwater projects. On average, gray infrastructure cost roughly $200 per square foot, a notable difference from the next highest NBI method.

Green Infrastructure Budgets and Policies

All three California cities that were evaluated for this study demonstrated varying efforts toward stormwater management and application of NBI/GI. When comparing the total investments in stormwater management plans, San Francisco invested 1% of FY 22 funding into green infrastructure. Sacramento invested roughly 9% and Los Angeles invested 28% of its funding towards green infrastructure projects. Due to San Francisco's unique combined drainage system, the major renovations were a combined effort to update the aged sewage and stormwater piping. Given that the city of San Francisco is conducting considerable gray infrastructure retrofits to current sewage infrastructure, the financial comparison of NBI investments to greater structure investments is slightly skewed (The estimates include O&M of both NBI and gray infrastructure projects with a considerable focus on the latter). Sacramento and Los Angeles' FY22 budgets seem to display more representative samples of annual stormwater management and GI investments.

The City of Sacramento has a unique partnership with Sacramento State University to implement and study green infrastructure. The stormwater management plan resulting from the partnership contains the most data collection of the three cities. The university has conducted several studies on LID that include groundwater sampling and infiltration rates. Overall, the city and the university had many small-scale successes with NBI implementation that reduced flooding and captured pollutants and large debris. According to the Sacramento FY22 budget, the city is allocating regular funding to wastewater treatment via LID and NBI. While the funding is seemingly small ($23,000), it seems relative to the size of the city. The funds in the budget does not include grant funding for private LID projects throughout the city.

San Francisco displayed the least comprehensive information on its public-facing websites to access information regarding green infrastructure implementation. The city did, however, provide guidelines and regulations from which to base green infrastructure projects. San Francisco's Stormwater Management Ordinance (SMO) is intended to decrease stress on the combined sewer system by decreasing the amount of stormwater that enters the system. While it is unclear, the SMO guidelines seem directed at property owners and private contractors rather than city officials rather than a city-wide implementation plan. SMO guidelines and regulations from which an entity is to base their GI projects, the public-facing data do not reference any timeframe for completion, cost of implementation, sponsor of the project (i.e public or private entity), and there are no metrics for stormwater capture or groundwater testing. Since there are no dates associated with the project sites, there is no way to discern how many of the projects were completed in the past year. In FY22, San Francisco began implementing a multi-billion-dollar investment to improve the existing combined sewer system throughout the city. The various projects associated in the investment plan include a portion of GI implementation projects but no mention of intentional placement for EAR. It appears that the city has significant funding for stormwater management but no discernable prioritization of NBI/GI implementation in relation to gray infrastructure.

Lastly, the City of Los Angeles showed a comprehensive account of stormwater projects. Los Angeles County Water Department (LACWD) has a substantial and robust tracking system, utilizing a GIS mapping application, that documents active and completed projects as wells as cost estimates and costs after completion. The mapping tool itself lacks metrics concerning water, quality, water, testing, and water retention. That said, the county does operate several groundwater wells for monitoring and has the capacity for continued groundwater monitoring for the purposes of NBI implementation. When comparing active and completed water projects to the NBI model that was created for this project, several projects that have been completed are in progress in "most suitable" groundwater potential zones. Additionally, LACWD is planning substantial investments to retrofit the Los Angeles River, which is a well-known gray infrastructure method of stormwater removal; The county plans to invest over $19 billion over the next 25 years. The plan does include NBI projects for stormwater capture along with gray infrastructure improvements. It is possible that the drastic difference in investment costs and funding could be due to the lesser cost of NBI implementation compared to gray infrastructure implementation. According to the preliminary data sample from LACWD, gray infrastructure projects are more than 10 times more expensive than the next highest NBI method (e.g., high-end urban green spaces). More data is needed to provide more thorough cost estimates for capital costs of gray infrastructure to compare. Due to the lack of information and data supplied in each of these cities' public-facing websites (including groundwater monitoring and stormwater retention metrics), it is difficult to compare all the costs associated with each infrastructure method in each city.

Limitations

This study was not able to integrate watershed modeling and water flow modeling to identify other key groundwater potential zones. Further studies would benefit from including these data as they could inform potential flood zones, debris build-up, and where NBI could be applied to maximize capture in a storm. Furthermore, this study did not include analysis of geochemical processes associated with groundwater potential sites. Groundwater quality is heavily dependent on naturally occurring minerals in aquifers and enhanced groundwater recharge could alter the chemistry within an aquifer. There is the potential for introducing constituents that could cause unforeseen reactions in aquifers that may inadvertently contaminate water. Furthermore, agricultural land makes up a large swath of developed land throughout California that was not considered in this study. Based on data from the USACE, row crops have similar run-off rates as dirt roads (SCS Curve number of 72, on a scale where 100 is the most impervious). Since the San Joaquin Valley Basin is an aquifer at critically low levels, NBI interventions would benefit agricultural land as much as urban land. Furthermore, the literature did not reveal any cases studies or example cities where NBI was the primary stormwater management infrastructure utilized. As such, there is no substantial/long-term data on the relationship between NBI methods and water quality in aquifers (available data only revealed decreased pollution levels in sub-soils underlying LID sites).

Conclusions and Recommendations

With more weather extremes predicted for California in the next 50 years, there is an increased risk of stormwater associated damages. According to the same modeled predictions, extreme drought conditions, like those experienced throughout the state in 2022, are also likely to increase and worsen. NBI, as a means to control stormwater and increase groundwater storage, could mitigate the extremes of both. Investing in NBI implementation should be a greater statewide priority, especially in highly developed and urbanized areas. The model developed for this project is a useful tool for identifying high groundwater potential zones and can be adapted and trained to identify practical sites for NBI application. Informed placement of NBI could increase infiltration and maximize groundwater storage during all rain events. California's 2022 Water Supply Plan hope to capture .25-1-million-acre feet (MAF) or 81.5-326 billion gallons of water to groundwater by 2030. This project demonstrates that California would not only reach their goal of adding .25 MAF to the ground water supply by 2030 but could potentially exceed that goal. If NBI is implemented in groundwater potential zones, just 1 inch of rain could, conservatively, result in 40 billion gallons of rainwater capture. This could make a significant difference in driest cities/counties in California where water demand is the highest.

Recommendations from this study include utilizing the groundwater potential model created to identify key locations to implement NBI methods. In conjunction with the CASGEM data, the groundwater potential model can be used to target critically low aquifers and those at risk of overdraft. Use of the tool could help California cities like Sacramento, San Francisco, and Los Angeles to more efficiently utilize existing stormwater funding to recharge groundwater aquifers. While it seems like the DWR is planning to increase available resources for agencies to increase groundwater recharge, the tools and NBI methods identified in this project can bolster the state's efforts. Further training of the groundwater potential model and incorporating additional watershed data could help target areas with higher stormwater flood potential.

This study identified six NBI methods that can increase groundwater infiltration, mitigate flooding, and filter pollutants and other harmful constituents from stormwater. All six methods decrease velocity of stormwater flow, filter stormwater for pollutants and large debris, and can recharge groundwater storage. Dry wells, "green streets" (including street planters and tree-lined streets), permeable pavement, green roofs, urban green spaces and biofiltration basins (including rain gardens and bioswales) have been utilized in urban areas around the country. More real-world application of NBI/GI is needed in California to understand patterns for reducing stormwater runoff and retention thus augmenting the state's groundwater supply. While there are other NBI/GI methods used for stormwater management, this study recommends implementing any or a combination of the six NBI methods identified above to enhance groundwater recharge and decrease stormwater pollution. Cost estimates from the EPA and other sources show that NBI/GI BMPs are a more cost-effective means of stormwater management than traditional gray infrastructure.

When evaluating current NBI implementation in California, the cities of Sacramento, San Francisco, and Los Angeles revealed greater investments in gray infrastructure to manage stormwater. At present, there is a noticeable difference in investments between gray infrastructure as a means of stormwater removal and NBI/GI implementation for stormwater capture and groundwater recharge. Data pulled from budgets and policies from all three cities show a continued gray infrastructure investment in FY22, a year when drying/drought conditions were severe throughout the state. While the City of San Francisco invested the largest amount of money toward NBI projects, it showed the lowest overall investment percentage when compared to Sacramento and Los Angeles. Furthermore, neither Sacramento nor Los Angeles invested more than 30% of their SWMP toward NBI/GI projects. This study recommends shifting stormwater investment priorities toward more NBI/GI projects. In addition to more overall allocations for NBI/GI, this study recommends that California and/or smaller water districts conduct more groundwater studies in relation to NBI application. To ensure adequate filtration of stormwater, more groundwater sampling is necessary to maintain national water quality standards. Similarly, more groundwater monitoring needs to be done to discern any alteration to geochemical processes and impact enhanced aquifer recharge, via NBI, has on aquifers.

There is currently little public data to suggest California and the three cities studied are intentionally placing NBI/GI. There appears to be no considerations made for geological conditions, watershed management, or regionally integrated efforts for groundwater recharge. A planned dispersion and/or an integrated implementation of NBI methods throughout a watershed could have significant positive impacts to decrease pollution of natural waterways and increase groundwater recharge. Instead, particularly in San Francisco and Sacramento, it is more of an unorganized, albeit regulated, arrangement of NBI projects on developed land by private entities and land developers. Furthermore, there is insufficient publicly available data on city-wide NBI/GI implementation and any resulting aquifer recharge. But increasing watershed mapping and utilization of integrated regional management programs with the DWR would enable cities to maximize stormwater retention and increase groundwater recharge. This study recommends a more holistic approach to NBI implementation, that not only meets NPDES standards but also restores hydrological processes to increase human and ecological health.

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