Spatial Methods for Green Infrastructure Planning. Strategies for Stormwater Management and Park Access

Thesis by
Silvia Sulis

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Committee:
Yi Qiang (Chairperson)
Mary Mostafanezhad
Brian Szuster

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University of Hawaiʻi at Mānoa
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Abstract

Planning sustainable and resilient cities is intricate. The variety and abundance of environmental, social and economic issues require systematic and comprehensive solutions, and the effectiveness of these solutions calls for strategic planning and design. Green infrastructure are engineered vegetated systems, such as green roof and rain gardens, and can support sustainability and resilience goals by proving opportunities to improve the natural, built and social environment of cities. The effective implementation of GI programs and project requires not only observing multiple and diverse criteria, but also considering how these criteria are distributed across space. This research proposes a framework for the spatial analysis supporting green infrastructure planning, and uses the Central Oahu Watershed (HI) as a case study. The framework provides guidance on where GI is most needed and would bring the most benefits across the study area, based on local sustainability and resilience goals. Priority was given to stormwater management and the creation of public open space, and suitability analysis in GIS was used to assign GI priority scores across the study area. First, stormwater runoff depths were calculated combining land cover, soil properties and rainfall spatial data according to the SCS-CN method. Second, public park access was estimated based on 10-minute walk network analysis from selected park entrances and on the ratio of resident of these catchment areas and surface of the park itself. Finally, GI priority scores were calculated by combining stormwater management and park access with elevation, a population-weighted vulnerability index, and zoning. The final output consists of a map showing the distribution of GI priority scores across the study area. This framework unpacks the complexity around sustainability, resilience and GI and provides a straight forward, replicable and flexible, approach to GI spatial planning.

Chapter 1 Introduction

The future is urban. By 2050, 66% of the world population will be living in cities (Department of Economic and Social Affairs of the United Nations 2014), dramatically increasing demands of land and natural resources and exacerbating environmental issues. The sustainability and resilience of cities is a pressing issue in contemporary urban research, policy and planning, with great efforts dedicated towards making cities less impactful on the planet and more livable for people. Stormwater runoff and flooding may lead to significant negative impacts on the environment and life of urban areas, and their management is essential to the sustainability of cities and city dwellers. Moreover, living in dense and busy cities may have considerable negative effects on the health, well-being and social capital of residents. In this regard, **Green Infrastructure** (GI) can help prevent and mitigate these adverse impacts, through the use of vegetated systems purposefully engineered to detain, filter and/or divert rainwater and runoff, while providing public green space where resident can relax, socialize and come in contact with nature.

1.1 Theoretical Framework

The complexity of the concepts of sustainability and resilience calls for a framework that combines social and environmental variables, highlighting similar goals and common characteristics. At the same time, the discussion around the implementation of GI programs and projects should be guided by theories that highlight the provisional and active nature of these natural and semi-natural features. The lens of ecosystem services serves this dual purpose of defining GI as tools for providing ecological and social service to city residents, as well as contributing to the balanced use of resources and development of land. The section below provides definitions of urban sustainability and resilience, and discuss the role of ecosystem services theory in translating sustainability and resilience goals into projects and programs through GI.

1.1.1 Urban Sustainability

There is no universal definition of the term **sustainable development** and frameworks that identify its key components, methods and processes are many and often not consistent. In general, sustainability refers to a relationship between humans and the environment that allows for growth without the depletion of natural resources, while addressing the Triple Bottom Line, i.e. economy, environment and equity (i.e. social equity and justice) (Elkington 1998; Hopwood, Mellor, and O'Brien 2005). In this sense, sustainability is a characteristic built into the development process, that fosters a mutually beneficial relationship between humans and ecosystems, by balancing trade-offs and enhancing positive interactions. The pace and magnitude of global urbanization calls for a shift in paradigms of development, one that acknowledges the role and needs of humans, limits their impact on ecosystems, and enhances the environmental performance of cities. In this regard, contemporary approaches to sustainable development are dynamic, operate at multiple scales, and incorporate all elements of human and natural systems. Overall, they aim at mitigating the impacts of humans and their actions on ecology, hydrology, climate, the economy and society.

In the urban context, the complexity of these issues is amplified. Cities are "hotspots of issues" (Lovell & Taylor, 2013), but also part of local and global sustainability solutions. On one hand, they have an immense demand for land and resources, generating critical environmental issues, such as the loss of biodiversity, the alteration of local climate, and the alteration of the hydrology of streams (Lovell & Taylor, 2013; Pakzad & Osmond, 2016; Wu, 2014). On the other hand, high population densities in cities are necessary to provide the services that ensure the livability of urban settlements such as parks, green spaces, and mass transit that can provide both environmental benefits (e.g. reduced emissions and *cleaner* air) and social functions (e.g. sense of place and gathering spot) (Ahern, Cilliers, and Niemelä 2014; Betterncourt and West 2010; Lovell and Taylor 2013). The United Nations highlights the importance of sustainability and sustainable cities, not only at the local level but also at the global scale. The UN Sustainable Development agenda, in fact, includes the "sustainable cities and communities" goal, aimed at (1) safeguarding and enhancing the social, cultural and economic development of cities; (2) reducing their negative environmental impacts; and (3) increasing access to green, open and/or public spaces within settlements (United Nations General Assembly 2015).

1.1.2 Urban Resilience

If planning for sustainability allows us to anticipate impacts and adjust the management of resources accordingly, the concept of **resilience** allows anticipating *disturbance* and planning for flexibility. In the urban context, resilience is “the ability of an urban system and all its constituent socio-ecological and socio-technical networks maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity” (Meerow, Newell, & Stults, 2016, p.39). Disturbances include natural disasters and extraordinary weather events, social and economic crisis, epidemics, and other non-ordinary events that may alter the day-to-day life of a system. All systems have an inherent level of resilience (and vulnerability) based on the existing conditions of social and natural systems, and the built environment (Cutter et al. 2008). Recovery from disturbance depends the preparedness of the system and its ability to adapt to the new post-event conditions. One strategy to build resiliency into a system is to act on those inherent characteristics and prepare the system *before* disturbance happens. In this sense, modifying the built environment is a key strategy for resilient cities, as it allows to purposefully design urban form and elements (i.e. buildings and infrastructure) that are adaptable and less vulnerable to the anticipated disturbances.

1.1.3 Ecosystem Services Provision through Green Infrastructure

There are numerous strategies to make cities sustainable and resilient, including changing the urban design and land use policies, renewing the transportation network and infrastructure, and using of vegetation and green spaces to provide ecosystem services (ES). The latter entails supplying natural and social features that can enhance the performance of natural elements and benefit humans while at the same time mitigating their negative impact. In fact, according to the Millennium Ecosystem Assessment (2005), ecosystem services include (1) “provisioning” services, e.g. food; (2) “regulating” services that can manage and mitigate the impact of climate, floods, diseases, waste, and water quality; (3) “cultural” services, providing recreational, aesthetic, and spiritual benefits; and (4) “supporting” services, e.g. photosynthesis (p. V). In cities, stormwater management is an essential regulating ES. It entails both the management of resources (i.e. stormwater, and water in the ground, streams, and oceans) and the increased of adaptive capacity. To this end, GI is an effective way to provide ecosystem services in urban areas, as they can enhance the overall environmental quality and provide goods and services to humans (Environmental Protection Agency 2017; Young et al. 2014). Generally, GI refers to an interconnected and multifunctional network of natural and semi-natural areas and features, vegetated spaces, and open spaces that contribute to the conservation, creation or restoration of ecosystem processes and functions, while providing synergistic benefits to the well-being of humans and ecosystems (Benedict 2006; Landscape Institute 2017; Pakzad and Osmond 2016; Tzoulas et al. 2007; Weber, Sloan, and Wolf 2006). In other words, GI are green features and patches inserted into the urban fabric to provide environmental, social and economic benefits.

In the urban context and in the prospect of climate change, stormwater management has become essential to ensure a city's environmental, social and economic sustaianbility and resilience. Sustainable stormwater management entails improving urban hydrology through the reduction of the volume of stormwater runoff as well as the slowing down of its flow. In urban basins the extensive and intensive presence of impervious cover significantly alters hydrology, increasing the peak flow while reducing base flow and time of concetration (Miguez and Veról 2017). A recurrent issue in contemporary cities is the "urban stream syndrome", which constists of flashy flow of streams after a rainfall event, stream morphology alteration, erosion, changes in water chemistry, accumulation of sediment, and the alteration of biological composition of streams (Walsh et al. 2005). In this case, it is important to decrease the amount of runoff generated by rainfall, and increase the opportunities of its storage and infiltration, while improving biodiversity and revitalizing the urban fabric (Miguez and Veról 2017).

Access to green open spaces is also essential to ensure the sustainability of a community, as it provides a space where residents can gather, socialize, and share. These interactions can help residents increase personal and communal social capital, and build strong, fair and just communities (Dempsey et al., 2011).

1.2 Research Goals and Strategies

Understanding the what, who and how of sustainability and GI planning is intricate, and identifying where to concentrate resources is necessary, but even more complex. Therefore, GI spatial planning requires a strategic framework that can help evaluate the spatial distribution of variables related to specific goal of sustainability of ecosystems and community, highlighting where GI is not only most needed, but also where it would bring the most benefits. The debate around sustainability and resilience Hawaii and Honolulu is rich, and initiatives, policies and projects have great momentum. Based on some of these goals and strategies, this research focuses on the hydrologic properties and access to public green space in study area, i.e. stormwater runoff deph and access to public parks, and proposes a framework for the identification of areas where GI projects and/or programs can be prioritized. The combination of these elements is novel and provides a practical example of how social and envrionmental aspects can be studied together and synthetized together in consistent goals, plans and projects. Moreover, this thesis hopes to contribute to the sustainability and resilience discourse in Hawaii and Honolulu, providing strategic insights. Overall, the **purpose of this research** is to investigate how existing spatial methods can be combined and used in the strategic identification of GI priority areas, proposing an operational framework that can guide GI spatial planning in professional settings. More specifically, the identification of GI priority areas across the research site is based on the combination of a stormwater runoff depth distribution map and public parks service area (i.e. access) map. Overlapping areas with high runoff volumes and no park access will have a higher priority for the implementation of GI measures. The study is organized around the following **research questions**:

1. Within the study area, where is GI needed and what areas are suitable for GI projects?
    a) Where is runoff more likely to accumulate?
    b) Where is accessibility to public green spaces lacking?
    c) How can these two variables be combined to inform the strategic planning of green infrastructure?

2) What geotechnologies can be used to answer these questions?

This thesis is structured in seven chapters (including this one). Chapter 2 discusses the existing literature on the main theories supporting GI spatial planning, namely sustainability and resilience in Hawaii, Green Infrastructure (definitions, goals, features), stormwater management and rainfall-runoff models, park access and related spatial methods, and spatial method specific to GI. Chapter 3 is an overview of the physical and demographic aspects of the study area, i.e the Central Oahu Watershed. Chapter 4 and 5 describe the methodology developed for mapping stormwater runoff depths and access to public parks, as well as the application of these methods to the study area. Chapter 6 discusses the methods used to identify GI Priority Areas (GIPA), illustarting how suitability analysis was used to combine data on stormwater runoff , park access, social vulnerability, elevation and zoning through. Fnally, chapter 7 suggests some ideas on how results can be interpreted and used in on-the-ground GI planning, discussing possible policy and program strategies.

The main findings include the development of a straight-forward and replicable framework for GI spatial planning and the identification of areas suitable and in need of GI. The framework guided (1) the identification of the overarching project **objectives** (based on local sustainability goals) and the **functions** GI can perform; (2) **mapping** the variables likely to influence decision-making; (3) establishing the hierarchy between these variables and mapping how different priority scores are distributed across an area; and (4) recommending possible strategies to implement GI programs and projects. Overall, a total of 2747.64 acres of land (mainly in Waipahu and Mililani) were identified as GIPA, i.e. in high need for GI. For these areas, five different implementation scenarios were calculated, estimating the conversion into GI of 35%, 40%, 45%, 50% and 100% of GIPA's impervious surfaces and GIPA's impervious cover located in FEMA flood zones.

Chapter 2 Literature Review

This section provides an overview of the existing literature on sustainability in Hawaii, GI (including its definition, the concept of its multi-functionality, spatial organization, and BMPs), stormwater management and rainfall-runoff models, park access and related spatial methods, and spatial methods for GI planning.

2.1 Sustainability in Hawai'i – *Aia ke ola i ka wai (With water, there is life)*

The State of Hawaii and the City and County of Honolulu promote varied and numerous initiatives around sustainability and sustainable development, ranging from renewable energy to food production. Hawaii has 1,052 miles of coastline and all of its land mass is considered a coastal zone (Hawaii State Office of Planning 2013) and, as a consequence, water resources are given great emphasis in sustainability planning. In this regard, management strategies entail comprehensive and holistic approaches for both Ocean and fresh water resources, and are based on a *mauka-makai* (mountain-to-sea) approach. Connecting land and sea is a recurrent theme in sustainability discourses and it takes into consideration the entire water cycle, starting from rainfall, stormwater runoff, groundwater recharge, evapotranspiration, and outflow.

For example, the Sustainable Hawaii Initiative, signed by Governor Ige, is a commitment to (1) interagency strategy for the management of invasive species by 2027 (which influence evapotranspiration and water use); (2) the protection of 30% of priority watersheds by 2030; (3) effective management of 30% of near-shore ocean waters by 2030 (State of Hawaii 2015). Complementary to this initiative, a dashboard of data, the Aloha+ Challenge Dashboard, was launched. This dashboard tracks the progress and achievements of the goals set by the State, based on specific metrics. The dashboard does not track GI metrics yet, but related goals include the increase fresh water capacity (MGD of water recharge, conservation and reuse); watershed forest management (acres of native watershed under high level protection); invasive species control (percent action items in implementation process) (State of Hawaii, 2018).

Along with these overarching goals, various State agencies have developed water-specific plans and programs targeting fresh water and management of coastal areas. In Hawai' i virtually all the fresh water supply comes from underground aquifers, and water sustainability goals emphasize both the improvement in stormwater runoff quality as well as the increase of opportunities for water to infiltrate the soil and recharge the aquifers (Honolulu Board of Water Supply 2016). Planning for the sustainable management of water becomes particularly important in light of future challenges and uncertainties. Oahu's population is expected to grow by 284,664 people (20.9% growth) by 2045 (Department of Business, Economic Development & Tourism - State of Hawaii 2017), rainfall is expected to increase in wet areas and decrease in dryer area (Honolulu Board of Water Supply 2016), and temperatures are expected to increase by 1F between 2021-2050 (in case of both high and low GHG emissions scenarios) (Keener et al. 2013). The Water Master Plan and the Watershed Management Plans (Honolulu Board of Water Supply 2016) lay out future strategies for the sustainable management of fresh water resources on the Island for the eight development districts of O‘ ahu. Sustainable strategies are planned at the watershed level and consistently with other State or local development plans, aiming at reducing water consumption and demand and encouraging conservation through stormwater reuse, recycle or capture. The use of GI is suggested as a possible implementation measure. More specifically, the Hawaii Community Foundation through the Fresh Water Initiative identifies the ambitious goal of provide additional 100 MGD of fresh water to the State's aquifers by 2030 (Hawaii Community Foundation 2015). This can be achieved through conservation (40 MGD), reuse (30 MGD) and recharge (30 MGD) (Hawaii Community Foundation 2015). In this case, using GI as a stormwater management measure can help achieve the recharge and reuse goals, by providing opportunities to capture water that can be redirected into the aquifers or reused. Among other strategies, the plan suggests increasing recharge by creating retention basins, GI, wetlands and reservoirs that allow stormwater to filter back into the ground. In terms of reuse strategies, the Fresh Water Initiatives focuses both on water quality and quantity, suggesting small-scale filter plant that can divert wastewater (from irrigation) and stormwater from parks, golf courses, and agricultural fields (Hawaii Community Foundation 2015). These strategies protect groundwater as well as ocean water, as they prevent nutrients, pollutant and sediment from seeping back into the ground or being discharged into the ocean.

Managing stormwater is also essential to keep the Ocean healthy. Many plans and initiatives that support and implement the State's Coastal Zone Management (CZM) program focus on stormwater as a source of nonpoint pollution and propose strategies and goals to reduce its quantity and improve its quality. The Ocean Resource Management Plan (Hawaii State Office of Planning 2013) is a framework that guides local agencies in protecting the ecological, cultural, economic and social values of Ocean resources and ecosystems. More specifically, the plan stresses the importance of watershed management and "appropriate coastal development". This entails reducing stormwater runoff, especially close to the shore, and implementing development and design solutions that allow the sustainable management of water (Hawaii State Office of Planning 2013).

2.2 Green Infrastructure – *Malama I Ka Wai (To care for the water)*

As introduced above, GI are green features and patches in the urban fabric that can provide a variety of ecosystem services and contribute to urban sustainability in many different ways. GI is often defined as **multi-functional**, as single features provide more than one type of ecosystem services, such as filtering and cleaning stormwater, carbon sequestration, or reduced temperatures. One of the most common application of GI elements and networks in urban environments is stormwater management, i.e. *regulating services* (Millennium Ecosystem Assessment 2005). This function is important to achieve sustainability goals such as water conservation, groundwater recharge, and reduction of pollutants in stormwater and marine ecosystem. In particular, GI can be planned for and designed so that features and networks can help reduce the quantity of stormwater runoff and modify its flow.

BMPs for urban stormwater management include rain gardens and bioretention ponds, vegetated roofs, greenways, and permeable pavements. These elements improve the hydrological performance of the site by mimicking pre-development conditions and/or disposing of stormwater onsite, through the use of specifically engineered soil/organic layer, mulch layer, and plants (Davis et al., 2009, 2009; Matlock & Morgan, 2011; PGCo, 2007). GI can be applied at different scales, including building, lot/site, and/or neighborhood scales, combining different features and practices

(Ahern 2007; Young et al. 2014). For example, Lovell & Taylor (2013) observed how lawns, playgrounds, gardens, parking, pathways, etc. form a network that can provide cultural, ecological, and production functions to urban systems.

2.2.1 Best Management Practices

This section is an overview of GI elements, i.e. Best Management Practices (BMP), their structure, function and application. This includes bioretention ponds and rain gardens, vegetated roofs, and permeable pavement.

Bioretention facilities consist of retention ponds of various configurations, such as rain gardens or bioretention basins. Their ability to remove pollutants from stormwater runoff, mitigate peak flow, reduce the concentration time of runoff, and recharge the groundwater (Davis, 2008; Davis et al., 2009; Hunt et al., 2012; PGCo, 2007) makes them one of the most effective stormwater management measures. This BMP consists of catchment areas in which stormwater flows and pools. The usual structure includes a soil or organic media layer (0.7-1 m), a surface mulch layer (2.5-8 cm), and a layer of vegetation on the surface, and are integrated with the sewer pipes (Davis et al., 2009; PGCo, 2007). The physical, chemical and biological properties and processes of the soil, mulch and vegetation layer (Davis et al. 2012) can increase infiltration and evapotranspiration of water, reducing or eliminate runoff. Through infiltration into the soil media, percolation and evapotranspiration, these elements slow down the peak flow of incoming rainfall and stormwater and increase the time of concentration[1] (Tc) (Davis 2008; Davis et al. 2009). For example, Davis (2008) observed that bioretention ponds improved the hydrological performance of undeveloped land by reducing runoff volume and decreasing the peak flow. In general, bioretention ponds and rain gardens should be located close to impervious area, so that runoff is collected close to its source and collection is distributed in a more manageable fashion (PGCo, 2007). Moreover, a system of bioretention cells diffuse across a watershed, can be helpful in improving the hydrologic

1 "Time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet" (United States Department of Agriculture - Natural Resources Conservation Service 2010)

processes by reducing the cumulative volume of stormwater runoff that flows downstream (Davis et al. 2009). These characteristics are essential in managing and enhancing urban hydrology, preventing nonpoint source pollution, erosion, flooding and the related social and economic impact.

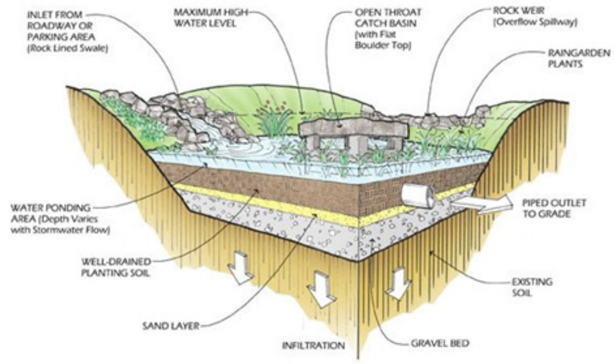


Figure 1. Structure of bioretention pond (http-// blueg`rasslawn.com/the-importance-of-bioretention-systems/.jpg)

Green roofs refer to those vegetated features located on the last layer of a building and specifically engineered to manage stormwater runoff, provide thermal insulation to the building, reducing the Urban Heat Island Effect (UHI), etc. One of the advantages of green roofs is that they provide stormwater management benefits similar to other BMPs, but without using any additional land at the ground level (Li, 2006; Versini et al., 2015). The structure of a green roof (see figure 2) includes a vegetation layer, a growth substrate, and a series of layers protecting the roof structure, i.e. drainage system, root barrier, insulation and water proofing membrane. Similarly to bioretention cells, vegetated roofs provide interception and storage of rainfall (preventing the formation of runoff), ET, and sedimentation. The physical, chemical and biological processes are also

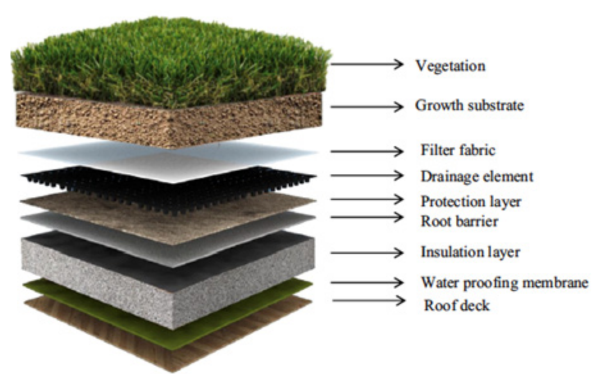


Figure 2. Structure of a Green Roof (Vijayaraghavan, 2016)

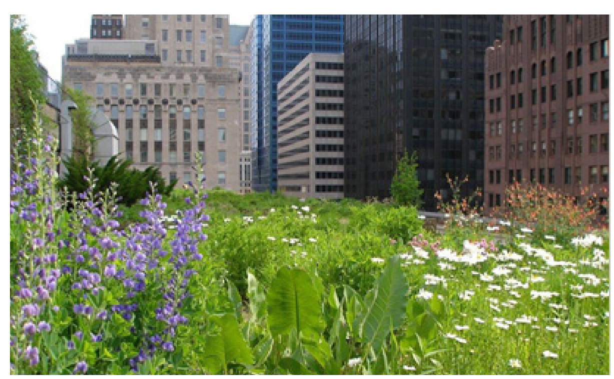


Figure 3. Green Roof on Chicago City Hall (http://www.greenroofs.com/projects/pview.php?id=21)

similar and provide similar environmental and ecological benefits, including thermal insulation, mitigation of UHI (Versini et al., 2015), the reduction of runoff flowing into the sewer system (Oberndorfer et al. 2007), and the removal of pollutant and the prevention of flooding and erosion (J. Li 2006). Green roofs can collect rainfall before it reaches the ground and becomes runoff. Traditional roof transform about 91% of rainfall into runoff, whereas some configurations are able to reduce this amount to 15% (Mentens et al., 2006) or 10-0% (Versini et al., 2015). Overall, the performance of green roofs depends on their configuration and structure (i.e. what and how layers are stacked) (Mentens et al., 2006; Versini et al., 2015; Zhang et al., 2018), and on the intensity of the rainfall event, whereby the smallest the event the better the performance (J. Li 2006; Versini et al. 2015).

Permeable pavements are porous surfaces similar to concrete, but able to capture, filter and retain storm water runoff. Materials include permeable concrete, crushed stones, and porous asphalts, and BMPs are usually used to replace traditional impervious pavement in parking lots, walkways and sidewalks, and low traffic roads (Yu, 2013). The structure is dependent on site and hydrologic conditions, but it usually includes surface pavement layer, a stone aggregate reservoir layer, and a filter or fabric layer at the bottom (Virginia Water Resource Research Center 2011). Overall, permeable pavement

Figure 4. Permeable Pavement at UH Manoa, ITS Building

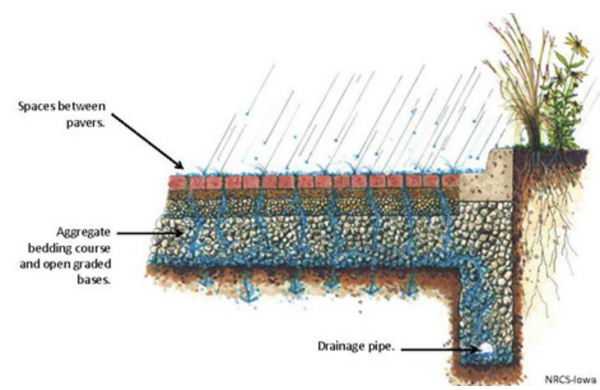


Figure 5: Structure of permeable pavement (https://metroblooms.org/2016/12/22/permeable-pavement-maintenance/)

can reduce stormwater runoff volume by 45% - 75% (depending on design characteristics) and can be used to capture rainfall directly or runoff coming from surrounding impervious areas (Cheesepeake Stormwater Network and Karst Working Group 2009).

2.2.2 Green Infrastructure in Hawaii

There are few examples of Green Infrastructure in Hawaii and comprehensive state or county strategies and plans are lacking. The only broad and large-scale initiative is the one of the State Department of Transportation which, through the Mālama i ka wai initiative, finances and implements features for stormwater management along State highways. Projects focus on both stormwater management and erosion control measures shoulders, medians and road barriers, such as the installation hydromulch, nutrients and grass layers on six sites along Kawainui Watershed (Oahu), or the layering of grass seed, mulch, and rows of vetiver grass on Kamananui Road in Wahiawa, just outside the study area (Hawaii State Department of Transportation 2018).

Building scale projects are also scarce. An interesting case study is the NOAA headquarters in Pearl Harbor (not too far from the study area), a former 350,000 square foot World War II aircraft hangar and airfield that has been re-adapted to house administrative offices. The project, includes high-performance buildings (designed by Ferraro Choi) and landscape (designed by Ki Concepts), including the tarmac that uses native grass bio-swales and porous paving to manage stormwater runoff volume and quality (Ki Concepts 2014). Another example is the ITS Building on the UH Manoa campus, which addresses stormwater management through the use of permeable pavement, bioswales with native plants, and green walls (Ferraro Choi and Associates Ltd. 2017).

At the community level, many projects are being supported by the non-profit organization Hui O Koʻolaupoko (HOK). The organization is active in restoration and LID projects providing coordination among stakeholders and partners as well as education, outreach and volunteer activities (HOK, 2018). Their LID projects include: (1) the retrofit of a 12,000 sqft concrete parking lot on Popoiʻa Street (Kailua), which entailed the installation of pervious pavements and the restoration of the riparian habitat with native plants and raingardens (HOK, 2018b); (2) the installation of 3,000 sqft of raingardens and native vegatation on the Windward Community

College campus; and (3) the Raingarden Program, which supports home or business owners in designing and installing small scale raingardens on their lots (HOK, 2018c).

In terms of larger GI plans, the City and County of Honolulu requested the assistance of the EPA Greening America's Communities program to elaborate strategies and conceptual designs for four selected sites in the Kapalama-Iwilei area (Environmental Protection Agency 2018). The project proposes the use of GI features and network not only to improve the environmental quality of the site (i.e. stormwater management) but also as a way to promote walking and biking (complementing the TOD objectives in the area), improve resilience to sea level rise and climate change, and provide places for community recreation and interaction.

Figure 6: Hydromulch project along the roads in the Kawainui Watershed

Figure 7: Tarmac at the NOAA headquarters (https://www.papahanaumokuakea.gov/news/irc_move.html)

Figure 8: Parking ot retrofit in Kailua (HOK)

2.3 Stormwater Runoff – Impacts and Spatial Methods

GI is able to manage the volume of stormwater through the various processes that take place within the different layers of the facilities. In general, BMPs such as bioretention and green roofs use their soil or organic layer and their vegetation layer to collect stormwater and/or runoff and eliminate it through evapotranspiration and infiltration through the soil or organic layers (Davis, 2008; Davis et al., 2009; Hunt et al., 2012; PGCo, 2007; Li, 2006; Purvis et al., 2018; Versini et al., 2015; Vijayaraghavan, 2016). The water that is not eliminated through these processes is slowly directed into the sewer pipes. The ability of GI in managing stormwater depends on complementary physical, chemical and biological processes performed by the various layers, including infiltration, evaporation, evapotranspiration, filtration, absorption, assimilation, nitrification, denitrification and thermal attenuation (Davis et al., 2012; PGCo, 2007).

The performance of bioretention and green roofs in stormwater management is well documented. For example, Davis (2008) observed that these facilities have the ability of mimicking the hydrological performance of the predeveloped site in terms of runoff volume, peak flow and peak delay. The study was conducted on two 28 m^2 - bioretention facilities collecting runoff from 0.24 ha asphalt parking lots for 2 years and during 49 rainfall events, and their probability of meeting (or improving) pre-development conditions was established to be between 31-55% (Davis, 2008). As far as green roofs, Mentens et al. (2006) estimated that runoff coming from a green roof represents only 15% of the stormwater from the rainfall event (for traditional roofs is 91%), and Versini et al. (2015) observed a 90-100% retention of stormwater from small rainfall events.

Reducing the amount of rainfall that stays and flows on the ground is only one goal of sustainable urban drainage. Reorganizing the patterns of stormwater is also important, as it allows to re-direct the flow to other areas where infiltration or storage is possible (Miguez and Veról 2017). In this context, it is important to consider the role of impervious land cover on urban hydrology. The ability of a surface to percolate water directly affects (1) the amount of runoff, the higher the imperviousness, the higher the runoff volume, the higher the volume of water that does not seep into ground; (2) the rates of shallow and deep water infiltration (the more extensive the impervious cover, the lower the rates); and (3) the rates of evapotranspiration (ET), which decrease as the amount of impervious cover increases (Matlock and Morgan 2011). Integrating GI into the urban fabric represents an effective way to reduce the volume of stormwater and increase the opportunities of infiltration and storage of the stormwater that are not captured in one area. GI can provide great help in *patching-up* the landscape and break the continuity of impervious land covers. BMPs can be single small items on buildings (e.g. green roof), block-wide elements (curbside bioswales), or large city-wide features, such as greenways. This great variety and flexibility create patterns inside the urban fabric, but also at the regional scale, connecting cities and landscape. As such, “co-benefits and trade-offs” not only transfer across scales and alter the flow of energy and materials across patterns and levels (Alberti et al. 2003), but also vary in significance and magnitude, influencing the achievement of specific goals, in this case stormwater management (Demuzere et al., 2014, p.13).

The spatial composition of cities is essential in understanding how green infrastructure works or will work, how it can be monitored, and/or changed to improve its performance. In this regard, Ahern (2007) observe that urban landscape elements can be classified in (1) patches, i.e. parcels with relatively homogenous features, such as parks and wetlands, providing habitat, aquifer recharge areas, source and sinks for local flows of species and nutrients; (2) corridors, i.e. linear area of one land cover type (e.g. rivers or roads), that provide habitat and corridors for flora, fauna, and nutrients; and (3) matrices, that are areas with distinct land covers and uses, such as residential neighborhoods or industrial areas. The concept of greenways is useful to GI planning because it can serve as a conceptual framework to connect BMPs across an area and design their network. These are linear elements of vegetated space that connect other vegetated spaces or ecological features along a linear path.

2.3.1 Spatial Methods for Runoff Mapping

The production of runoff is complex and produced volumes are dependent of multiple factors such as precipitation depth, land geology and geomorphology, land cover, land uses, soil, atmospheric interaction, vegetation, etc. Rainfall-runoff models capture this complexity and simulate the transformation of rainfall events into stormwater runoff, as well as its impacts. Water coming from a precipitation is deposited on the surface and involved in a series of loss processes that transform or transported it. Figure x illustrates the various processes of the water cycle on land. These loss processes are dependent on evapotranspiration rates and the lag time between a specific precipitation, and include (Maidment, 1993):

- **Interception**, i.e. when water is intercepted and retain by vegetation or other surfaces;
- **Depression storage**, i.e. water travels to and pools in depressions in the basin surface (e.g. lakes and swamps), and is finally lost to evaporation or infiltration;
- **Evapotranspiration**, which can happen during infiltration and while water is inside a depression;
- **Infiltration**, i.e. when water is absorbed back into the soil.

The process of infiltration is the most important of the loss processes (Maidment, 1993), and it is therefore central when calculating and modeling stormwater runoff. Generally, in fact, stormwater runoff can be defined as the “surface runoff produced at the ground surface when the rainfall intensity exceeds infiltration capacity” (Maidment, 1993, p. 9.2). The existing methods and calculations to estimate runoff are multiple and their differences depend on the relationship established between rainfall and runoff. Choosing a specific method depends on the research question, the availability of data, and the existing hydrologic conditions (Maidment, 1993).
The two most commonly used deterministic methods are the Rational Method and the U.S. Soil conservation Service relation, or SCS-CN. The **rational method** is widely used to estimate flooding in small rural drainages as well as urban drainage design. It is a simplified analysis of runoff that calculates peak discharge as a function of rainfall intensity, runoff coefficient, and drainage basin area (Maidment, 1993), based on the following equation:

$$q = F\ C\ i\ A \tag{1}$$

where q represents peak discharge; F is a unit conversion factor equal to 1.008 for intensities in *in/h*; C is the runoff coefficient, i.e. the ratio of runoff to rainfall; i is the rainfall intensity; and A is the area of the area of the drainage basin. When used for design of urban drainage, this method needs to include the calculation of both the time of concentration, t_c, and the runoff coefficient. The first is function length of the channel from divide to outlet (in feet) and the average channel slope (in *ft/ft*). The runoff coefficient is dependent on land use and is usually calculate based on standard values. This method allows to estimate the travel time of runoff through basins and it is particularly useful in the urban context as it includes the consideration of different uses and land covers, which directly affect stormwater infiltration.

The **Soil Conservation Method** (SCS-CN) estimates the volume of runoff based on land cover and rainfall intensity as well, but also includes soil hydrologic conditions. This method is widely used globally and in the United States was adopted by the Department of Agriculture as the main method for hydrologic studies in urban watersheds. More specifically, the SCS-CN method is part of a "simplified procedure to calculate storm runoff volume, peak discharge, hydrographs" etc. (United States Department of Agriculture, 1986, p.i), and it can be used for the design of soil conservation and/or flood protection projects (Maidment 1993). The SCS-CN method is based on the following equation:

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

Where Q is the runoff depth in inches, P is the rainfall depth in inches, S is the potential maximum storage, and is the initial abstraction, i.e. the result of loss processes antecedent to runoff and generally depending on land cover and soils (USDA, 1986). Empirically, initial abstraction is assumed to be equal to I_a=0.2S, which can be substituted in 2, giving:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \tag{3}$$

Potential maximum storage, S, is dependent on the specific combination of land cover and soil condition across the watershed, which can be expressed by the value CN. This value ranges from 0 to 100, where 0 is the most permeable (e.g. a body of water) and 100 is the least permeable (e.g. a concrete parking lot) and can be calculated by the formula:

$$S = \frac{1000}{CN} - 10 \tag{4}$$

The combination of soil and land cover characteristics takes into account (1) the actual land cover of an area and/or the existing land use on it; and (2) the hydrologic conditions of the soil, or Hydrologic Soil Groups (HSG). The ability of water to percolate into the soil is in fact influenced not only by what covers the ground, but the characteristics of the ground itself. HSG are determined based on surface permeability and surface intake rates (USDA, 1986, p. 2-1) and consist of four different classes (Maidment 1993):

- A: soils with high infiltration and low runoff, such as deep sands or aggregate silts
- B: soil with moderate infiltration, such as sandy loams
- C: soils with slow infiltration, such as clay loam, shallow sandy loam, and soils whose organic content is low
- D: soils with very low infiltration, such as swelling plastic clay.

Equation (3) and (4) can be solved based on figure 9 (showing the relationship between runoff, precipitation and curve numbers) and table 1.

As highlighted above, the production of runoff is inherently spatial and dependent on variables that vary across space, such as land cover and soil characteristics. There spatial methods to model hydrologic processes and watershed hydrology are many, some examining the morphology of the land and its relation to the movement of water, and other looking at the direct relationship between rainfall and runoff. Overall, methods are based on the spatial delineation of basins and catchment areas, or on distributed models of rainfall-runoff. The most commonly used and easily accessible of these models is the Hydrology toolbox in ArcGIS (ESRI 2015). This suite of tools uses elevation data, in the form of Digital Elevation Models (DEM), to derive information relative to the movement of water across an area. Single tools produce raster files describing flow direction, flow accumulation (i.e. the linear paths along which water accumulates), basin and watershed delineation, which trace the boundaries of catchment basins based on the flow accumulation map or points of high flow accumulation such as rain gauges (ESRI 2015). These ArcGIS tools represent an excellent resource to model and map the movement of water across a basin, and efficiently support more sophisticated methods of hydrologic analysis in general, and runoff production in particular. For example, Jain et al. (2004) developed a DEM-based process based on computational sequencing and a specific *ad hoc* algorithm that provides a rainfall-runoff model for a catchment area, producing information on flow routing for isolate storm events. This model simulates the sequence of events during a rainstorm in each pixel based on the phenomena and equations governing these events, for example using Philip two-term infiltration model for soil infiltration and St, Venant equations for overland flow (Jain, Kothyari, and Ranga Raju 2004).

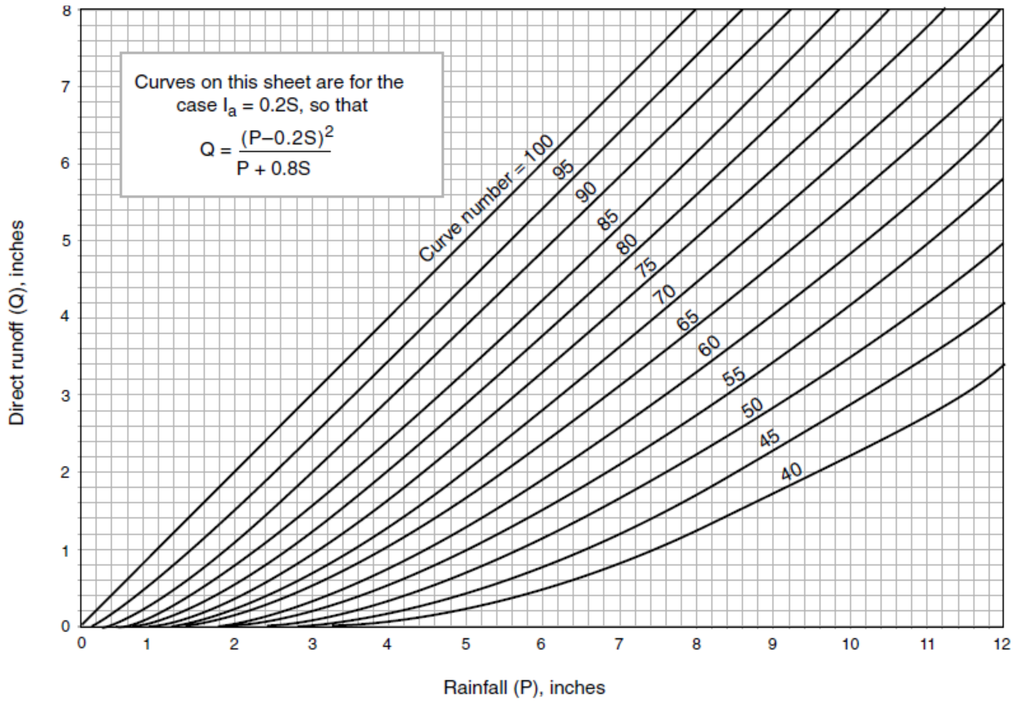


Figure 9:Curve numbers representing the relationship between rainfall and runoff volume (in case of equation 1.3). (USDA, 1986

		Curve numbers for HSG			
Land Cover Type and Hydrologic Conditions	**Avg % of Impervious Cover**	**A**	**B**	**C**	**D**
Open space (lawns, parks, golf courses, cemeteries, etc.)					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Urban districts:					
Commercial and business	85	89	93	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)		77	86	91	94

Table 1: Runoff Curve Numbers for Urban Areas. Adapted from USDA (1986)

The model incorporates information such as land uses, slope, soil and rainfall, and the outputs of their analysis included flow velocity, depth and discharge at the catchment outlet, that allow to visualize and assess the spatial patterns of flow depth and runoff (Jain et al., 2004). This method provides clear visual and quantitative information the paths through which runoff flows across a catchment, and includes soil and land cover consideration in routing simulation. Another example of stormwater runoff modeling using GIS is the study of Li et al. (2011) that used topography, soil properties, land cover, location of sewer lines, rainfall, and runoff coefficients to estimate drainage areas. The use of storm sewer information (i.e. slope, direction, pipe capacity, etc.) can be useful to GI planning because it portrays the patterns and flow of runoff across the area, but also shows the presence of the existing grey infrastructure, highlighting opportunities for integrating grey and green systems.

2.3.2 SCS-CN based Applications

Besides GIS there are other models that study the spatial distribution and/or the spatial information relative to the production of stormwater runoff. The applications of the SCS-CN method are multiple and play an essential role in GI decision making, planning and siting. The method is widely used and established as it relies on "well documented" environmental data and is adopted not only in the US, but across the globe (Soulis et al., 2009). Some of these models do not necessarily use or produce maps (see the EPA's SWMM and L-THIS-LID models below), but are nonetheless able to generate data on quantity and quality of stormwater runoff based on topography, land cover and land cover and rainfall data. Interestingly, many of these models were specifically developed to support GI design, as they allow not only site assessment but also the evaluation of alternatives. The US Environmental Protection Agency (EPA) developed several tools and models to model watershed hydrology and rainfall-runoff relationships. In particular, the Storm Water Management Model (SWMM), designed specifically for GI planning and based on the SCS-CN method, can be used to predict the quantity and quality of runoff in urban areas, and forecast or evaluate the impact of GI implementation (Environmental Protection Agency 2015). SWMM is an application that allows the integration of various types of data and the creation of hydrologic models for an urban watershed. More specifically, the hydrologic modeling function includes several hydraulic models (including the Curve Number method) that can help determine the flow and quality of runoff moving through and exiting the storm sewer system. In SWMM users can draw a simplified version of a site and its system of drainage areas, outlets, conduits, and a rain gauge (see fig. 10), to which information such as land cover and slope can be added. The software then combines this information with precipitation data (also input by the user) and generates information on stormwater flow (e.g. hydrograph), quality, and quantity for the catchment area, conduits or outlets. Figure 10 illustrate some of the results produced with SWMM. Despite its capabilities and utility, the main limitations of this application are that analysis can only be performed at the site level and that it does not generate data applicable to distributed analysis of rainfall-runoff. In terms of input, each study area needs to be sketch from scratch in the “map” interface of the software and land cover, slope, and technical information need to be input manually for each element. In terms of outputs, SWMM does not generate any spatial outputs (i.e. shapefile or raster) and importing the outputs available into GIS would require time consuming conversions, coding, etc. In general, this application is useful to perform site-specific assessments, but presents limitations when applied to strategic, large-scale analysis. Harbor (1994) provided one of the first examples of spatial application of the curve number method, developing a local planning tool to evaluate the impacts of land use change on surface runoff. This method consisted in (1) identifying the different combinations of land use and HSG across an areas; (2) delineating them by hand on

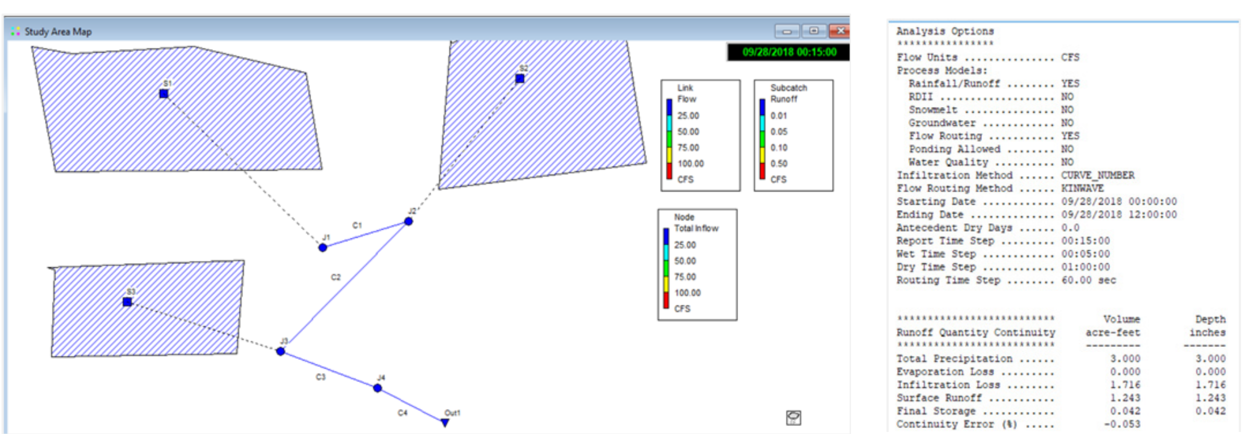


Figure 10: Example of SWMM map and results (EPA, 2015)

a separate map; (3) determine their CN based on the USDA (1986) guidelines (see table x) and reporting it on a spreadsheet; (4) determining an area-weighted CN; and (5) finally compute runoff estimates using a SCS-CN based equation:

$$Q = \frac{(P - \frac{200}{CN} + 2)^2}{P + \frac{800}{CN} - 8} \tag{5}$$

Where P represents seasonal or yearly rainfall data. Overall, current GIS application of the curve number method are based on the same assumptions of Harbor's (1994) procedure and automate the process of overlaying layers and using equation 1.3. This approach is widely employed in the research on land use changes impacts on watershed hydrology, as it allows to highlight the direct relationship between soil, land use and runoff and make direct connections between these variables. Another example of rainfall-runoff model based on the curve number method are the Long-Term Hydrologic Impact Assessment (L-THIA) and the Long-Term Hydrologic Impact Assessment for Low Impact Development models, or L-THIA-LID. This modeled was developed by researchers at Purdue University with the aim of understanding the benefits of LID practices in the improvement of the hydrology and water quality of a lot, site or watershed (Ahiablame et al., 2012). This model is available online on Purdue's website and it allows to estimate the average runoff volume and nonpoint source pollution loads for the various land use and HSG combinations in a given area (Purdue University 2015). Results are computed based on (1) rainfall and soil data specific to the state or county specified by the user; (2) the different combinations of land use (i.e. commercial, industrial, low-density residential, high-density residential, water/wetlands, grass/pasture, agricultural, forest) and HSG; and (3) the area of each one of these unique combinations for the current conditions and scenario conditions. This model uses the SCN-CN method to estimate the volume of runoff and the Event Mean Concentration for nonpoint source pollutant loads. More specifically, the volume of runoff is calculated for each combination of land use and HSG by multiplying the runoff volume obtained in equation 1.3 by the area of these units, according to the following equation (Ahiablame, A. Engel, and Chaubey 2012):

$$Q_u = Q \times A_u \tag{6}$$

As intended by the name, this method was developed specifically for the evaluation of

LID practices application and the development of GI scenarios, and it is widely used not only as a decision-making support tool but also as a way to evaluate the impacts of land use and land use changes on runoff quantity and quality. For example, Wang (2005) combines L-THIA and GIS to estimate the depth and volume of runoff (and related NPS pollutants load) produced by the current and simulated land uses. The workflow to estimate runoff depths consist in reclassifying the land cover layer based on the 8 land use types used by L-THIA, combining this land use types layer with the HSG layer and assigning a CN to each combination, and finally combing CN with daily rainfall series to obtain runoff depth for each land use type (Wang et al., 2005). Similarly, Liu et al. (2016) developed a decision-making support tool based on the L-THIA-LID model as well, and integrated not only with GIS tools, but also with spatial optimization algorithms and framework. More specifically, runoff volume estimate were computed for each unique combination of land use and HSG (i.e. Hydrologic Response Units, HRU) based on SCS-CN-based structure of the L-THIA-LID model. The optimal locations of BMPs in the watershed were determined by the combination of the L-THIA-LID results with spatial optimization algorithm, that generated a number of possible BMP combination scenarios. Results did not include the identification of specific sites for BMPs, but larger areas were single features would maximize the environmental benefits with minimum costs. Furthermore, L-THIA-LID can be used to calculate runoff generated by different GI features and evaluate their effectiveness in reducing stormwater management. For example, Eaton (2018) used the online tool to evaluate and compare how much runoff different BMPs produce in an urban watershed, not only assessing the efficiency of features, but also providing support to decision making.

Besides those based on the L-THIA-LID model, simple and user-friendly rainfall-runoff models include methods that apply the SCS-CN principles directly into GIS. This approach is, in fact, common in the research on the impacts of land use and land use changes on urbanized watersheds. These studies can be based on vector or raster data and use common GIS tools, such as map algebra, to overlay land use/cover, soil, and rainfall data as a functions of the SCS-CN equation. In other words, each layer will represent a term of equations 1.2 and 1.3 (i.e. CN, S and P) and will be combined in a final layer *Q*. For example, Yao et al. (2018) apply the method to the evaluation rainfall-runoff risk in different land use areas in Beijing (China). First, satellite imagery of Beijing was reclassified into different Urban Function Zones (UFZ), i.e. areas dedicated to specific social and economic activities. Second, these were UFZs were combined with three different Antecedent Soil Moisture Conditions and a CN was assigned to each combination (a constant HSG (i.e. B-group) was assigned to the entire area). Using modeling tools is ArcGIS, runoff depths were obtaining by combining CN with design rainfall amounts (Yao et al., 2018). This analysis was performed on vector polygons and results were generated at the UFZ scale. A similar approach to SCS-CN but performed in a raster environment comes from Weng (2001). Their study was focused on calculating the impact of the increase of impervious cover on the hydrology of the Zhujang Delta (China) between 1989 and 1997, by estimating the depth of stormwater runoff and its patterns across the watershed in these two different years. The analysis was focused on creating a layer for each of the terms in equation 1.3, and then using map algebra to combine these layers with rainfall data and compute runoff depth. First, the following layers, and associated equation terms, were created (Weng 2001):

- Curve Numbers, i.e. the term “CN” in equation 1.3: Land cover and HSG were combined into one raster and then recoded based on the SCS-CN table (United States Department of Agriculture 1986).
- Potential maximum storage, i.e. the S in equation 1.3: this was done using map algebra, which created an S value for each pixel in the raster grid.

Second, the runoff depth raster was created by combining the above layers with a rainfall raster using map algebra and equation 1.3 (Weng, 2001). Finally, the runoff layers for 1989 and 1997 were compared.

2.4 Sustainability of Community - Access to Public Green Space

The role of vegetated spaces in the life or urban residents and communities is invaluable and indisputable. In the current global context, urban vegetated spaces, such as parks, garden, riparian buffers, etc., are key elements of sustainability and sustainable development. In this regard, urban *green* can be the element that improves not only the environmental and ecological quality of a city, but also the quality of life of residents and users. In particular, parks are essential in providing public open space where people can meet, gather and mingle, increasing their social capital. This section reviews the literature on social capital and its role in building sustainable and resilient communities, and the role of public space in general (and parks in particular) in producing and enhancing social ties. As introduced above, the concept of sustainability is complex, and understanding what it means and entails in the social sphere is equally intricate. Dempsey et al. (2011) provide a useful discussion of the social dimension of sustainability, and distinguish between social equity and sustainability of community. The first, is concerned with distributive justice and the fair allocation of resources and service (e.g. housing), while the second one focuses on social capital and cohesion. More specifically, social capital refers to the networks, norms and level of trust that organize a community (e.g. a neighborhood) and contribute to cooperation and coordination (Putnam, Leonardi, and Nanetti 1993). Sustainability of community deals with "the collective aspects of social life" (p.294), and social capital become the element that can help building a strong, fair and just community that can sustain and reproduce itself (Dempsey et al., 2011). The built environment plays a key role in building sustainable and cohesive communities, serving as the backdrop of social life where residents interact and participate, and where they can find a sense of pride and attachment to the community and/or the neighborhood (Dempsey et al., 2011; Forrest & Kearns, 2001). In this context, public space provide opportunities on one hand for informal contact among neighbors (Kaźmierczak 2013; Sullivan, Kuo, and Depooter 2004), and on the other for community gatherings and activities. These formal and informal, organized or in promptu encounters play an essential role in building cohesiveness in the community, increasing the induvial and communal social capital. The quality of the design of public spaces influences the probability of people interacting and forming bonds (Ijla 2012), and the presence of vegetation (i.e. grass and trees) can encourage residents to gather and engage with each other (Sullivan, Kuo, and Depooter 2004). Therefore, parks become instrumental in building those "residential-based network" that encourage tolerance, cooperation, social order, and a sense of belonging

(Forrest and Kearns 2001), producing benefits such as mutual support and help, civic engagement, neighborhood regeneration, disaster preparedness and resilience.

2.4.2 Defining Park Accessibility

As highlighted above, access to open and vegetated green space is beneficial to the social cohesion of a community and its members. In this section, parks are the main example of public green space and the access to them is consider a proxy for the amount of vegetated elements and land cover (e.g. tree canopies, vegetated medians) present. It is assumed that areas where residents have a low level of park accessibility would benefit more from the implementation of green infrastructure as a form of *public green*.

Besides landscape and spatial planning, public health and environmental justice are the main contributing disciplines to the discourse around park access. The first focuses on parks as enjoyable and walkable locations for physical activity, analyzing how access relates to the healthy or unhealthy conditions of residents (Giles-Corti et al. 2005; Pikora et al. 2002; Sugiyama et al. 2008). While environmental justice studies the distribution of vegetated spaces among different demographics (e.g. race, ethnicity, income) and highlights any unjust differences in the possibility of accessing green space and related environmental, social and economic benefits (Dai, 2011; La Rosa, 2014; Nesbitt et al., 2019; Nicholls, 2001; Wolch et al., 2014). Despite the differences in objectives and methodologies, different disciplines aim at identifying the ease (or lack thereof) with which residents can access nearby parks in terms of distance to be covered (on foot, by car or mass transit), and/or the amount of green space available to each individual living around it. In general, accessibility can be defined as the opportunity of contact with a specific phenomenon (Johnston and Gregory 1981) or "the potential for reaching spatially distributed opportunities" (Páez, Scott, and Morency 2012). The definition of park accessibility is complex and depends on the theoretical and methodological combination of spatial, demographic, social and built environment data. Overall, it can be considered a "multidimensional construct" (Wang et al., 2015, p.53) that influences people's attraction to parks based on a combination of (1) the physical dimension, such as parks' surface, proximity, walkability; (2) transportation networks and options, such as travel cost and time; (3) the knowledge of available parks and service offered; (4) social variables, such as safety or issues of social or ethnical/cultural exclusion; and (5) personal characteristics, such as availability of leisure time, an active or sedentary lifestyle, and financial affordability. At the broader community and institutional level, the ParkScore™, developed by the Trust for Public Land, ranks a city's park supply based on acreage (i.e. median park size and park acres as percentage of city area), investment per resident (including public and private investments and volunteer hours), availability of amenities (i.e. basketball hoops, dog parks, playgrounds, recreation and senior centers, restrooms, splashpads/spraygrounds), and access, i.e. the percentage of population living

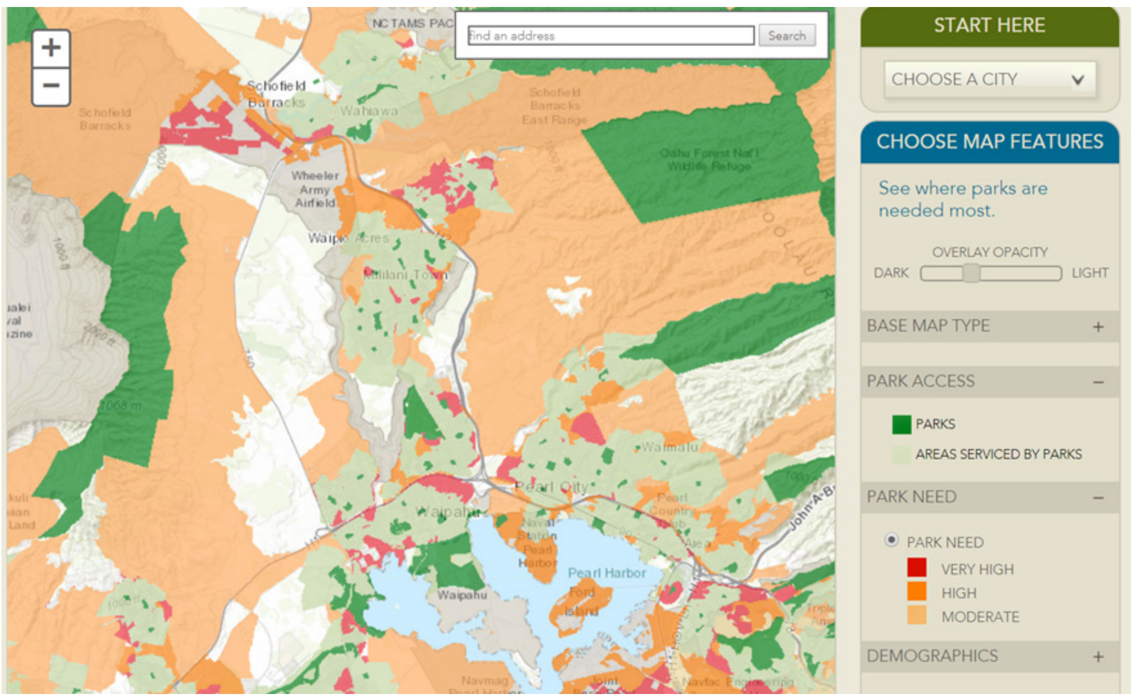


Figure 11: ParkScore map of the study area (https://parkscore.tpl.org)

within a ten-minute walk of a public park (Trust for Public Land, 2018). Figure 11 represents the spatial distribution of the ParkScore™ in the study area.

An interesting general framework that can be applied to the majority of park accessibility studies is the one developed by (Dony, Delmelle, and Delmelle 2015). At the base of this framework, parks are considered commodities and the spatial access to them is a function of (1) **willingness to pay**, i.e. the material and/or physical utility the average resident is willing to cover to use the park; (2) **supply,** i.e. the presence and quantity (e.g. acreage) of park available to the individual and/or the community; and (3) **demand**, i.e. is the number of people that use or may use the park.

Distance to parks is the cost that influences park accessibility the most, and determine what distances residents are willing to cover (i.e. "pay") are the cornerstone in park accessibility studies. Since the distance between a person's residence and a park has a high influence of park usage, i.e. people living closer to the park are those that visit the park more often (Giles-Corti et al. 2005; National Recreation and Park Association 2017), recommendation for a specific physical distance or an amount of time are always discussed in the literature. In general, people are more likely to visit a park if the live about 10 minute away from it (on foot), and the common recommendation of authors and planners is to locate parks within 800 m or ½ mile of residences. (National Recreation and Park Association, 2017; Nicholls, 2001; Oh & Jeong, 2007; The Trust for Public Land, 2018)

Supply of parks and green space is another essential variable in assessing the opportunity for residents to access park. In general, authors look at the amount of park surface or the type of facilities that are available to citizen in a given unit of space. The unit of space and the scale of the analysis varies, but in general the literature includes the analysis of parks within administrative boundaries, e.g. Census Block Groups or Tracts (e.g. La Rosa, 2014; Nesbitt et al., 2019; Nicholls, 2001), or within areas around parks, e.g. ½ mile buffers (Cutts et al., 2009; Oh & Jeong, 2007) or Euclidean distance from park centroids (e.g. Wang et al., 2015) .

Finally, **demand** is essential in understanding park access as observers if the supply of park is large enough to satisfy the needs of a community. In other words, looking at demand allows to determine if parks' surface, conditions and/or amenities are adequate to what the people require or may require in order to optimally access or use the park. Again, the literature focuses on thresholds and requirements for ideal park accessibility, recommending for example surface-to-people ratios. In this regard, the National Recreation and Park Association (NRPA) recommends to plan for 10 acres of park for every 1000 people (Nicholls, 2001).

2.4.2 Spatial Analysis of Park Accessibility

Determining the physical distance between parks and residents is the first and most important step in assessing park accessibility. In general, this is a "container" approach (Dony, Delmelle, and Delmelle 2015) focused on determining a geographic unit inside which park access is possible and outside which park access is impossible. These geographic units, i.e. catchments or service areas, are traced around a park based on specific parameter, e.g. maximum walking distance, based on a variety of spatial tools such as buffers and Euclidean distance, network analysis, and Floating Catchment Area (FCA) methods.

Park accessibility analysis based on buffers and Euclidean distance is the less complex and the most straightforward method, as it based on distances measured along a straight line. More specifically, in the context of ArcGIS (ESRI 2015) the Buffer tool creates buffer polygon(s) around inputs (point, line, or polygon) based on a given distance, while the Euclidean Distance tool calculates a straight-line distance from a specific input for each cell in the raster. Given the simplicity, these two methods are widely applied both as stand-alone tools and as part of more complex models and methods.

For example, Nesbitt (2019) analyzed the equity of park accessibility across 10 cities in the United States focusing on the variation in the resident-park distances across categories of income, race, ethnicity and race. First, authors calculate the Euclidean distance within 1000 m (3280 ft) of population-weighted block group centroids [2]and identified the parks contained within this spatial unit. Second, they calculated the surface of these parks (in m^2) and calculated the availability of green space for each census block by summing up the surfaces of the parks located within the same 1000m Euclidean distance of the same block group centroid. Finally, demographic data of residents were compared in order to highlight the just or unjust distribution of green features. Straight-line methods represent a valuable tool in simple and large-scale analysis, as they are able to portray well the general spatial characteristics of the distribution of parks or other services. However, they present limitations in smaller and more detailed contexts, such as urban environments, where movement on a straight line is not feasible or natural. To this end, network analysis can bridge the

2 These are points representing "the spatial distribution of the population" in each census block (Office of National Statistics 2016). Since population is rarely distributed across a block evenly, these points are not at the center of the block, but are shifted to represent the population distribution according to finer-scale data. They considered a better representation of the geographic location of population within a census block (Dai, 2011)

gap by allowing to look at pathways, right-of-ways, barriers, travel speed, etc. The network analyst extension in ArcGIS is a suite of powerful tools that allows to solve problems related to routes, service location and mobility in general. In the context of park accessibility, the Service Area tool is useful to identify the region that contains all the possible accessible streets around a specific point or set of points based on travel distance or time (ESRI 2018). The input of this tool include "facilities", i.e. a layer of the locations for which service areas are to be determined, and "street network". This is the dataset representing not only the configuration of the streets but also their characteristics such as speed limits or travel speed, length, direction (if one-way) and the presence of any impediments (physical barrier, traffic light, etc.).

Nicholls (2001) analyzed the equity of park accessibility in Bryan, Texas, based on both buffers and network analysis, but concluded that the latter is a "more realistic representations of the geographic extent of service areas" (Nicholls, 2001, p.216). In terms of methodology, the study was articulated in two phases, tracing park service areas first and then observing the density, race, ethnicity, age and economic status of the population living in these service areas. First, network analysis was used to estimate the actual routes residents would have to take to reach a park, i.e. the physical distance between residents and parks, based on a ½ mile distance (i.e. 10-minute walk) (figure 12). More specifically, the park entrances were used as facilities and the dataset of selected city streets (i.e. pedestrian paths) as the street network, and single service areas were generated for each park. Second, to evaluate the equity of the spatial distribution of parks, the author estimated the characteristics of the population by intersecting census block data and the park service areas previously determined. This approach is simple but accurate in the

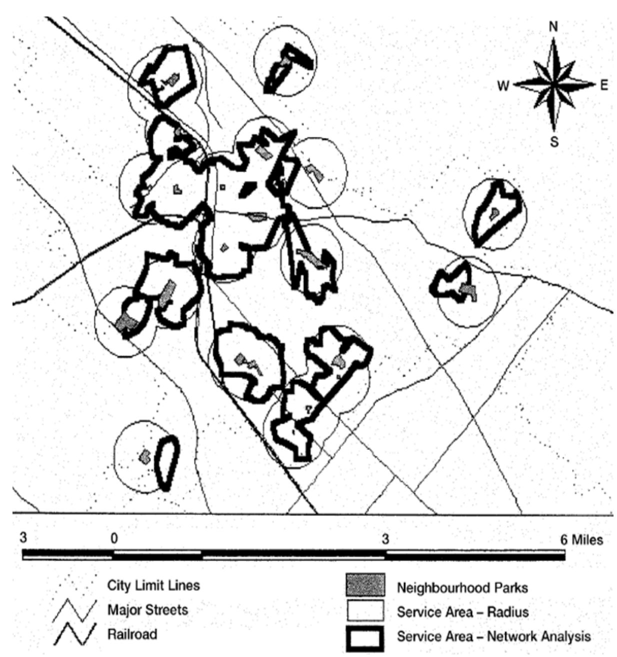


Figure 12: Delineation of service areas based on network analysis (Nicholls, 2001)

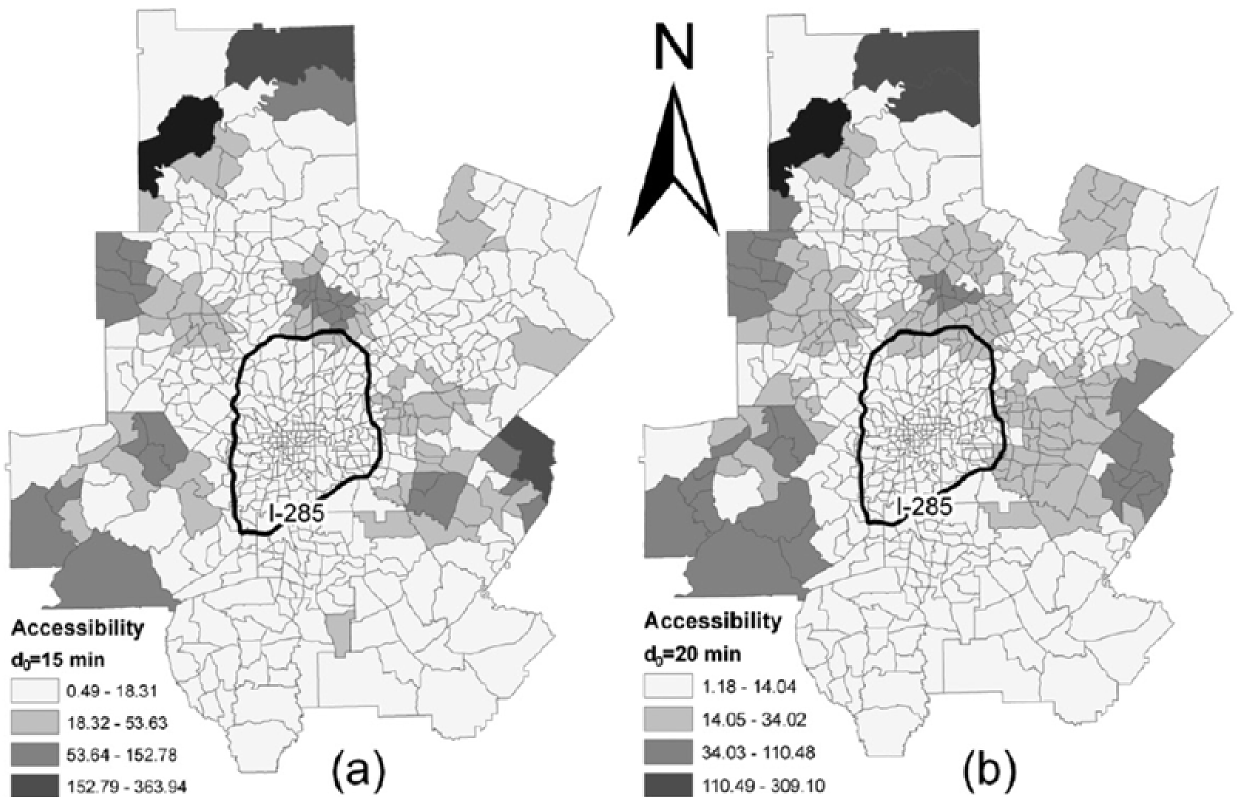


Figure 13: Accessibility scores for census tracts in Atlanta (GA) (Dai, 2011)

determination of service areas and offers an interesting example on how to infer demographic data from the combination of physical accessibility and census data.

The main limitation associated with the method described above is the assumption that (1) residents exclusively patron the park in the service area they live in and that individual parks are used exclusively by the people residing in its associated service area. In other words, catchments represents barriers that may misrepresent the actual interaction between users and service, and misinterpret accessibility. To overcome this, Floating Catchment Area (FCA) methods are common. These methods define accessibility as the ratio of services-to-residents inside a unit of space (usually Census Blocks) and calculate it not inside a static buffer, but inside a catchment radius or area that floats across the study area, moving using as centers the location points of services or residents (Luo and Wang 2003). More specifically, points represent services and residents (generally physical addresses for services and population-weighted centroids for residents) and the circle the maximum distance people are willing to cover to access the service. By moving the circle across the study area it is possible to capture the changes in number of services and residents and their ratio, and, similarly to kernel methods, understand how the "density" of accessibility varies among Census blocks (Luo & Wang, 2003). The most applied variation of the FCA is the 2-Step FCA (2SFCA), in which the accessibility of a unit of space is the sum of the accessibility scores calculate at each "shift". This method was developed by Luo & Wang (2003) to observe residents' accessibility to physicians in Chicago, and it is widely applied in the study of park accessibility. For example, Dai (2011) estimated the disparities in potential spatial accessibility to green spaces among communities of different racial/ethnical and economic status in Atlanta, GA. To this end, demographic data were represented as census tracts population-weighted centroids and physical accessibility was estimated based on driving travel time along the street network. The 2SFCA methods was used to observe the relationship between the number of residents and the amount of parks that they can potentially access both within and around catchment, and accessibility scores were calculated for each census tract based on this method (fig. 13).

2.5 Spatial Methods for Green Infrastructure

Due to its multifunctional nature, decisions around GI are complex. Policy, planning and design of these features requires carefull strategies and benefit from the support of articulate decision-making frameworks. Moreover, the inherently geographic nature of GI networks and features calls for tools that can perform spatial analysis and produce spatial data. In this sense, GIS is applied to GI in a variety of ways, including the siting of BMPs and their networks, the assessment of their performance, and the evaluation of costs. Overall, authors have dedicated considerable energies to the spatial analysis of GI, but few used GIS to support strategical siting decisions. Zhang & Chui (2018) call for the development of Spatial Allocation Optimization tools that would tackle the multi-dimensional and multi-disciplinary problems related to GI planning, identifying the spatial variation of environmental, social and economic benefits and constraints. In this regard, they encourage the development of comprehensive and cyclical frameworks that can (1) quantitatively assess and describe the differences between BMPs and features; (2) provide indicators to monitor the performance of GI; and (3) identify optimal location based on multiple criteria (Zhang & Chui, 2018). More specifically, optimal locations should consider local policies and plans, stakeholder involvement in and willingness to pay the costs of GI projects, socio-economic variables, land use, and hydrology (i.e. rainfall and groundwater). Similarly, (Hansen et al. 2019)) discuss the importance of the concept of GI multifunctionality in strategic decision-making around urban green space planning. In this sense, the assessment of the functions of existing ecosystem services and the identification of where these can/should be improved, is the base of the identification of GI priority areas. Furthermore, the use of GIS to visualize, produce and store spatial information is essential to this process of analysis (Hansen et al. 2019).

One of the first examples of spatially explicit GI planning is the study of (Li et al., 2005), that proposed a conceptual model for GI planning for the Beijing area. The model is based on the ecological concepts of patches, corridors, and matrices and aims at creating a large and integrated ecological network that would connect ecological patches inside the city as well as connecting the ecological system of the city with the broader region. At the neighborhood level, authors proposed to connect existing parks, urban forest and agricultural land through green wedges, i.e. vegetated patches and lots. More broadly, within the city population centers (i.e. city centers, satellite towns and settlements) will be connected not only by traffic and development axis, but also by green belts, corridors and patches. Finally, at the regional level, Beijing and its ensemble of ecological features would be connect to the city of Tianjin through an ecological buffer (Li et al., 2005). These ideas are represented graphically and spatially by conceptual maps that cleverly visualize the relationship of each vegetated space across the region. However, the maps *is* conceptual and methods do not include the spatial analysis of variables of different natures, which would not support the complex decision-making process around GI.

Rogers & Hiner (2016) discuss the use of urban agriculture lots as GI features and propose a method for their strategic siting in Austin, Texas. In this case, the main environmental goal for which GI is being evaluated is stormwater management, and the prioritization and selection of sites is based on the Hydrologically Sensitive Areas (HAS). HSAs are areas prone to flooding and are represented by a topographic index determined based on elevation, soil hydraulic conductivity and depth of soil restrict layer (Rogers & Hiner, 2016). In summary, the identification of optimal GI locations were based on a combination of Digital Elevation Model (DEM), soil data, and an inventory of land suitable for agriculture (based on land use and farmland data). A similar approach was adopted for the identification of sites suitable to the application of LID measures in the Lake Thunderbird Watershed in central Oklahoma ((Martin-Mikle et al. 2015). The research was divided in two phases and combined DEMs, soil data, street centerlines, stream networks (30m- buffers), and land use. The first identified HSAs using the topographic index, while the second selected specific BMPs based on land use, spatial scale, and ability to interact with impervious covers at different scales of application across the watershed. Results included not only the selection of 140 sites suitable for GI implementation, but also the classification of these sites based on their most appropriate type of BMP. Despite the multifunctionality of GI, the methods discussed so far focus only on environmental aspects and benefits of GI, leaving behind any consideration of social and community considerations. In this sense, Vallecillo et al. (2018) identified different GI designation areas across Europe based on the potential of local ecosystem to produce services, including open space recreation, and assessed GI scenarios also based on the proximity between ecosystem services and residents. More specifically, the method, based on Spatial Conservation Prioritization, allowed to observe the potential of different land uses to produce ecosystem services, and to estimate the spatial distribution of 11 of these services, namely soil erosion, water retention, net ecosystem productivity, pollination potential, pest control, habitat for common birds, habitat for species of conservation concern, and outdoor recreation potential. The different priority ecosystem service were modeled across space using three different spatial constraints scenarios, one based only on the potential for ecosystem service production, the second based on service production and proximity of services to centers of population; and the third one, based on the location of areas where ecosystem conditions are poor (and potential for service scarce) (Vallecillo et al., 2018). The major shortcoming of this analysis is that it does not consider any specific characteristic of communities and societies (e.g. income or employment rate) leaving out information that may greatly impact GI implementation in either a positive or negative way. An example of combination of social and environmental variables GI spatial planning comes from Norton et al. (2015). Their research focused on identifying possible BMPs and their locations across Melbourne, Australia, as means to reduce UHI and related environmental and public health issues. More specifically, the analysis starts by overlaying (1) thermal exposure, i.e. remotely sensed thermal data as proxy for air temperature; (2) vulnerability of citizens to heat, combining the number of senior citizens, the number of children under five, and the Index of Relative Socio-Economic Disadvantage; and (3) behavioral exposure, i.e. those areas in the city where people are likely to gather, such as parks. Once this first step was concluded, sites were selected based on the combination of data on the existing gray infrastructure and vegetation, and the each street's need for GI implementation. The latter is based on the ratio of street width to height, i.e. canyon geometry, which influences solar radiation and heat accumulation (Norton et al., 2015). This method is a good example of strategic framework as it combines both socially and environmental goals across space, and identifies precise areas in which GI is most needed.

2.5.1 Land Suitability Analysis for Green Infrastructure

As discussed above, the spatial methods applied to the study of green infrastrcture are many, but methods that support the multi-criteria strategic planning of GI are scarce. Currently, a common method applied to strategic planning and siting problems is Suitability Analyis (SA), a spatial Multi-Criteria Decision-Making method (MCDM) (Malczewski 2004) able to combine information from diverse sources and identify their trade-offs and priorities across space. More specifically, SA can combine and overlay environmental, social and econmic data and, based on previously determined criteria, idenitify the areas that are most suitable for a specific land use, zoning class, activity or building type. SA was originally developed by landscape architects such as Ian McHarg (see (McHarg 1992)), Charles Elliot and Jaquiline Tyrwhitt, that would overlay transparent maps of natural and human-made features with each other in order to visualize their overlaps and identify the suitability of areas for a given purpose (Malczewski 2004). With the advancement of GIS and GIScience, SA increased its scope and methods, and is today used for a great variety of site decisions. The application of SA are multiple and are highly used in the context of urban and regional planning and development, and it can be performed at variaous scales and used to answer a variety of questions. In this regard, it can be used to select areas based on Boolean criteria (i.e. yes/no questions) or more detailed and complex issues, for which it is necessary to establish priorities and hierarchies (Malczewski 2004). In the first case, for example, polygons that are determined to be suitable can be used to *carve-out* areas from a larger study area. This allows to keep the areas within the threshold of suitability, and eliminate those that are out. In the second case, SA can be used to model continous and categorical criteria, assigning a higher relevance to one layer versus the rest layers in the model. Often,in fact, spatial methods are integrated with MCDM methods such as the Analytic Hierarchical Process (AHP) in order to assign a weight to each layer. Weights are usally assigned based on empirical evidence of experience, and reflect the order of priorities assigned to variables. To this end, raster analysis and weighted overlay[3] are considered ideal, as they perform map algebra on each cell of the grid taking into consideration assigned weights too. For example, (Zomer et al. 2008) used SA to evaluate the availbility of suitable land for the climate change mitigation activies (afforestation/reforestation) proposed by the United Nations Framework Convention on Climate Change and the Kyoto Protocol. At the finer scale, SA was used to evaluate the suitability of land covers and select specific site for the installation of wind and solar farms in Colorado (Janke 2010). The analysis included wind potential, solar potential, distance from cities, ideal land cover, distance to transmission lines, population density, federal land, and distance to roads. In order to better capture the trade-offs between the variables and reflect the relance of the weights assigned to them, the analysis was performed using raster data.

Despite the inherently spatial nature of green infrastructure and the complexity of its multi-disciplinary applications (Benton-Short, Keeley, and Rowland 2017), the research on suitability analysis for GI is scarce. (Uy and Nakagoshi 2008) combined air pollution, the presence of water systems, industrial zones, existing land use, and "valuable" landscape in the evaluation of possible sites and configuration of a comprehensive GI plan in Hanoi (Vietnam). The method is a valuable

3 In ArcGIS, this tool "Overlays several rasters using a common measurement scale and weights each according to its importance" (ESRI 2016)

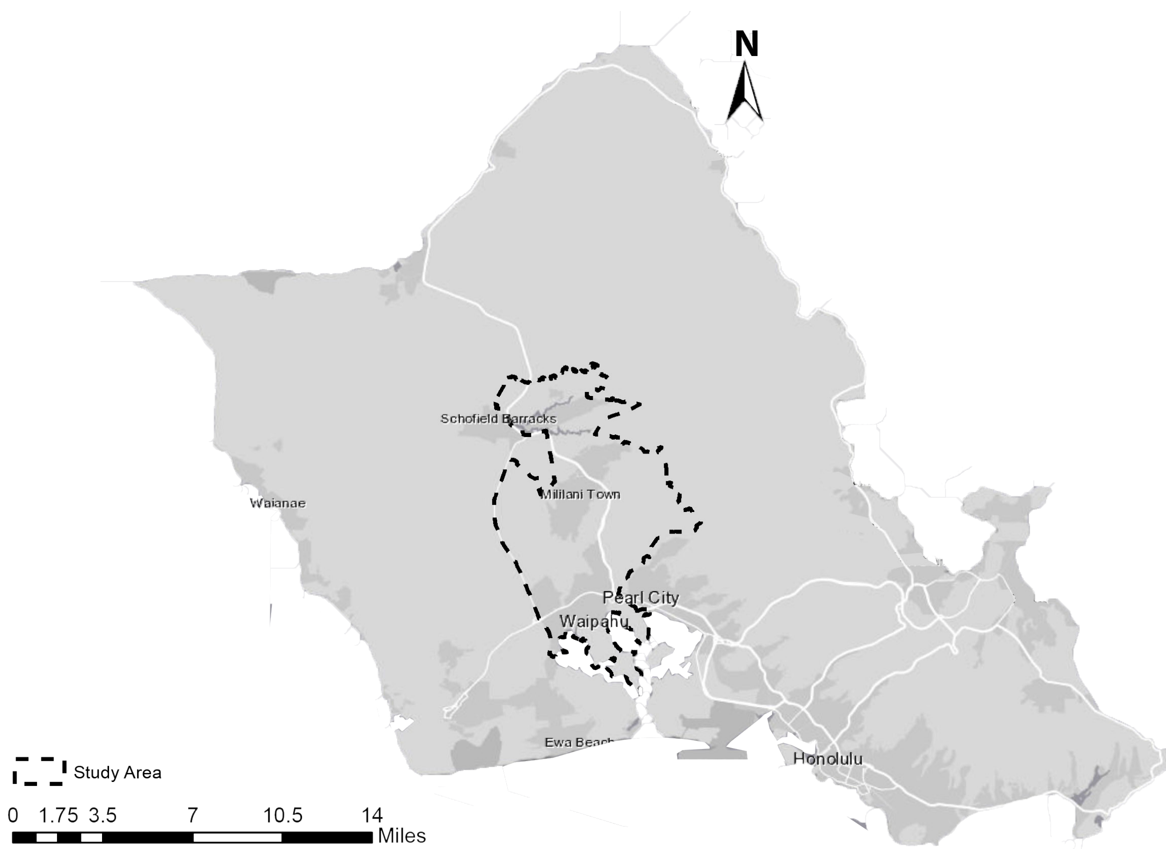
strategic tool as it allows to compare the existing conditions of green spaces in Hanoi to the current city master plan, but it does not include any information on hydrology or data on community and society. Another interesting strategic use of SA for GI comes from (Meerow and Newell 2017), who proposed to evaluate the trade-offs and synergies of GI-provided ecosystem services and identify the areas were GI is most needed through the use of a Green Infrastructure Spatial Planning (GISP) model. The variables considered include stormwater management (i.e. precipitation and runoff coefficient), the Social Vulnerability Index (SoVI) [4], access to green space, air quality, urban heat island effect, and landscape connectivity. On one hand, the variables selected reflect the multiple functions that GI can perform, but the analysis is performed at the census block scale and does not allow the identification of scatter plots and lots.

4 See http://artsandsciences.sc.edu/geog/hvri/sovi%C2%AE-0

Chapter 3 Research Site – Central Oahu Watershed

3.1 General Information

The research site located in the Central Oahu Watershed, which is identified by by the Watershed Management Plan of the Honolulu Board of Water Supply (Board of Water Supply 2018). More specifically, the study area includes all the Census Block Groups contained within the boundaries of the Central Oahu Watershed, and excludes the conservation areas in the Koolau Mountains and the military zones of Wheeler Army Field and Schofield Barracks (map 1).



Map 1: Study Area

This area was chosen for its geographical scale, i.e. watershed, as well as for the opportunity of exploring and combining several sustainable development strategies adopted by the City and County of Honolulu (C&C) and the State of Hawai‘ i (SOH). As introduced above, one of these strategies is the Watershed Management Plan, while the other one is Transit-Oriented Development (TOD). The latter, in fact, will affect the southern portion of the study area where two stations will be located (West Loch and Waipahu), and for which a TOD Neighborhood plan has been adopted (City and County of Honolulu, Department of Planning and Permitting 2018) (figure 14). The redevelopment opportunity offered by TOD and the conservation strategies of the Watershed Management Plan represent excellent opportunities for rethinking the development, transportation, infrastructure, urban form and the decision-making process. Moreover, despite clear sustainability and resilience goals and initiatives, GI is not explicitly discussed by the State of Hawaii and the City and County of Honolulu. In other words, the area provides an excellent opportunity to explore the theme of sustainability and explore the potential for a strategy that has been explicitly planned for yet.

Figure 14: Rail stations and TOD areas in Waipahu (https://www.honolulu.gov/tod/neighborhood-tod-plans/dpp-tod-waipahu.html)

3.2 Environmental Conditions– Land, Topography, and Hydrology

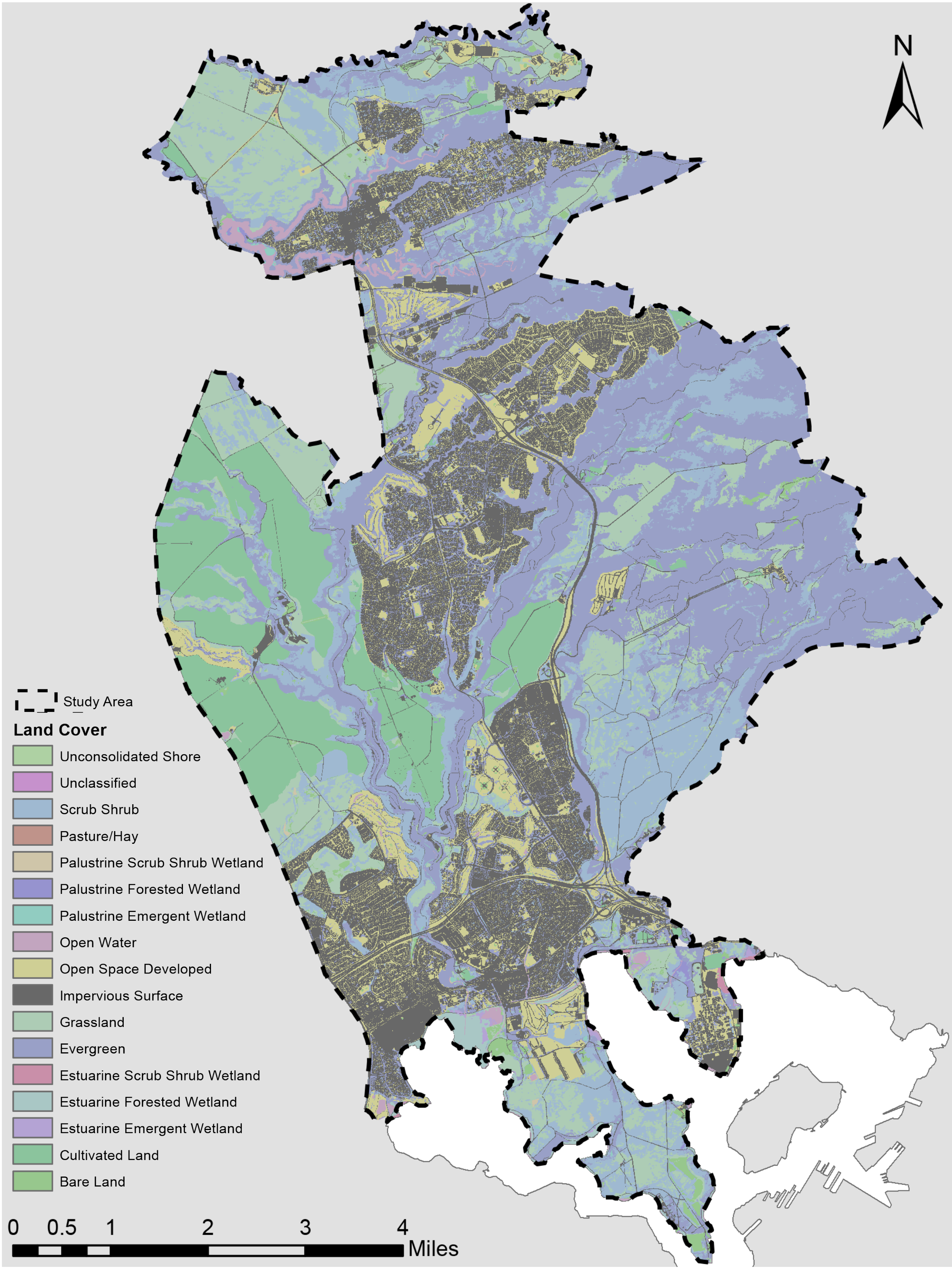
The area is 33,397 acres wide and includes the communities of Waipahu, Waikele, Waipio, Kunia, Mililani, and Wahiwa. Current land use in the area is varied, including agricultural, conservation and urban. The urban area included residential, mixed-use, industrial and commercial uses (see map 3), and change is expected following the implementation of the City's TOD plans. In terms of land cover (map 2), almost 22% of the study area is impervious with development concentrated in the main centers of population (i.e. the mostly dense populated areas) and along the major roadways. Other land covers include bare and cultivated land, pasture, shrubs, open space development, and wetlands. In terms of zoning, 45% of the study area is dedicated to agriculture and the second largest uses are low-, medium- and high-density residential (24%), and federal/military (17%). Other uses include business, mixed-use, industrial and preservation.

Zoning Class	Area (acres)	% of Study Area
Agriculture	15055.44	45.55%
Business	365.76	1.11%
Federal/ Military	5627.15	17.02%
Industrial	594.60	1.80%
Mixed Use	326.33	0.99%
Preservation	3125.90	9.46%
Residential	7959.04	24.08%

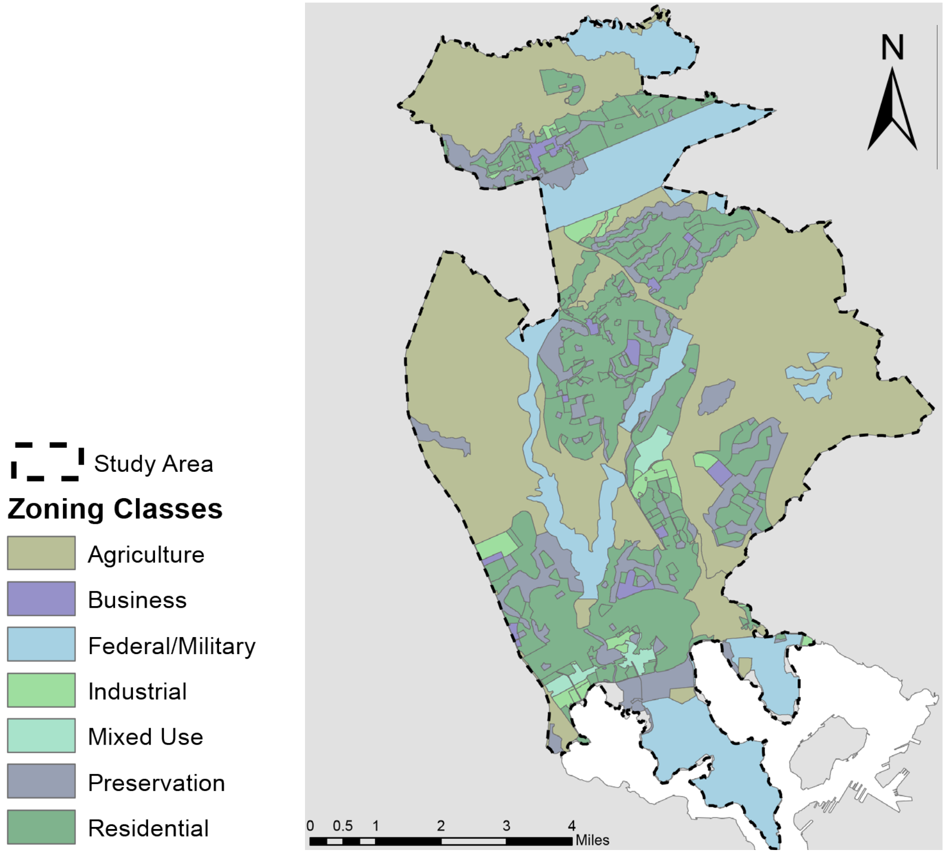
Table 2: Summary of Zoning Classes

The study area is part of the in ‘Ewa moku, the group of ahupua‘a enclosed between the Wai‘anae Mountains on the West and the Ko‘olau mountains on the East, and includes the watershed of Kapakahi and Waipio and part of the Waiawa, Waikele and Kiikii watersheds. Since this is the central part of the moku, elevation is moderate and ranges from 0 on the shoreline to 1466 ft in the areas closer to the mountain ranges and the center of the island (see map 4).

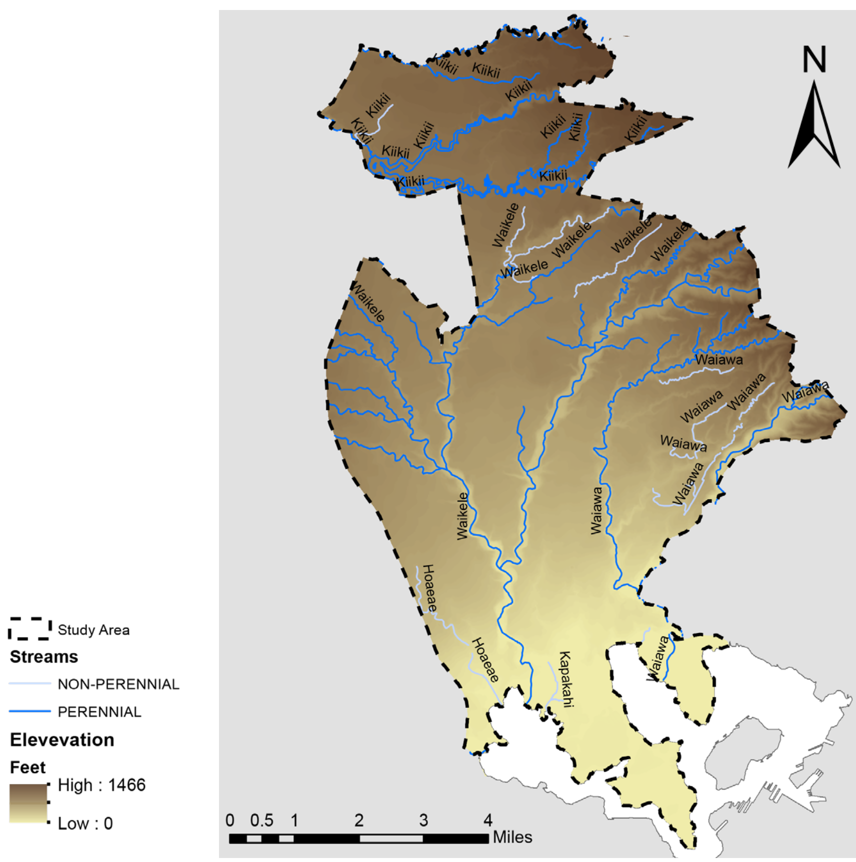
In terms of hydrology, the State of Hawaii extracts most of its drinking water from groundwater aquifers. The study area is located in the Waipahu-Waiawa Hydrologic unit (Department of Land and Natural Resources - Commission on Water Resource Management 2008), which has a sustainable yield of 104 MGD (i.e. 25% of Oahu’s sustainable yield) and every day about 50-69% of this amount is used (Commission on Water Resource Management - Department of Land and Natural Resources - State of Hawaii 2014). As discussed earlier in 2.1, water conservation and reuse strategies in this hydrologic unit are extremely important and are included in the Water Master Plan and the Watershed Management Plans of the Honolulu Board of Water Supply (2016). Surface water is also an important environmental consideration of the study area. In total, there are 118 miles of perennial and non-perennial streams that belong to eight different main streams, namely Hoaeae, Honouliuli, Kapakahi, Kiikii, Waiau, Waiawa, Waiawa Springs, and Waikele (see



Map 2: Land Cover



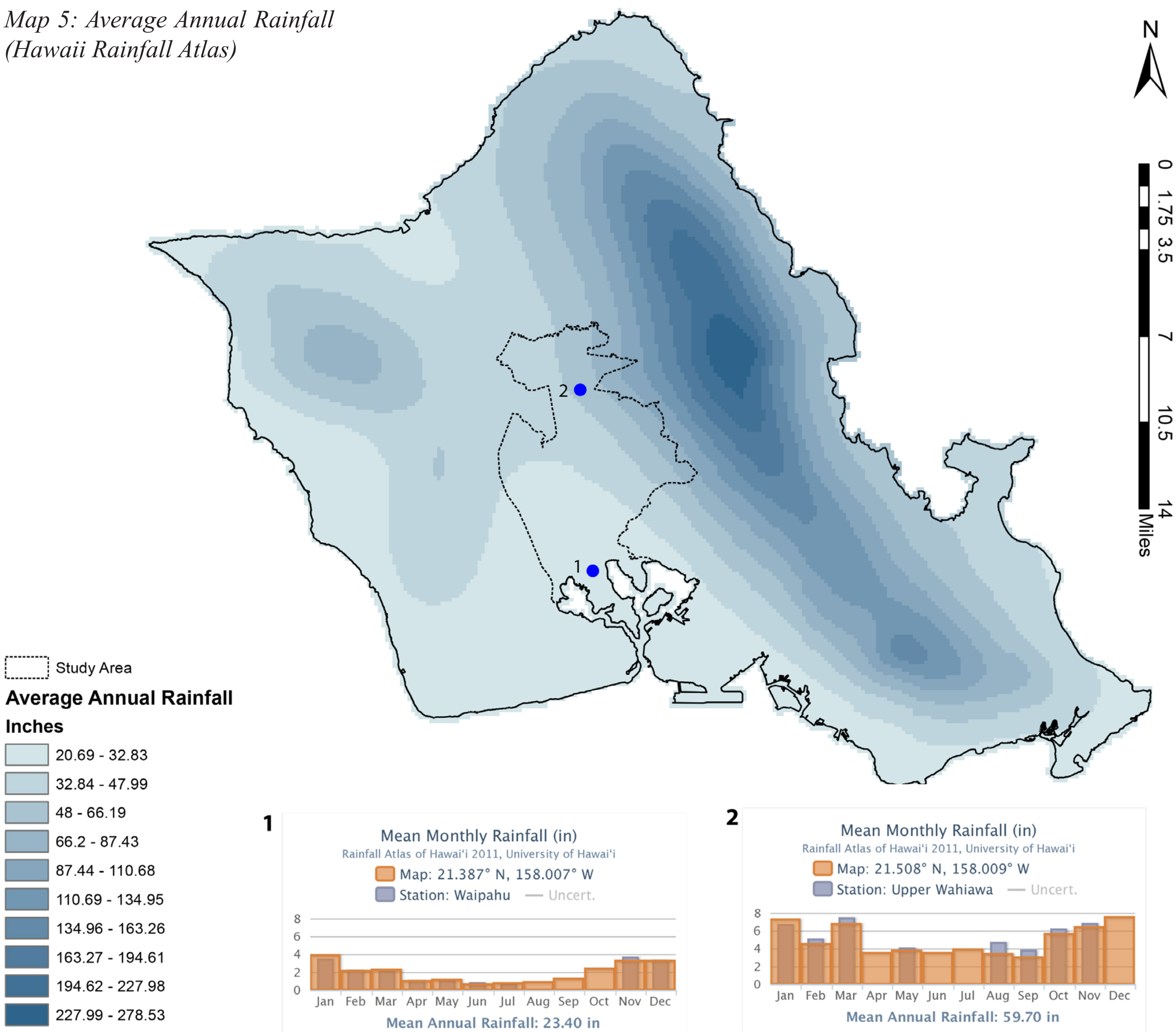
Map 3: Zoning



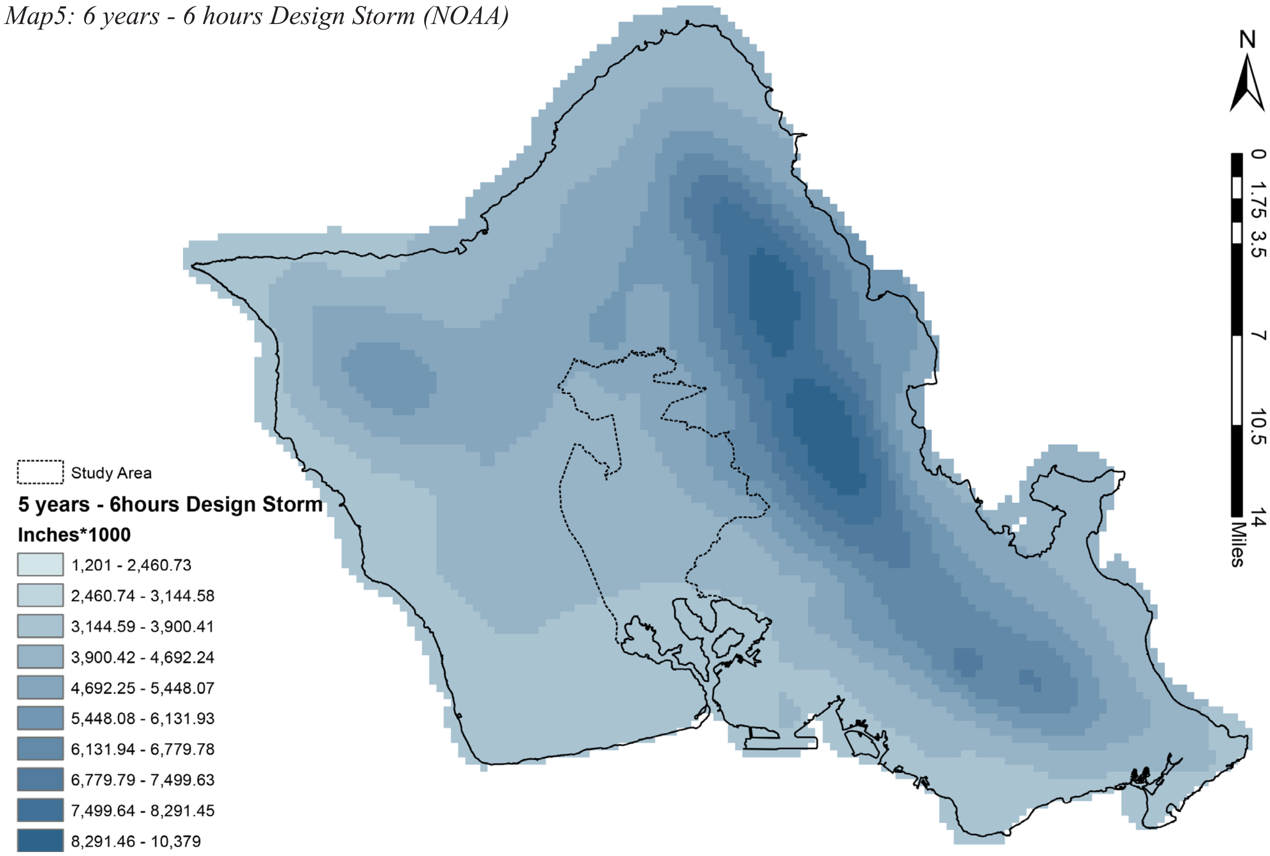
Map 4: Elevation and streams

map 4). Maps 5-7 show the average annual rainfall and the distribution of predicted rainfalls for two different design storms, namely 5 years-6 hours and 100-years, 6hours. In terms of rainfall spatial distribution, the three maps show similar patterns with highest amounts of rain on the Ko‘olau Mountains and the Northen part of the Waianae Moutains, and drier areas in the south west region and the center of Oahu. In the study areas, average annual rainfall ranges from 23.40 inches in Waipahu to 59.70 inches in Wahiawa (map 5). NOAA predicts between 0.0012 and 0.0039 inches in 6 hours for more common design storms (5 years, i.e. 20% probability) and 0.00258 and 1.66 inches in 6 hours for less probable storms, i.e. 100-years and 1% probability) (NOAA's National Weather Service - Hydrometereological Design Studies Center 2018).

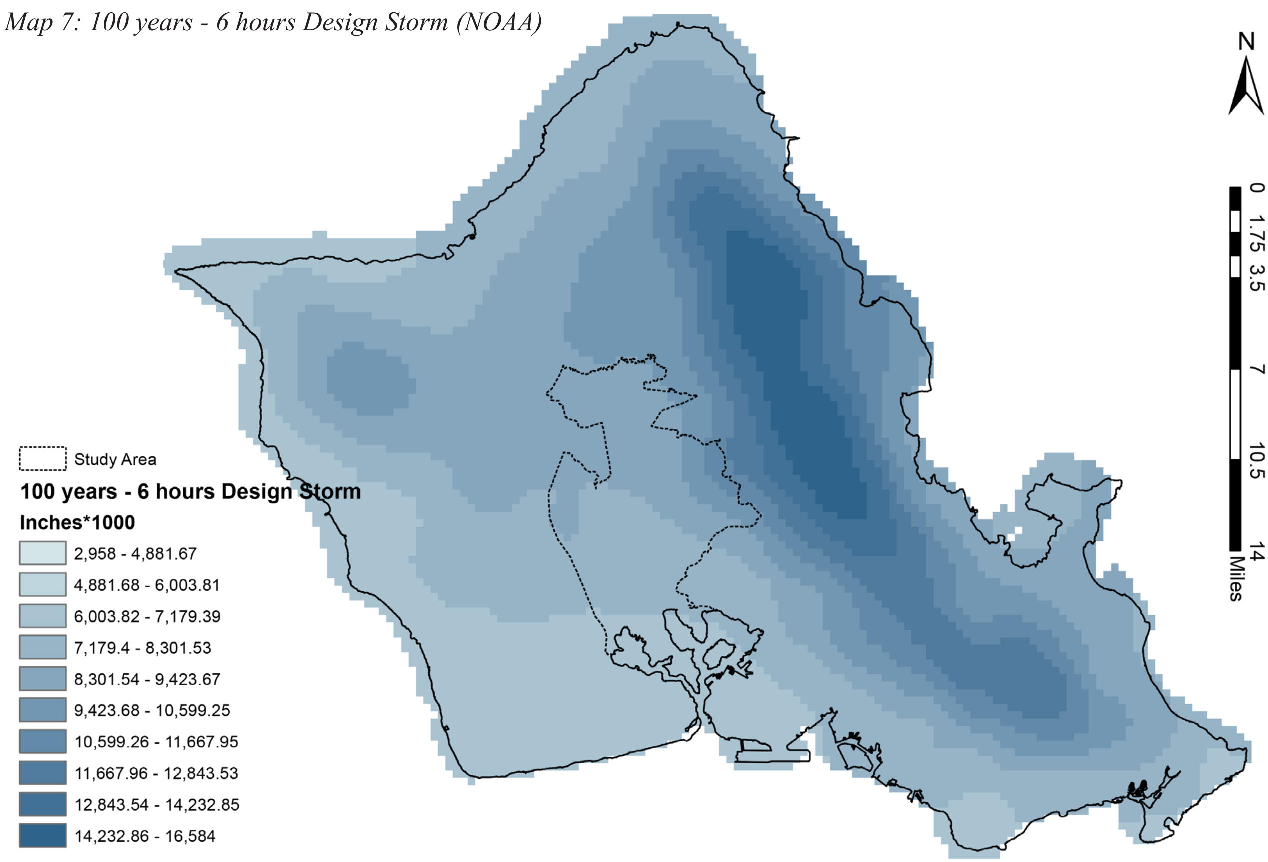
Map 5: Average Annual Rainfall
(Hawaii Rainfall Atlas)



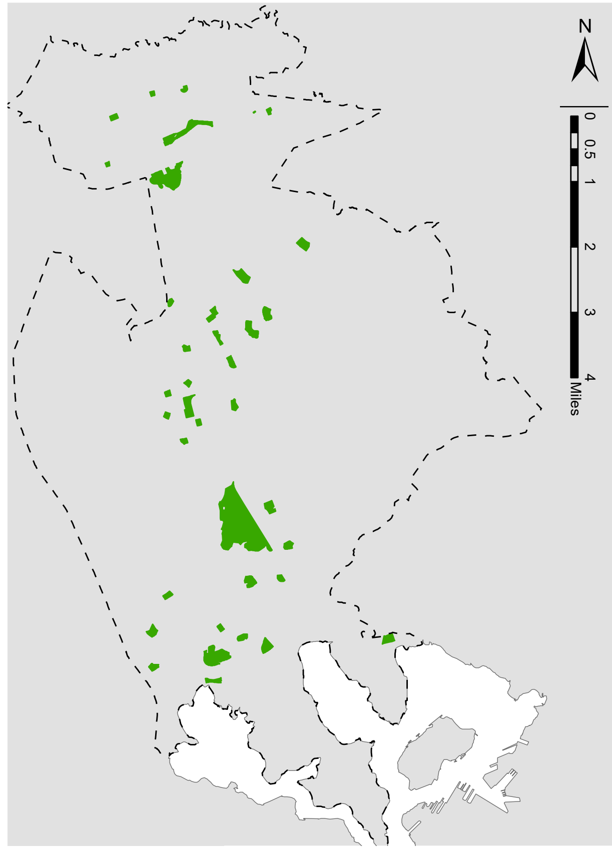
Map5: 6 years - 6 hours Design Storm (NOAA)



Map 7: 100 years - 6 hours Design Storm (NOAA)



Open green space is distributed across the residential area in the form of regional, neighborhood, community and mini parks. There overall quality of the parks varies significantly across the study area, with large, well maintained and with good amenities park (e.g.Wahiawa Botanical garden, fig. 15) and inaccessible (though beautiful) areas such as the Pouhala Marsh Wildlife Sanctuary (figures 16 and 17). For the analysis (see chapter 5 for more details), 38 parks were selected for a total area of 673.24 acres which, based on the minimum recommended ratio of 10 acres/1000 resident (Trust for Public Land 2018) is only 43% of the ideal park surface recommended for this study area, i.e. 1586.62 acres, but existing parks only add up to. At least 913 acres of additional park space would be required to meet this general standard.



Map 8: Parks selected for the analysis

3.3 Socio-Economic Conditions

The study area includes the communities of Waipahu, Waipi‘o, Waikele, Village Park, Mililani, and Wahiwa, home to 158,652 residents (United States Census Bureau 2015). Acccording to the 2017 estimates (United States Census Bureau 2017), the racial makeup of the study area is varied. 68-87% of the residents idenitfying with one race (figure 18) and within this majority, most are Asian (67-42%) while the concentration of other races varies among communities, e.g. Waipahu is 15% Native Hawaiian and Pacific Islander and 3.7% white, while Mililani Town is only 0.9% Native Hawaiian and Pacific Islander and 17.4% white (figure 19).

In order to assess the potential vulnerability of the population to natural disasters and social hardship, and to assess the overall stability of communities, a vulnerability index was calculated for each Census Block Group. More specifically, the analysis focused on the age of residents, highlighting the presence of children and senior citizens, income compared to the local poverty line, non-owner occupied housing and unemployment rate, which have been used as indicators of social sustainability (Cutter, Boruff, and Shirley 2003). First, within the CBG the percentage of children of ages between 0 and 17 ranges from 0 to 38.85% and sees the lowest concentration in South of Wahiwa and in the Eastern part of the study area (i.e. between Mililani and the Ko‘olau Mountains) (see map 9a). The areas where children make up a larger part of the population are in some parts of Mililani Mauka and the lower coastal areas of Waipahu. As far as senior citizens, the concentration of residents older than 65 range from 0 to 42.01% of the CBG population (map 9b). It is interesting to notice that some areas where there is a high concentration of senior citizens, correspond to lower concentration of kids 0 to 17, such as the central parts of Waipahu or some CBG in Mililani Town. The concentration of households that live at or below the 2015 poverty line for Hawaii, i.e. $13,550 - $ 47,010 for one-person and 8-persons

Figure 15: Wahiwa Botanical Gardens

Figure16: Pouhala Marshes Gate

Figure 17: Pouhala Marshes along Waipahu Depot Rd

households respectively (US Department of Health and Human Services 2015), ranges from 0 to 39% (only one CBG shows that 100% of its 5 surveyed residents have an income equal or lower than poverty line). Overall, the majority of CBG see a concentration of poor households between 0 and 50%, and the big exception is a large area in the East of the study site (map 9c). In terms of housing arrangements (map 9 d), the highest concentration (39.75-100%) of residents living in rented properties are concentrated at the Northern and Southern boundaries of the study area, i.e. Waipahu and Wahiawa, while the more suburban and agricultural areas seem to be home owners. Finally, the unemployment rate across the study area (map 9e) reaches 20.95% in certain CBG, a dramatic difference compared to the 3.2% average for Hawaii in 2015. However, the majority of

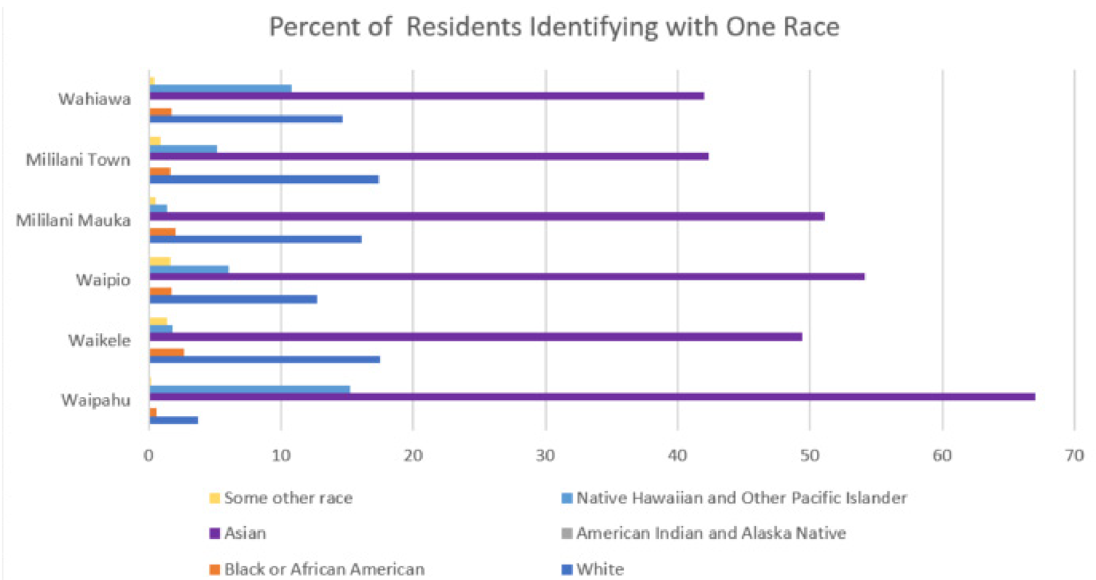


Figure 18: Racial Makeup of Study Area based on the 2015 Community Survey

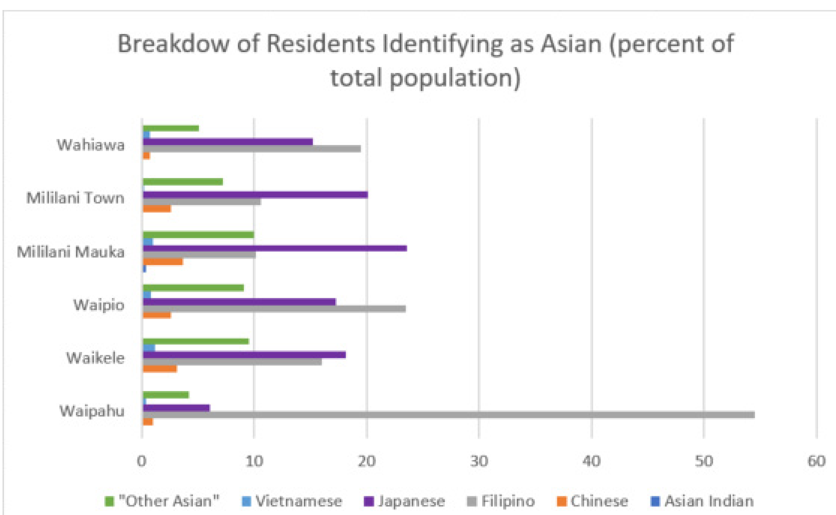


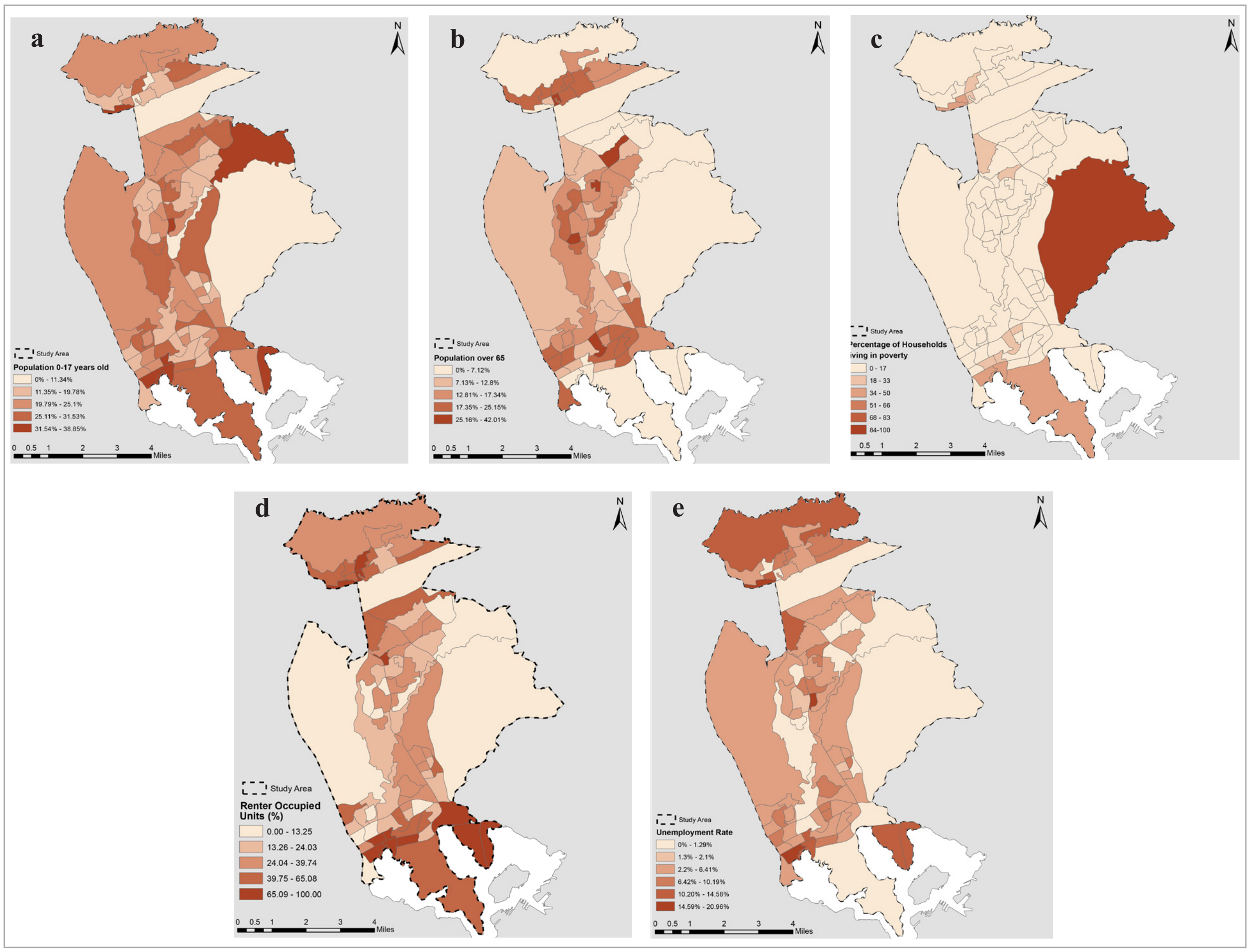
Figure 19: Breakdown of Asian Community based on the 2015 Community Survey

the CBG see lower unemployment rates, with peaks of 6.41%.

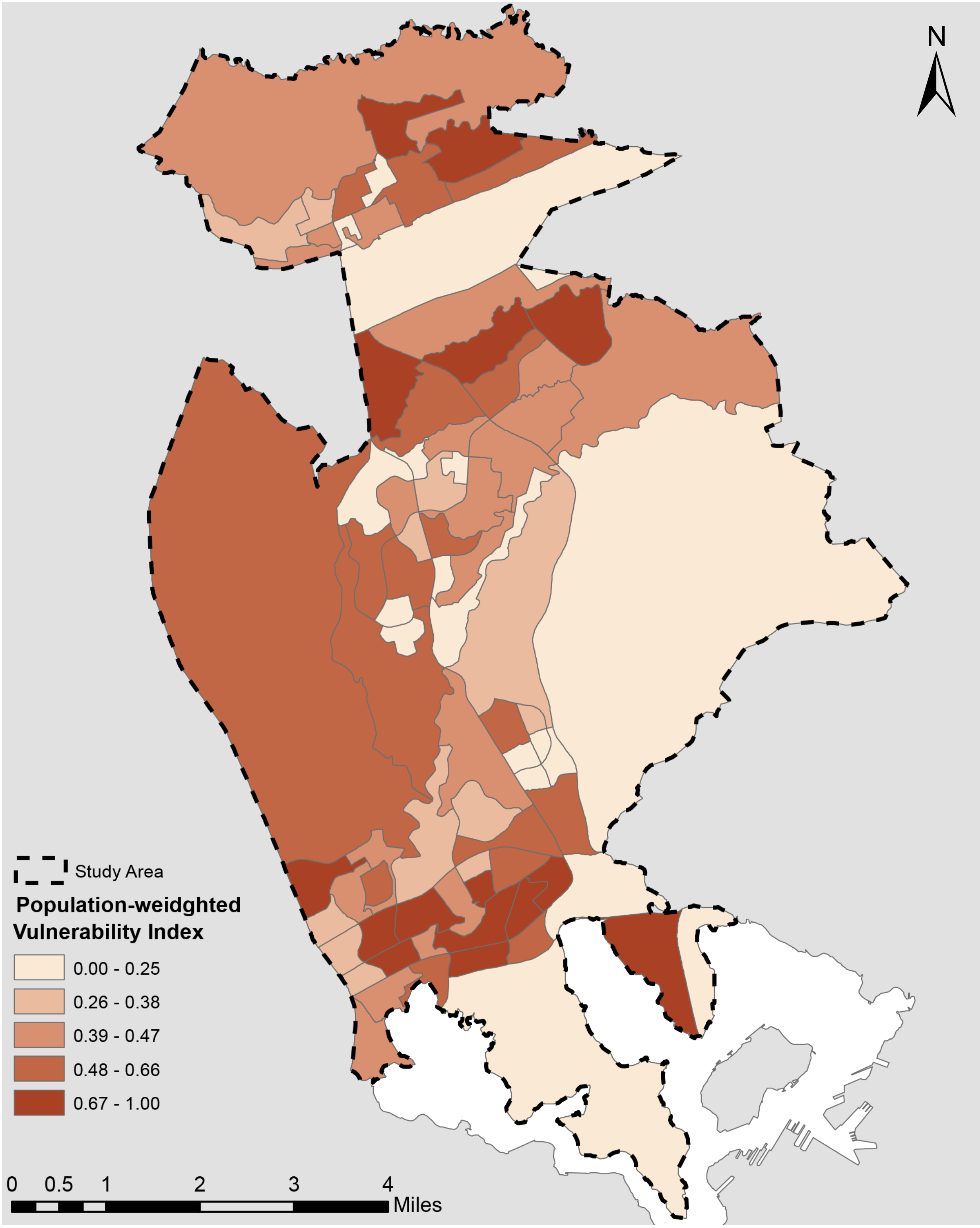
Vulnerability was assessed by combining the variables described above, giving priority to the ratio of children and senior citizens, followed by the ratio of households living in poverty, renter occupied housing, and finally unemployment rate. Other weighting schemes can be applied when relative importance among the indicators is known. Using the field calculator in ArcGIS, the variables were combined using the equation below:

$$VI = 25\%\ Childen + 25\%\ Seniors + 20\%\ Poverty + 15\%\ ROH + 15\%\ UR \quad (7)$$

The initial score obtained was then normalized and weighted for the population of the CBGs. As shown in map 10, large portions of the study area show a population-weighted Vulnerability Index (PVI) between 0.39 and 1, with higher concentration in Waipahu and Wahiawa. Overall, the mean PVI is 0.44 and the most frequent scores are those in the 0.41-0.5 range (see figure 20).



Map 9: a, percentage of population between 0-17 years old; b, percentage of senior citizens; c, percentage of population living at or below poverty line; d, percentage of housing units that are occupied by renters; d, unemployment rate. (US Census, 2010)



Map 10: Population-weighted Vulnerability Index in the study area

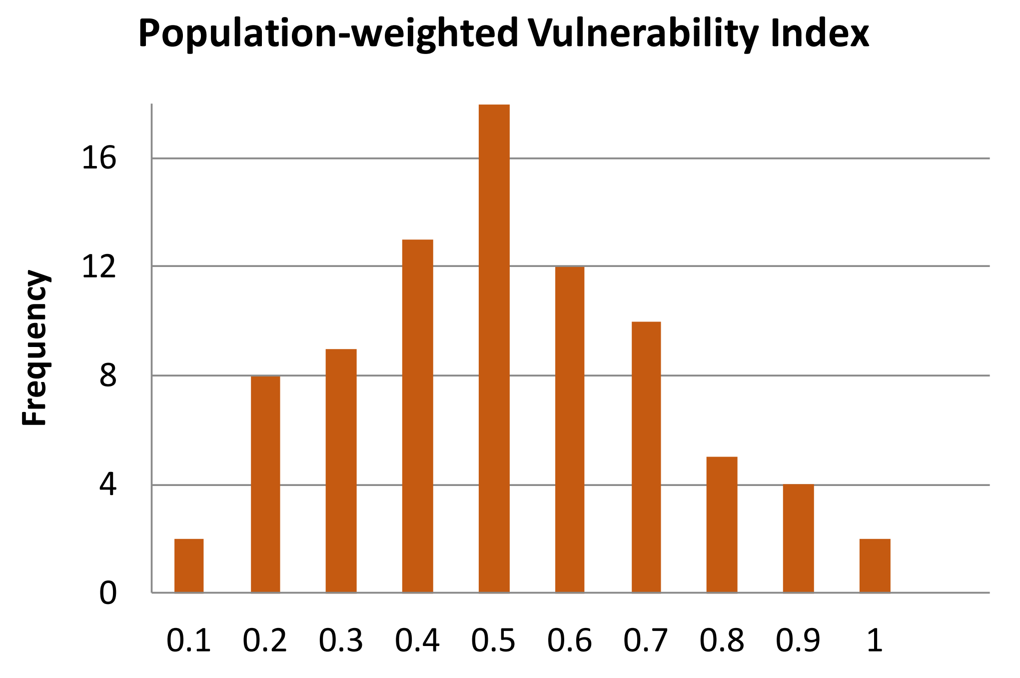


Figure 20: Frequency Distribution of Population-weighted Vulnerability Index in the study area

Chapter 4 Methods: Runoff Depth, Park Access, and GI Priority Areas

Spatial analysis is essential to strategic and effective GI planning. Chapter 2 reviewed the multiple methods used to analyze and combine the selected ecological and social variables, and this section illustrates the mapping methods developed for this research. In particular, it describes the workflows and tools developed to map stormwater runoff and park accessibility, and obtain GI Priority Scores and Areas using suitability analysis.

4.1 Stormwater Runoff

Stormwater runoff plays an important part in the ecology of a city, and its proper management is essential to urban sustainability and resilience. As discussed in the introduction, the purpose of this research is to identify areas of intervention in which GI can be deployed to meet sustainability and resilience goals, including stormwater runoff volume management. To better meet this goal in the relatively small study area, the SCS-CN method was applied to calculate runoff depth using rainfall, soil, and land cover data in raster format (the dimensions of the final runoff layer's grid are 2.4 m x 2.4 m). Using rasters with a small grid (2.4m x 2.4m) allowed to estimate runoff volumes in each pixels and visualize its distribution and patterns at a fine spatial resolution. Data included:

- Land Cover from(National Oceanic and Atmospheric Administration, Office for Coastal Management 2018): classified into impervious, open space developed, cultivated land, cultivated land, pasture/hay, grassland, scrub shrub, palustrine forested wetland, palustrine scrub shrub wetland, palustrine emergent wetland, estuarine forested wetland, estuarine scrub shrub wetland, estuarine emergent wetland, unconsolidated shore, bare land, open water, and unclassified.
- Hydrologic Soil Groups from the (United States Department of Agriculture - Natural Resources Conservation Service 2018): classified in A, B, C and D (see 2.3.1 for a description of these classes);
- Design rainstorms from the NOAA's National Weather Service - Hydrometereological Design Studies Center (Accessed 2018): 5 years, 6 hours.

The method was developed based on Weng's research (2001) described in 2.7.1. The main workflow is summarized in figure 21 and was based on the following phases:

1. Combine land cover and HSG data: the two rasters were combined using the "Combine" tool in ArcGIS, which produces a raster representing all the unique combinations between the two input rasters. In this case, 76 combinations of HSG and land cover were generated.
2. Recode LC-HSG combination and assign a CN to each unique combination based on the SCS-CN table (USDA, 1986): In order to assign a Curve Number to each combination, the table of content relative to the HSG-land cover combination was exported into Microsoft Excel and each combination was recoded based on the CN summarize in table 4.1. The CN table was imported into ArcGIS, were the combinations were recoded using the "Reclass by table" function.
3. Potential Maximum Storage layer: This layer was generated based on equation (4), which was solved for *S* as follows:

$$S = \frac{1000}{CN} - 10 \tag{4}$$

Using the Raster Calculator, equation 4 was applied to the study area, using the CN values generated in the previous step.

4. Combine Potential Maximum Storage and Design Storm: In order to calculate the depth of stormwater runoff generated in each pixel, the layers generated previously were combined with rasters of design storms. More specifically, equation 3 was entered in Raster Calculator using as inputs the potential maximum storage layer (*S*) and the design storms layers (*P*) (2year-1h, 5years-6hours, 100y-6hours), as show in figure 22.

In the case of this research, the assignment of CN numbers to the HSG-Land Cover combinations may represent a limitation. In fact, land cover is inferred based on a third party layer that was not specifically generated for hydrologic calculations, which may lead to inaccuracies. A potential improvement of this method may include the integration of the analysis of satellite images with field work and ground truthing, with the aim at determining more specific

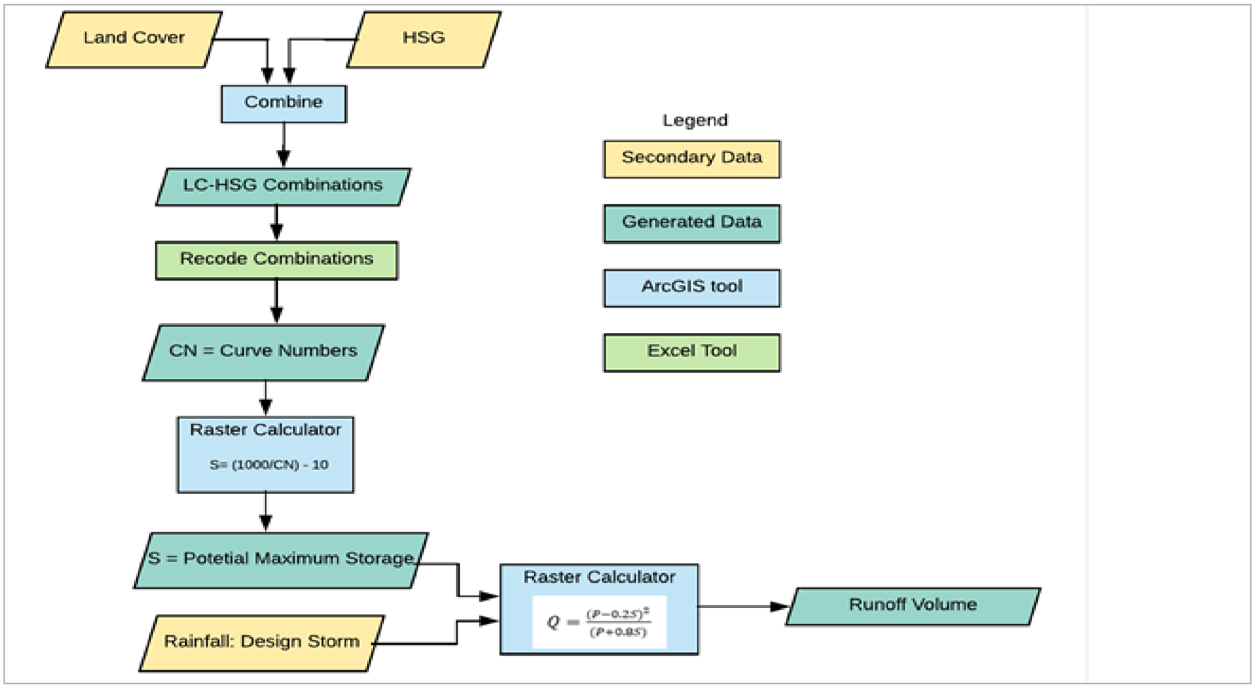


Figure 21: Workflow for the creation of the runoff layer

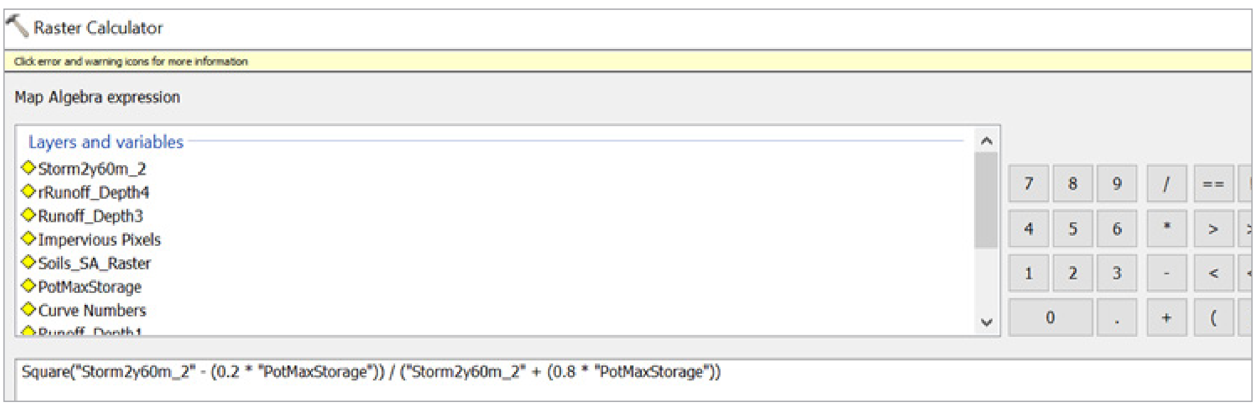


Figure 22: Raster calculator window used for calculating runoff depth based on equation 4

properties of the vegetation, improving the estimate of curve number and retention capacity.

4.2 Access to Parks

Proving public space and increasing social capital are essential in building sustainable communities. The potential spatial accessibility to public parks in the study area is determined by observing the supply and demand of these spaces and is based on the assumption that people are not willing to walk more than 10 minutes from their residence to arrive to and use a park. In order to do so, the first phase determined the park service area while the second evaluated supply and potential demand of parks by estimating the ratio of acreage-to-resident. Overall, the analysis was focused on identifying (1) areas across the study site that are located outside the 10-minute walk service area of local public parks; and (2) the ratio of acreage-to-resident within those areas that *do* belong to a park service area, and whether this measure is in line the 1000 acres/10 people standard recommended by the NRPA. In this regard, the results of a network analysis were combined with park characteristics and census data. Since the objective of this research are combining park access data with other continuous data in raster format, such as runoff depth and elevation, the analysis focused on those methods that allow to observe park accessibility across newly created spatial units, i.e. service areas, rather than estimating it within set boundaries such as census tracts or blocks. Therefore, the method developed was similar to the one adopted by Nicholls (2001) (see 2.8.1) and based on network analysis and the observation of demographics within service areas.

The first phase focused on network analysis. First, the street network dataset was prepared in order to reflect the constraints and possibilities of pedestrians moving along them. In this case, roads that do not allow pedestrians were deleted from the original street centerline dataset (City and County of Honolulu 2015), including H1 and H2 Freeways, freeway ramps, highways service roads, Kamehameha Highway (except in Wahiawa, where a sidewalk is present) and Farrington highway (except the long segment from Kahualii St to Kunia Rd, i.e. in Waipahu, where a sidewalk is present). The rest of city streets were used in the analysis and no other constraints were added to the dataset. For example, due to the lack of data, the time and route constraints that crosswalks and traffic lights may cause were not considered. To complete the network dataset a speed of 246 ft/min, i.e. the walking speed required to cover ½ mile in 10 minutes, was assigned to it. In terms of park, only neighborhood, community, district parks and one botanical garden (Wahiwa Botanical Garden) were included in the final analysis, while other facilities (i.e. golf courses and sport complexes) were eliminated. This allowed to focus the analysis on open green spaces that offer more and more varied opportunities for outdoor recreation (Nicholls, 2001), from playgrounds to community events, and have a greater role in the public life of residents. In order to better represent the routes to parks and obtain more accurate service areas, park access points were used in the analysis. More specifically, the points retrieved from the (City and County of Honolulu 2018) park shapefile were modified so that each point would represent a park entrance, rather than the centroid of the park parcel. In this regard, park entrances were verified by consulting Google Maps and/or Google Streetview, and through field observation. For fenced parks, entrance were located on the actual opening of the fence or entrance, while the entrances of non-fence parks were positioned along the edges (i.e. on street centerlines) and on the opposite ends of the park.

Park service areas were determined with the Service Area tool within the Network Analysist suite in ArcGIS. More specifically, park access points were used as "facilities" and the roads dataset described above as the street network, and an impedance of 10 minutes, as recommended by ParkScore™, was set for the analysis. This tool generated service areas around each park entrance point and, in order to have one single service area per park, the polygons belonging to the same park (i.e. part of the same service area) were merged together.

In order to estimate the **supply** of and **demand** for parks in the study area, the results of the network analysis were combined with 2010 Census data the Block Group Level. More specifically, this phased focus on estimating the population living in the park service areas determined previously and comparing it to the acreage-to-resident ratio recommended in the literature, i.e. 10 acres for 1000 residents (National Recreation and Park Association 2017) or 0.01 acres per person. First, population density was calculated in each census block group as:

$$PD_{cb} = \frac{P_{cb}}{A_{cb}} \tag{8}$$

Where population P_{cb} is a Community Survey estimate for the year 2015 (included in the 2010 Census data), and A_{cb} surface is calculated in square miles. Second, the park service areas were intersected using the "intersect" tool in ArcGIS, which generated one polygon for each one of the combinations of service area and census block group polygons (all records were kept for both dataset). For each one of the "intersected" polygons, area was calculated in square mile and, assuming population is distribute evenly across census block groups and service areas, population was calculated by reversing equation 8 as follows:

$$P_u = A_u * PD_{cb} \tag{9}$$

Where the area A_u is the surface of unique service area/census block group combination and population density PD_{cb} is the value previously calculated for each census block and associated with each combination. This step estimated the number of people living in each service area/census block group combination and, in order to calculate the number of people living in each service area, all the units associated with one park were grouped together and populations P_u of each were added up.

$$P_{sa} = \sum_{n=1}^{i} P_u \tag{10}$$

In order to calculate the ratio of acres of park per resident and evaluate the supply of and demand of parks, the dataset of service area population was combined with parks polygon, containing information on parks' acreage. In the newly joined attribute table a new field was added and the ratio of acres to people (AP_{sa}) was calculated (using Field Calculator) by dividing the area of each park (A_{sa}) by the number of people estimated to live in each service area (P_{sa}):

$$AP_{sa} = \frac{A_{sa}}{P_{sa}} \tag{11}$$

This last step allowed to evaluate the supply of parks in each service area and produced a dataset in which each polygon represents a different ratio of park surface per number of resident. Finally, these polygons were then combined with all the areas in the research site that are outside park service areas and an accessibility score was assigned. The areas with no access to parks (i.e. outside service areas) were assigned a score of 0, while the acres/population ratio was divided in four classes based on Jenks breaks, whereby values lower than 0.01 are considered highly underserved, underserved or inadequate. Results are shown in map X and discussed in the following paragraph.

4.3 Strategic GI Planning: Priority Scores and Priority Areas

The final step of this research is to combine all relevant variables together, giving higher strategic priority to stormwater runoff and park accessibility. As discussed in 2.6.1, the spatial connectivity characteristics of GI make land suitability analysis an essential tool for strategic siting and the combination of social and environmental data. In order to do so, SA was conducted in ArcGIS by building a suitability model that combined five different layers based on a weighted overlay. The goal of the suitability analysis was to assign a priority score to each pixel (5 being the highest priority, and 1 the lowest) and to select those areas where the implementation of GI and the increase in vegetated cover would contrast impacts and bring the most benefit. Figure 23 summarizes the workflow behind priority score assignments and patch selection, while figure 24

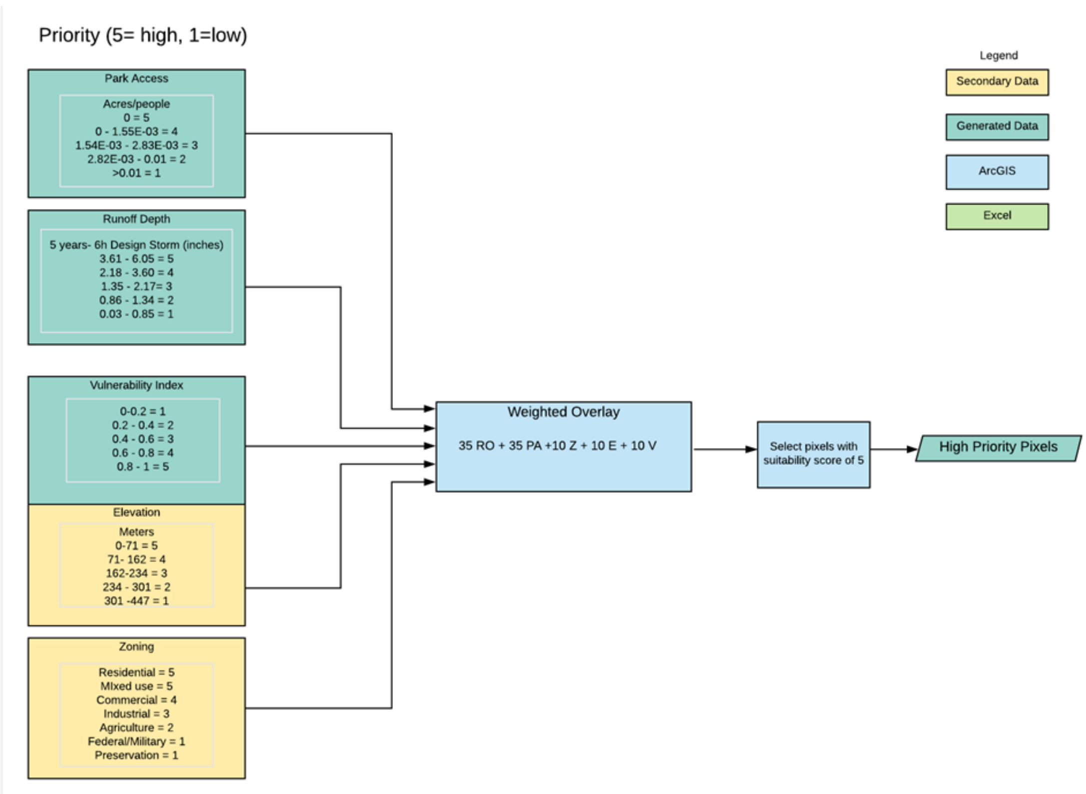


Figure 23: Workflow for the suitability analysis

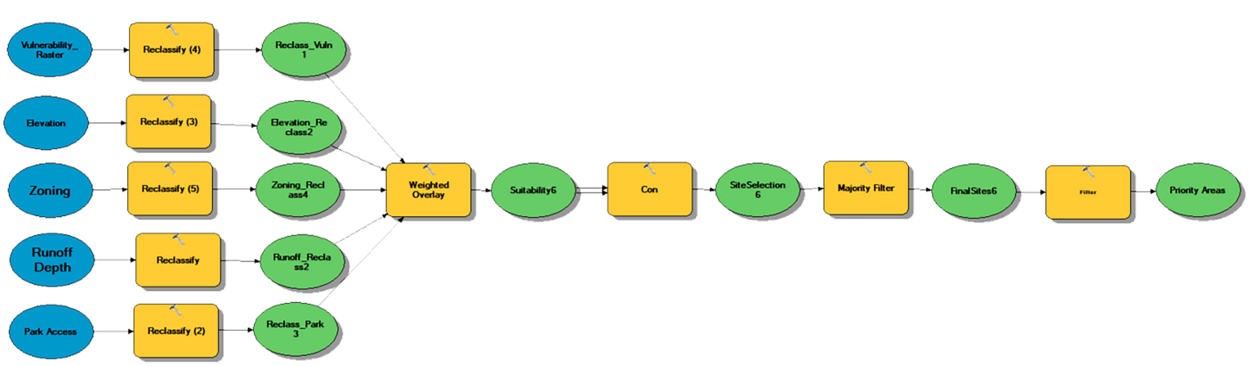


Figure 24: Model Builder for the suitability analysis

represents the model (i.e. Model Builder) used to conduct the SA in ArcGIS.

Priorities were assigned based on the *need* for GI implementation, assigning a score of 5 to pixels with high priority and 1 to the ones less in need of additional vegetated cover, stormwater management measures and/or park space. Priority were assigned as follows:

- **Park access**: areas outside park catchments (i.e. accessibility score of 0) have a value of 5, while the areas inside catchments and with a acres/people ratio equal or higher than 0.01 were assigned a score of 1.
- **Runoff Depth**: values were divided in 5 classes based on natural Jenks breaks and higher priority scores were assigned to higher runoff depth values.
- **Vulnerability Index**: the normalized population-weighted index was divided in 5 classes based on Jenks breaks. Low scores received lower priority, and high values were given a higher score.
- **Elevation**: areas of low elevation (which in this case are also coastal areas) were considered more vulnerable to stormwater accumulation and flooding, and therefore in higher need of GI implementation. The lower the elevation, the higher the score assigned.
- **Zoning**: This category considers the need of GI implementation based on the use of space and land. More specifically, residential and mixed use areas were given the highest priority score, followed by commercial, industrial, and agricultural. The lowest score (i.e. 1) was assigned to Federal/military and preservation land, because of their different governance and land management priorities, such as homeland security and defense for the former, and complex environmental goals for the latter.

Datasets were reclassified based on the parameters discussed above and combined using the Weighted Overlay tool. This tool allows to assign a coefficient (i.e. weight) to each data set and combine them based on these ratios. This tools assigns a coefficient to each dataset and sums the products together. In order to reflect the priorities assigned to stormwater runoff and park access, 70% of the weight was assigned to runoff and park access (30% respectively) and the remaining 30% was equally divided among elevation, zoning and community vulnerability data. In summary, data were combined according to the equation below:

$$Suitability = 0.35\,Runoff + 0.35\,ParkAccess + 0.10\,Zoning + 0.10\,Elevation + 0.10\,VulnerabilityIndex \quad (12)$$

After applying the weighted overlay tool, all the pixels with priority score of 5 were selected into a new raster. These high priority pixels were then filtered using Majority Filter and Filter (with high filter type) in order to transform clusters of high priority pixels into patches. These were then transformed into polygons to facilitate field calculation and export of tables.

Chapter 5 Results

5.1 Stormwater Runoff

As discussed in chapter 3, maps 6 and 7, the differences in the distribution of rainfall intensity observed in the two extreme design storms (5 years- 6 hours, 100 years – 6 hours) are minimal. Therefore, runoff depth was calculated only for one of the datasets, i.e. 5 years – 6 hours. Results are show in map 11, where each pixel on the 2.4m x 2.4m grid represents runoff depth in inches. As expected, results show higher accumulation of runoff in impervious cover (i.e. developed areas) than vegetated land covers, and where rainfall is projected to be more intense, i.e. on the Koolau Mountains and in the center of the Island. The lower values of runoff depth were observed in the agricultural and preservation areas, were HSG and vegetated land covers allow more water to seep into the ground. Overall, the Waipahu and Waikele area (south in the study area) show lower runoff depths that Mililani and Wahiawa, while the highest in urban/developed areas are located in Wahiawa and the communities closer to the center of the island. In these developed and urban communities pixels of high runoff are alternated with patches of higher perviousness, i.e. vegetated cover. In Mililani most of the non-impervious covers generate lower amounts of runoff (i.e. 0.3 – 0.83 inches), whereas in Wahiawa and the southern part of the research site these surfaces are estimated to generate runoff depths between 1.93 and 3.15 inches. Furthermore, high runoff depth pixels appear to be more dense (i.e. more concentrated together) in the area around Waipahu and Waikele, suggesting a higher connectivity of impervious surfaces and potential higher accumulation of runoff volumes compared to more scattered and balanced developed areas.

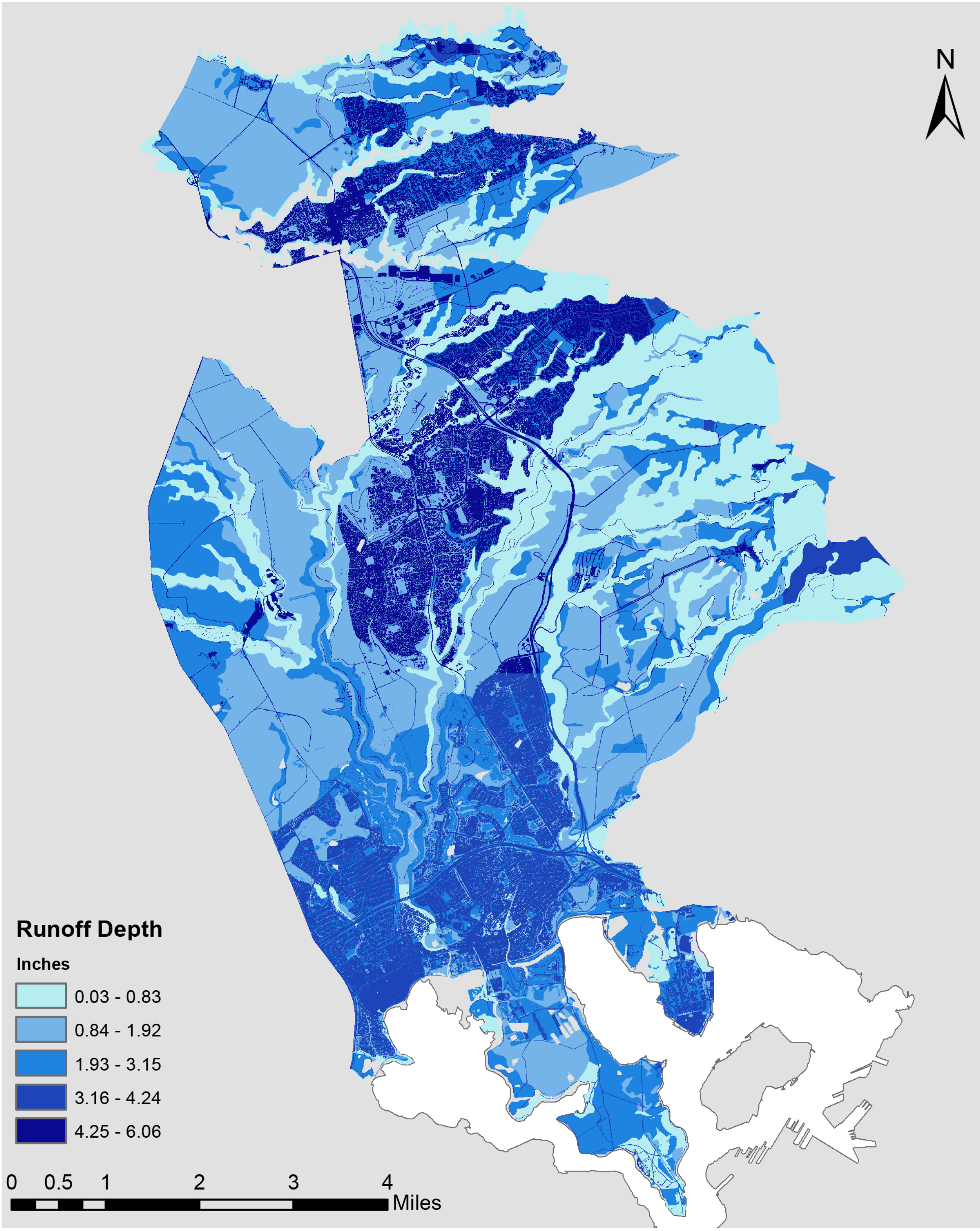
5.2 Access to Parks

Map 12 represents park accessibility in the study area. Overall, only six service areas (Waikele Community Park, Waipio Neighborhood Park, Lehua Community Park, Kaomaaku Neighborhood Park, Wahiawa State Freshwater Park, and part of the Wahiawa Botanical Gardens) provide an adequate amount of park surface for their resident (i.e. more than 0.01 acres per person). In the rest of the park service area the demand for park (i.e. the number of residents) is higher than what the surface of the parks should support. In particular, Waipahu and Wahiawa are areas where park access is more challenging, while Mililani, although still underserved, sees accessibility values closer to the recommended acres/resident ratio. In the context of this research, the areas with none or low park accessibility were considered in higher need of an increase in vegetated cover and/or implementation GI features. Compared to the ParkScore™ map (see 2.8, fig.11) results are similar in the way service areas were assessed, but different in the way the "park need" was determined. Overall, the boundaries of service areas determined by the two different methods (in green in figure 11 and the polygons in map 12) are similar, except for the parks that were exclude from analysis in this research (e.g. golf courses, soccer fields, etc.). However, this research did not automatically consider park service areas as areas that supply park space to residents, but went a step further and estimated the potential demand for those parks as well. This allowed to identify larger and more specific areas where park surface is needed, even where parks exist already.

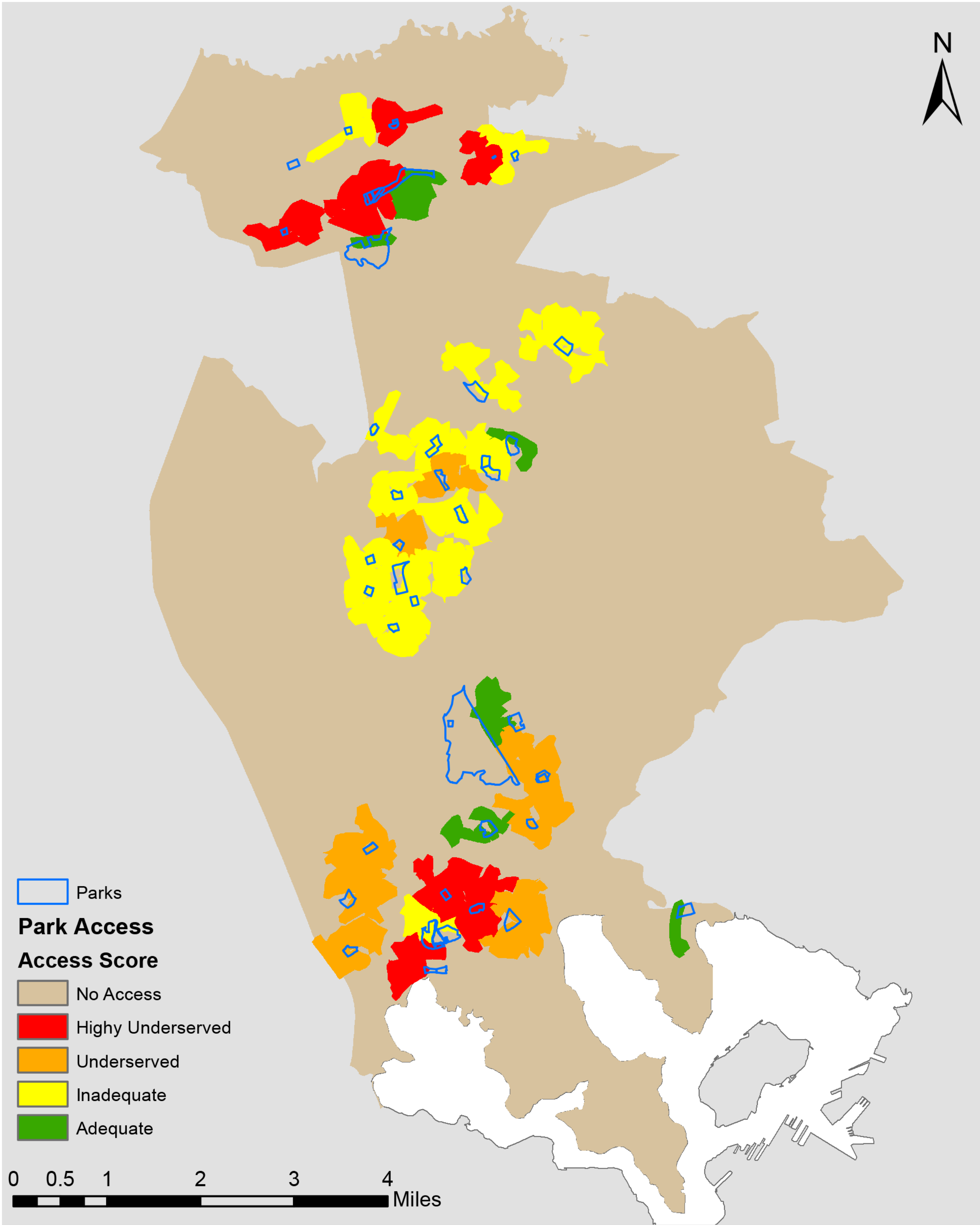
5.3 Green Infrastructure Priority Scores and Areas

Map 13 shows the result of the suitability analysis and map 14 the final selection of high priority areas. Overall, most of the study area has high or very high GI priority scores (i.e. 4 and 5), stressing the need for GI and additional vegetated cover in the area. Very high scores of 5 were observed in the most dense residential areas, with highest concentrations in Waipahu and Mililani Mauka. Medium priority areas are located in agricultural and conservation land, accordingly with the low runoff depths and low zoning priorities observed. Low-priority areas, i.e. score [1-2], are rare and extremely small in size. In general, these areas coincide with well-served park catchments located in area with higher concentration of vegetated cover. The analysis discussed in the previous chapters identifies areas across the Central Oahu Watershed where GI should be prioritized to improve the management of stormwater while also proving public open space.

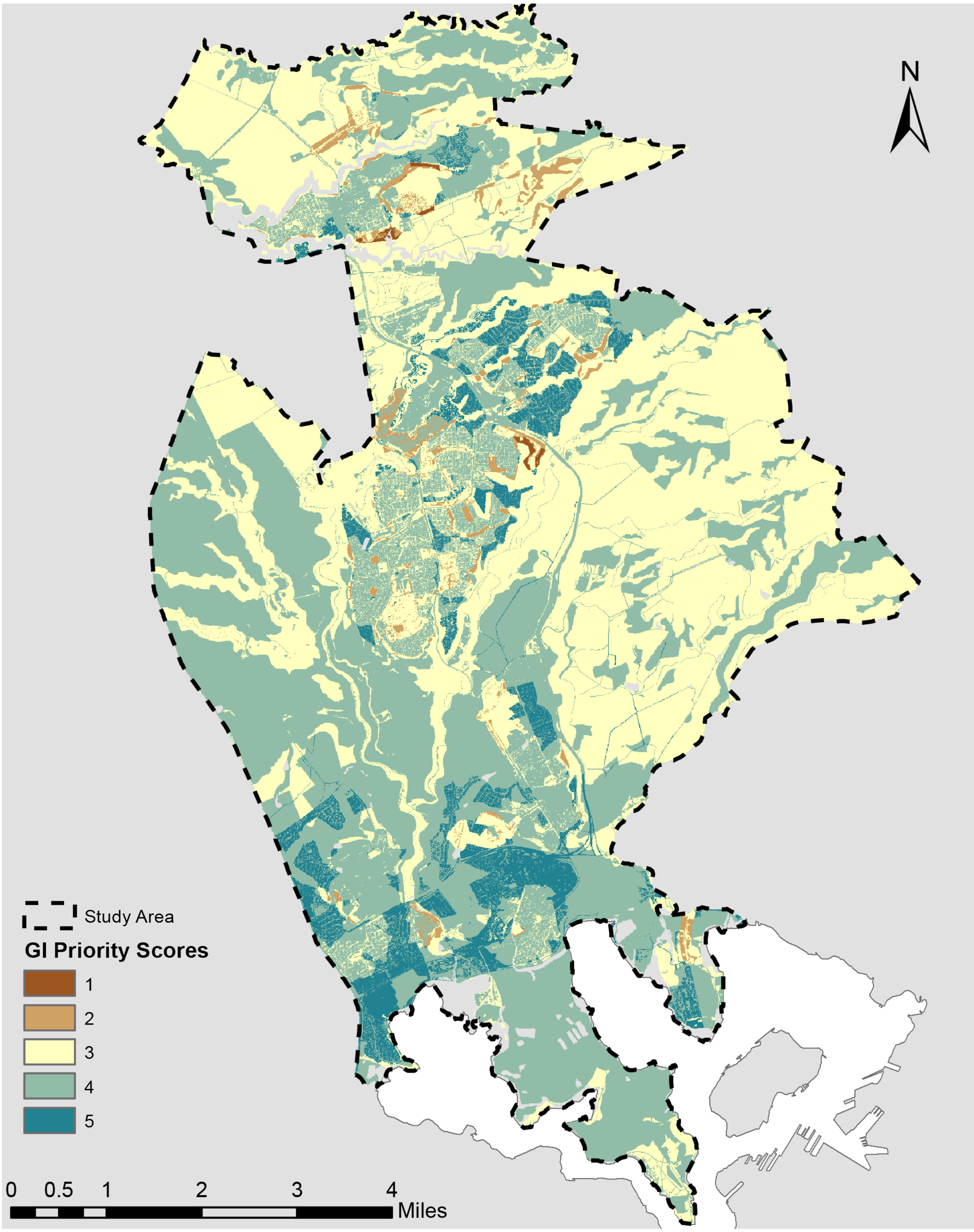
The interpretations of results are varied and versatile and can be a useful tool for public and private entities involved in sustainability and resilience goals, programs and projects. The spatial distribution of GI priority scores is important to understand where GI can bring the greatest benefits and where it is most needed. In order to make these results more meaningful and applicable to other studies, it is interesting to isolate the patches with the highest scores. In this regard, the **GI Priority Areas** (GIPA) selected are pixels with priority score of 5 (highest score) clustered in patches larger than 15 acres. According to the findings of the suitability analysis, within the research site 2747.64 acres of land (mainly located in Waipahu and Mililani) are in high need of and suitable for additional vegetated land cover and/or GI. In order to understand how these surfaces can contribute to sustainable stormwater management and park access, it is interesting to develop implementation scenarios and consider how park surface and GI features can be allocated.



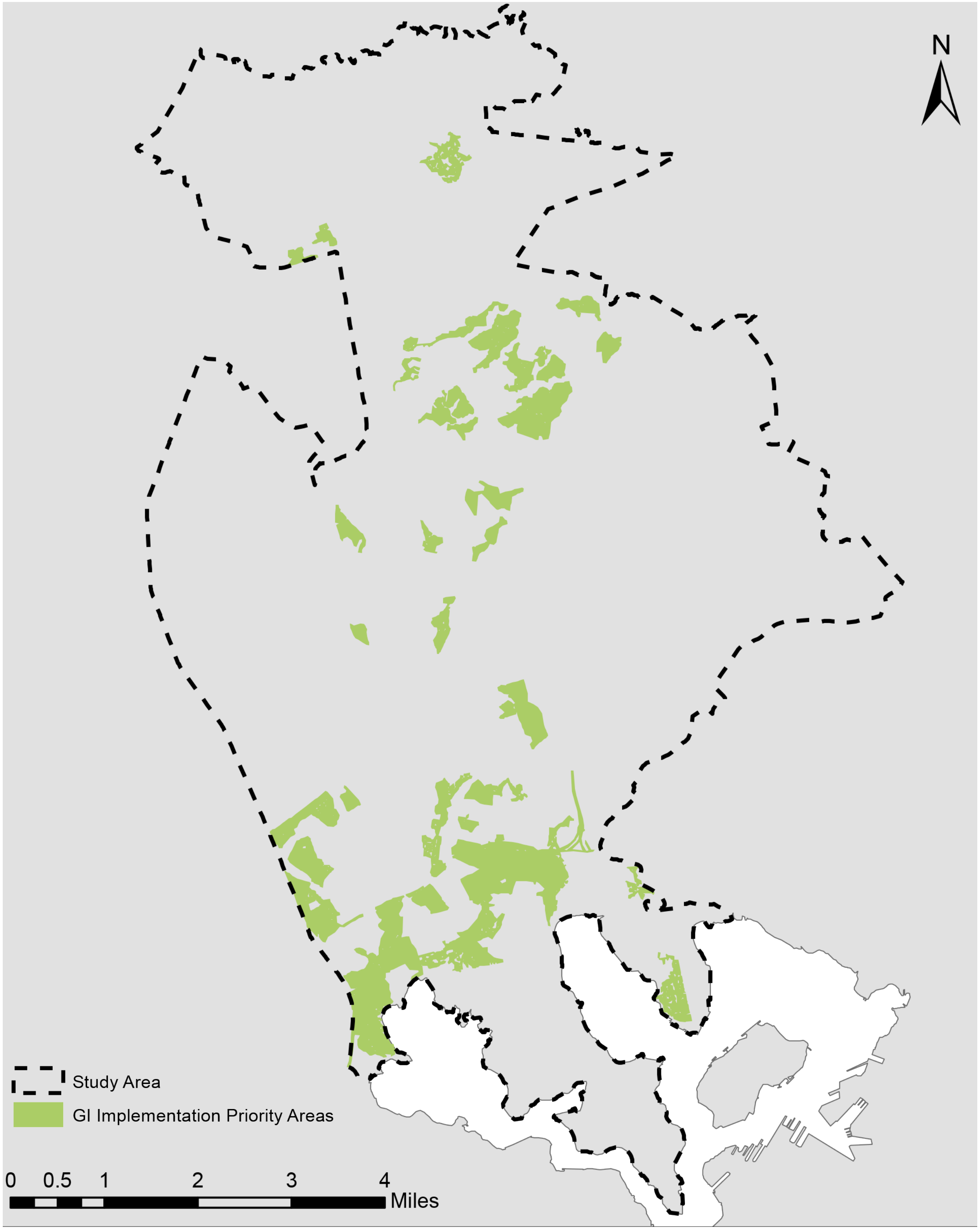
Map 11: Runoff Depth for 5 years- 6 hours design storm



Map 12: Park Access in the study area



Map 13: GI priority scores: 5=highest need for GI implementation, 1=lowest



Map 14: GI Implementation Priority Areas

5.4 GI Implementation Scenarios – Changes in Impervious Cover and Park Surface

The first step to develop GI implementation scenarios, was determining how much of the GI priority areas needs to be specifically allocated to parks and not other specific BMPs. In order to do so, the surface of GI priority areas was divided by the amount of additional park surface needed calculated in chapter 3, i.e. 913 acres, determining that at least 33.24% should be dedicated to park space. Based on this number, five different GI implementation scenarios were developed, observing the increase in vegetated cover and the reduction of impervious surfaces if 35%, 40%, 45%, 50% or 100% of the GI priority areas are converted to vegetated land covers. Overall, the scenarios predict adding between 961.68 acres and 2747.64 acres of new pervious covers and reducing the amount impervious surfaces across the study area by 13.38% - 38.22%.

Second, based on amounts of new vegetated cover determined previously, it was determined how much of the GI priority areas land should be allocated to parks and how much to other GI features, such as curbside raingardens, green roofs, or pervious pavement. More specifically, the recommended park surface determined in chapter 3 (i.e. 913.28 acres) was subtracted from the new vegetated cover that each implementation scenario would produce, and the difference was allocated to GI features (Table 3). Table 4 summarizes this break-down, and shows that, after converting GI priority areas to parks, the land left to other types of GI features ranges from 48 to 1834 acres across the five different scenarios. Figure 25 is a summary of GI implementation scenarios and their impacts. Unsurprisingly, the most effective scenario is the 100% implementation, as it allows achieve a robust balance of impervious and vegetated covers as well as performing landscape surfaces and elements. However, this scenario is also unrealistic, as it would require the planning, implementation, financing and conversion of over 2700 acres of new land cover. In contrast, the 40% and 45% scenarios represent a more realistic (and still rather optimistic) examples, and may be able to offer the most benefits of stormwater management and park access, without radically altering the status quo.

	GI Implementation Scenarios				
	35%	40%	45%	50%	100%
New Vegetated Cover (acres)	961.68	1099.06	1236.44	1373.82	2747.64
IS after new VC	6227.32	6089.94	5952.56	5815.18	4441.36
Reduction of IS in Study Area	13.38%	15.29%	17.20%	19.11%	38.22%
IS in Study Area after new VC	18.70%	18.29%	17.88%	17.46%	13.34%

Table 3: Introduction of vegetated cover and changes in impervious surfaces for five GI implementation scenarios

	GI Implementation Scenarios				
Areas (Acres)	35%	40%	45%	50%	100%
New VC	961.68	1099.06	1236.44	1373.82	2747.64
Park Area Needed	913.28	913.28	913.28	913.28	913.28
GI Features	48.39	185.78	323.16	460.54	1834.36

Table 4: Allocation of park space and GI features for five implementation scenarios

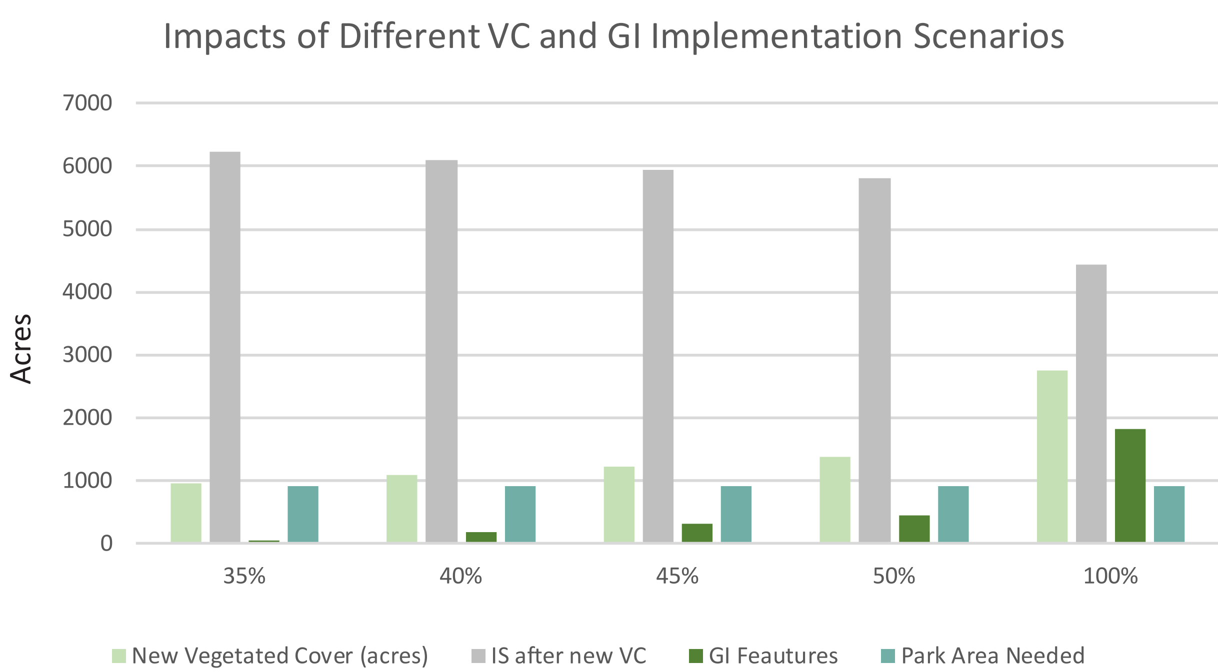


Figure 25: Allocation of park space and GI features and related impacts on Land Cover for five implementation scenarios

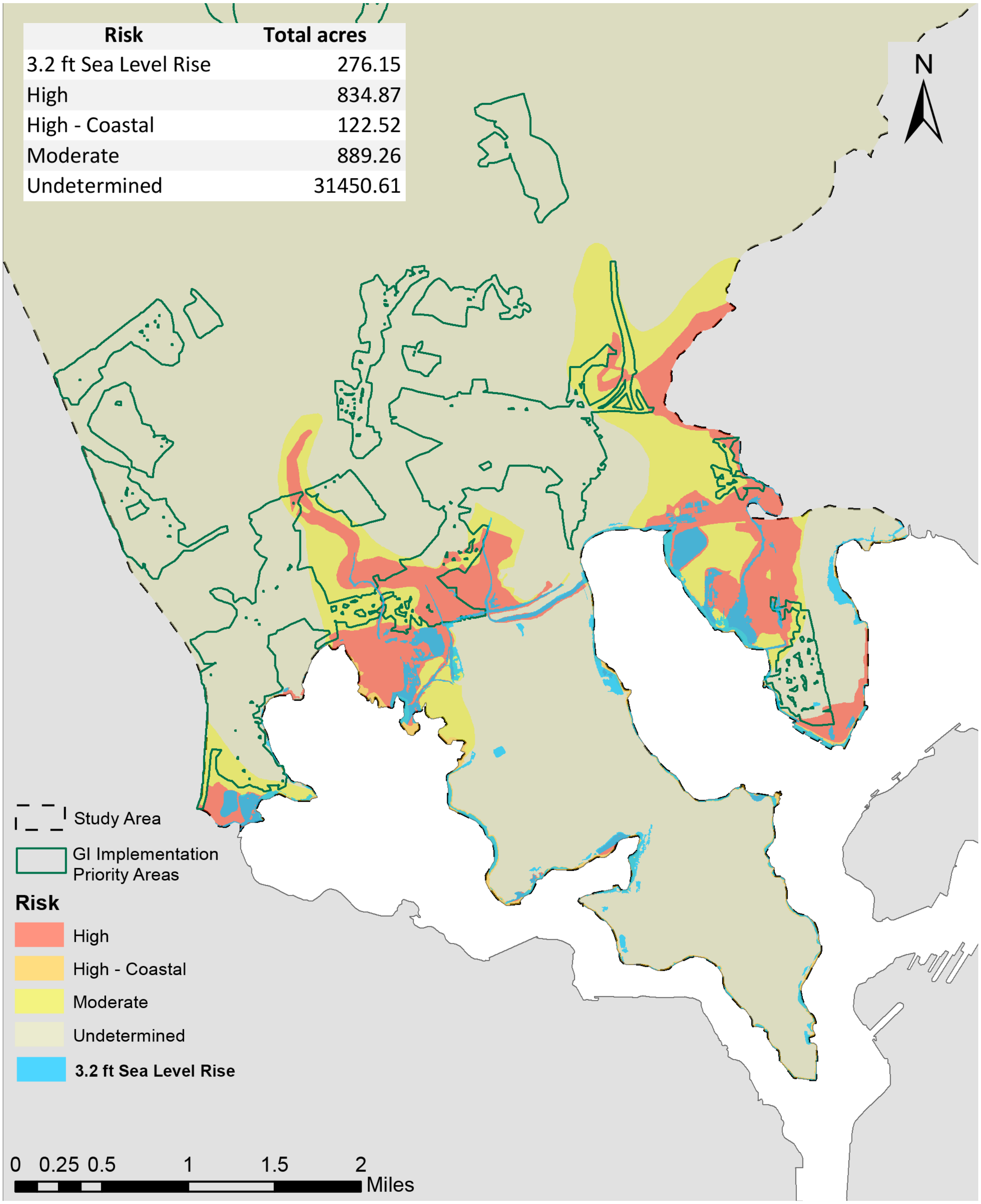
Similar scenarios can be developed to support the implementation of GI in conjunction with other more specific sustainability and resilience goals, such as the reduction of impervious covers in flood zones and areas were sea level is expected to rise. Most of the study area is classified as "undetermined" risk by FEMA (Federal Emergency Managemence Agency 2014), and the areas of higher risk are located in the southern part, in Waipahu and around West Loch. Similarly, for most of the GI priority areas (88.9%) the risk of flood is undetermined, but there are areas where the risk of flooding is high and moderate, which accounts for 33.37% of the moderate-to-high-risk zones in the whole study area (see tables 5). Assuming the moderate-high risk areas are 90% impervious, based on the highly developed nature of the area (see map 2 in 3.2 for land cover), GI implementation scenarios of 35%, 40%, 45%, 50% and 100% were simulated again to evaluate the impact of GI implementation on impervious cover (table 6). Overall, converting impervious cover in moderate-to-high risk zones to GI would introduce between 173 and 267 acres of permeable cover, which would reduce the amount of impervious cover in the whole study area by 2.41% and 3.72%.

Risk	Total Acres	Percentage of GIPA	Percentage of Risk Area
3.2 ft Sea Level			
Rise	6.37	0.23%	2.31%
High	103.29	3.76%	12.37%
High - Coastal	0.57	0.02%	0.47%
Moderate	192.89	7.02%	21.69%
Undetermined	2443.54	88.96%	7.77%

Table 5: Acreage of flood and SLR risk areas in GIPA compared to the total risk zones in study area

	GI Implementation Scenarios				
	35%	40%	45%	50%	100%
New IS after GI implementation in GIPA	173.60	160.25	146.89	133.54	267.08
New IS after GI implementation in SA	7015.40	7028.75	7042.11	7055.46	6921.92
Reduction of IS in SA after GI Implementation	2.41%	2.23%	2.04%	1.86%	3.72%

Table 6: Impervious cover impacts of GI implementation scenarios in moderate-to-high risk areas in GIPA



Risk	Total acres
3.2 ft Sea Level Rise	276.15
High	834.87
High - Coastal	122.52
Moderate	889.26
Undetermined	31450.61

Map 15: Flood and Sea Level Rise risk and GIPA in study area

Chapter 6 Discussion and Conclusion

6.1 A Framework for Strategic Green Infrastructure Planning

The identification of Green Infrastructure Priority Areas discussed in this research offers a new perspective on how to observe and synthetized social and environmental elements when planning sustainable and resilient cities. Spatial analysis is a useful tool effective GI and sustainability planning. This thesis offered the opportunity to reflect on the theoretical and operational framework that guide these processes. Overall, strategic GI spatial planning can be articulated in four phases. The first phase focuses on setting the overarching **objectives** of a potential plan or project, based on the review of both local sustainability and resilience goals and the range of ecosystem services that GI features may provide. This phase can be supported by the input of the community and stakeholders, by consultations with experts, or (like in the case of this thesis) on empirical research. Once objectives and solutions were clear, the process enters a second phase of **research**. This phase reviews the selected elements and establishes what metrics should be used and how variables should be measures, outlining methods for data collection and analysis. In case data for the selected variables is not available in spatial formats, new dataset will be created in this phase. In the case of this research, for example, it was decided that stormwater management was going to be measured in terms of runoff depth, and the creation of a specific spatial dataset was based the appliaction of the SCS-CN method through map algebra in ArcGIS. The third phase of the strategic GI spatial planning framewotk is **assessment**. During this phase, trade-off and synergies are evaluated and priorities are assigned to the chosen variables. This can be done by consulting community members and/or experts, and/or collecting and analyzing empirical and field data. Finally, the last phase overlays all the maps obtained so far (considering the priority and weights assigned to each variables in the previous phase), and uses the data to elaborate specific stragegies for implementation. Stategies are numerous and may include the development of scenarios (like in the case of this research), the selection of specific parcels of land, or the selection of suitable GI features.

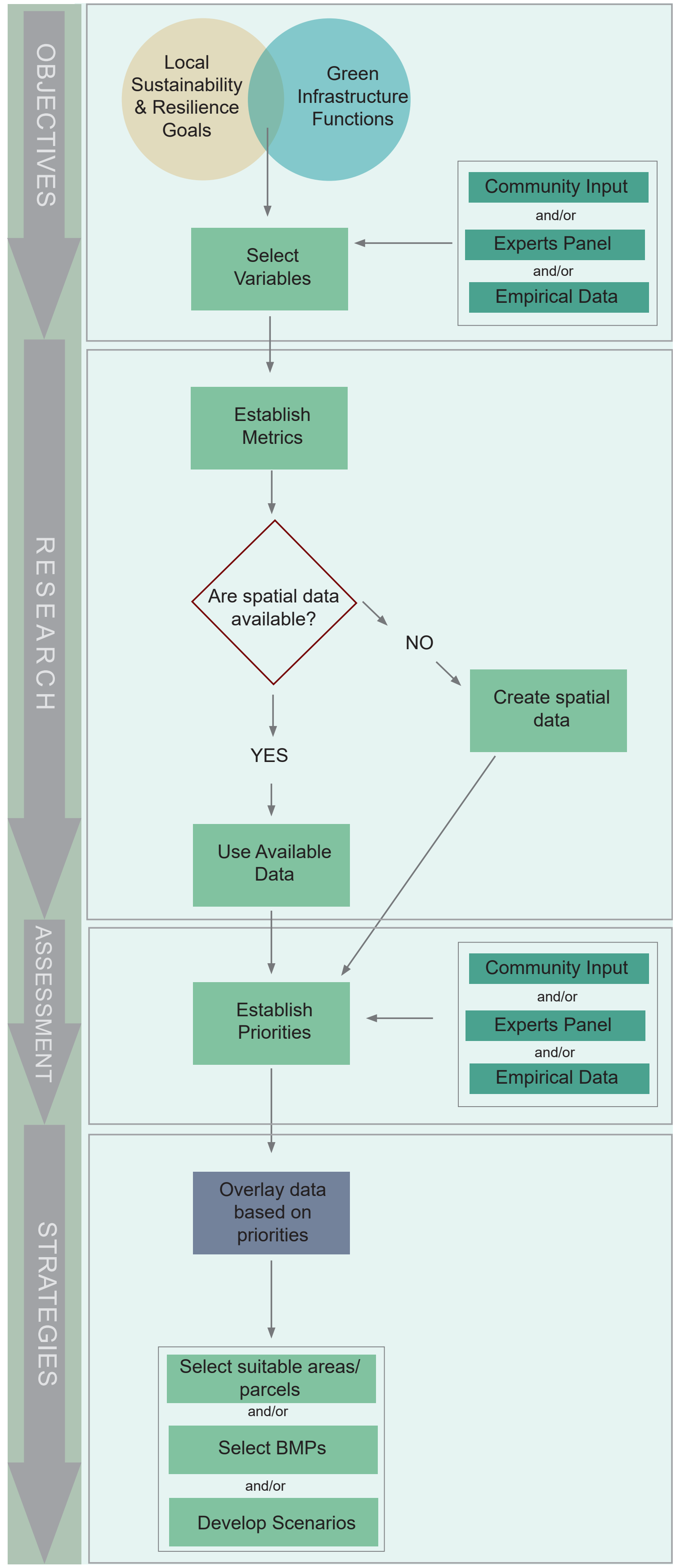


Figure 26: Operational Framework for Strategic GI Spatial Planning

6.2 Policy Implications – Board of Water Supply, City and County of Honolulu, State of Hawaii

Scenario building plays a vital role in policy making, as it allows to forecast trade-off and costs as well as benefits. The result of the suitability analysis and the scenario describe above may represent useful tools for public agencies that want to integrate GI into their sustainability strategies. For example, the Board of water supply could use a similar analysis to identify areas where GI could support their stormwater reduction, capture and recycle, including environmental goals such as groundwater recharge and social variable such the ratio of water consumption and water price to household size and income.

Another interesting application of this framework is the strategic integration of GI location into zoning regulations and building codes. For example, the areas identified as GIPA may be designated as areas of interest for sustainability and resilience for which special provisions and incentives are created, such as integration of specific GI standards and requirements into the building codes or monetary incentive programs for home and business owners. In this sense, knowing where to focus policy and planning is key to the optimization and implementation of sustainability goals, as it makes strategic decisions easier and clearer.

Another approach to the selection of GIPA is the possibility of expanding or complement existing programs and projects. For example, GIPAs can be identified across TOD neighborhoods and in proximity to transit stations and thoroughfares, and the introduction of new vegetated features and spaces can be integrated in existing projects. This type of integration can help existing projects, e.g. including the introduction of mitigation measures to environmental and social issues, and at the same time ease the process around GI implementation, optimizing spending and decision-making.

6.4 Conclusion

Sustainability and resilience are complex issues, especially in cities. The improvement of the natural, built and social environment is key to addressing these problems, but elaborating effective solutions across space is, again, complex. Green infrastructure consists of engineered vegetated systems that can bring many benefits, including stormwater management and the creation of public space, and can represent one way to turn sustainability goals into concrete projects. But, again, green infrastructure planning can be a though puzzle to solve. This research proposed a framework to support green infrastructure planning complex the use of spatial analysis in the Central Oahu Watershed (HI). Based on local sustainability and resilience goals, priority was given to stormwater management and the creation of public open space, and suitability analysis was used to assign GI priority scores across the study area. First, the spatial analysis of stormwater management was based on the combination of land cover, soil properties and rainfall according to the SCS-C method. Second, public park access was estimated based on 10-minute walk catchment areas around selected park entrances and on the ratio of resident of these catchment areas and surface of the park itself. Finally, GI priority scores were calculated by combining stormwater management and park access with elevation, a population-weighted vulnerability index, and zoning. This thesis contributes to the literature on GI spatial planning by not only proposing a theoretical framework of analysis, but also providing practical examples that can be used and applied in a professional setting. More specifically, the combination of data on stormwater runoff and park access offer a novel approach to urban sustainability, illustrating how ecological and social variables can be combined. In other words, the approach to the issue of GI spatial planning is straight forward, replicable and flexible, as it uses publicly available data and improves on existing and validate methods.

6.5 Limitations

The main limitation of this research is associated with the calculation of social vulnerability and GI priority scores. The selection of variables of social vulnerability and the assignment of weights was based on the author's personal knowledge of the study area, the island of O'ahu and the State of Hawai'i. The priorities and hierarchy established for the suitability analysis were also based on personal judgment, and scores were assigned in order to give greater significance (i.e. 70%) to stormwater management and park access, and distribute the remaining weights equally among elevation, zoning, and social vulnerability. In order to improve results, it is recommended that weights and priorities should be determined based on empirical research (e.g. meta-analysis), and/or consultation with experts, stakeholders and/or community members.

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