Modeling Cost Effectiveness of Green Infrastructure at Stormwater Runoff Critical Points in Maunalua Bay Watershed, O‘ahu

by

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Final community report submitted in partial fulfillment of the requirements for the NREM 601 course

for

MALAMA MAUNALUA

UNIVERSITY OF HAWAII MĀNOA
Honolulu, Hawaii

Spring 2018

I. *Introduction*

Like many urbanized areas, the Maunalua Bay Watershed is highly developed with impervious surfaces and channelized water ways. Originally designed to prevent flooding and property damage, this infrastructure has exacerbated the degradation of Maunalua's water quality and ecosystem health via increased sedimentation and pollution.[1] Fortunately, green infrastructure techniques can be implemented as an alternative to conventional methods to help enhance stormwater management and decrease negative impacts to stream and environmental health.[2] Most commonly, "green" techniques are designed to increase infiltration of water into permeable areas (i.e. permeable pavement) or provide a system of water retention, such as rain barrels and water catchment.[3] Different strategies of green infrastructure can specifically address key issues within the watershed, however, the effectiveness of each technique depends on site specific factors and ranges in initial cost and maintenance upkeep. Therefore, it is necessary to run a place-based cost-benefit analysis of implementation of different green infrastructure techniques to facilitate appropriate selection for highly impacted areas within the Maunalua Bay Watershed.

Our research identified critical source areas within the Maunalua Bay watershed that have the highest potential for storm water mitigation via green infrastructure. We also have provided a framework for choosing solutions that give the most "bang-for-the-buck" based on site specific attributes and budget. The larger questions explored are: What factors make an area a "critical source area" for stormwater management and why should we target these areas? What makes green infrastructure cost-effective and which stakeholder groups should be targeted? By identifying critical areas for stormwater improvements, along with a property level cost-benefit case study analysis, we are able to provide Malama Maunalua practical target areas for focusing their resources.

There were two main objectives to our green infrastructure project. The first objective was to create maps of the "critical source areas" (CSA) within the Maunalua Bay watershed and identify areas of highest priority for storm drain management. The second objective was to use overlayed maps to identify a critical area and create a low impact development plan to target site specific green infrastructure improvements. This work and related findings were provided to Malama Maunalua to address the stormwater remediations challenges in the area from Black Point to Portlock.

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[1] Jolie R.Wanger. 2011. "E Mālama I Nā ʻĀina Kumu Wai O Maunalua: A Watershed Handbook for the Residents of Maunalua" *University of Hawaiÿi Sea Grant College Program* pp. 1-52.

[2] Kramer, Melissa G. 2014."Enhancing Sustainable Communities with Green Infrastructure: a Guide to Help Communities Better Manage Stormwater While Achieving Other Environmental, Public Health, Social, and Economic Benefits." U.S. Environmental Protection Agency, Office of Sustainable Communities

[3] Choi, Jiyeon, Maniquiz-Redillas, Marla C.,Hong, Jungsun,Kim, Lee-Hyung. 2017. "Selection of Cost-Effective Green Stormwater Infrastructure (GSI) Applicable in Highly Impervious Urban Catchments." *KSCE Journal of Civil Engineering*, vol. 22, no. 1, pp. 24–30., doi:10.1007/s12205-017-2461-1

II. Critical Source Areas (CSAs) Suitability Mapping

Creation of the suitability maps evolved from the main points of our conceptual model; what is the stormwater issue, how has the stormwater issue been influenced, what are the input datasets available and then performing the analysis. We utilized ArcGIS to create 3 different CSA suitability maps. We performed the analysis by utilizing the existing datasets: land cover, stormwater drains, slope, and soil permeability. These datasets were chosen because of their availability as existing layers and their relation to the health of the watershed determined by an extensive literature review of classifying the CSAs.[4,5,6]

All relevant data layers were imported from the Malama Maunalua Resource library and Honolulu City and County Planning Office GIS database as shapefiles or raster format into ArcMap. These layers were then transformed to the NAD 83 projection to allow for seamless overlay for further spatial analysis. All layers were then clipped using the geoprocessing tool to the Maunalua watershed boundaries (Appendix C). The stormwater drain layer was then transformed using proximity analysis to develop a new density layer to later be reclassified. The DEM (Digital Elevation Model) layers used to show the elevation of the watershed. Using ArcToolbox, spatial analysis was performed to define the slope of the watershed from this elevation layer, which is the desired characteristic of our analysis for determining runoff potential.

Next, we reclassified the layers to accommodate a numeric ranking system that valued terms of risk for stormwater issues. 1 is the low risk for stormwater issues while all higher integers increased risk. The numerical range for each layer ranking was 1 to 5, with 1 being low stormwater risk and 5 being highest stormwater risk. This ranking system is grounded in several suitability map ranking values for studies with similar goals, found through our literature review. The defined breaks and classification scheme for each ranking delineation is described in Appendix B. After assigning ranks to the reclassified layers within our model we were able to integrate them using the weighted overlay tool from ArcToolbox. The weighted overlay tool overlays several raster files using a common measurement scale and weighted importances of each raster layer. These weighted importance for each raster layer were determined by our developed literature review. Each layer defined in our map has at least 3 supporting papers that validate the weight and rationalize its use. We subsequently proposed three weighting schemes to explore the relationships between parameters (Table 1). In model 1, we weighted each of our four layers equally. Model 2 emphasized topography and permeability, dividing the weight between slope, soil permeability, and land use, and disregarding storm drain density. Lastly,

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4 Niraula, Rewati, et al. "Identifying Critical Source Areas of Nonpoint Source Pollution with SWAT and GWLF." *Ecological Modelling*, vol. 268, Oct. 2013, pp. 123–33. *CrossRef*

5 Thomas, I. A., et al. "Improving the Identification of Hydrologically Sensitive Areas Using LiDAR DEMs for the Delineation and Mitigation of Critical Source Areas of Diffuse Pollution." *Science of The Total Environment*, vol. 556, June 2016, pp. 276–90. *CrossRef*, doi:10.1016/j.scitotenv.2016.02.183.

6 Hahn, C., et al. "A Comparison of Three Simple Approaches to Identify Critical Areas for Runoff and Dissolved Reactive Phosphorus Losses." *Hydrology and Earth System Sciences*, vol. 18, no. 8, Aug. 2014, pp. 2975–91. *CrossRef*, doi:10.5194/hess-18-2975-2014.

model 3 emphasized storm drains' role in transporting stormwater by ranking it higher than the other three parameters.

Table 1: *Weights and ranking for 3 CSA suitability map models: Even Weight, Permeability, Storm Drain*

Parameters	Model 1: Even Weight		Model 2: Permeability		Model 3: Storm Drain	
	Weights	Ranking	Weights	Ranking	Weights	Ranking
Slope	0.25	1-5	0.33	1-5	0.2	1-5
Soil Permeability	0.25	1-5	0.33	1-5	0.2	1-5
Land Use	0.25	1-5	0.33	1-5	0.2	1-5
Storm Drain Density	0.25	1-5	0	1-5	0.4	1-5

Using theses weighting systems each map was drawn using ArcMap as an output of weighting overlay tool. The high density stormwater risk areas are shown by darker red colors while the lighter red to white shows the low stormwater hazard risk areas. Using these maps the areas of high stormwater risk can be identified and limited resources for implementing green infrastructure can be focused on these target areas.

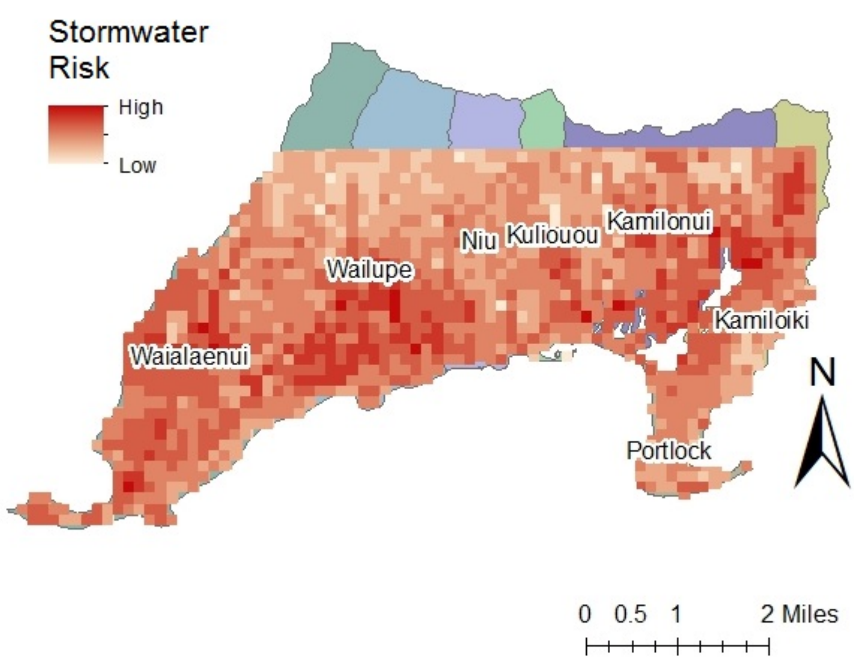

Figure 1: *Stormwater suitability map for Maunalua Bay using model weighted importance "Even Weight."*

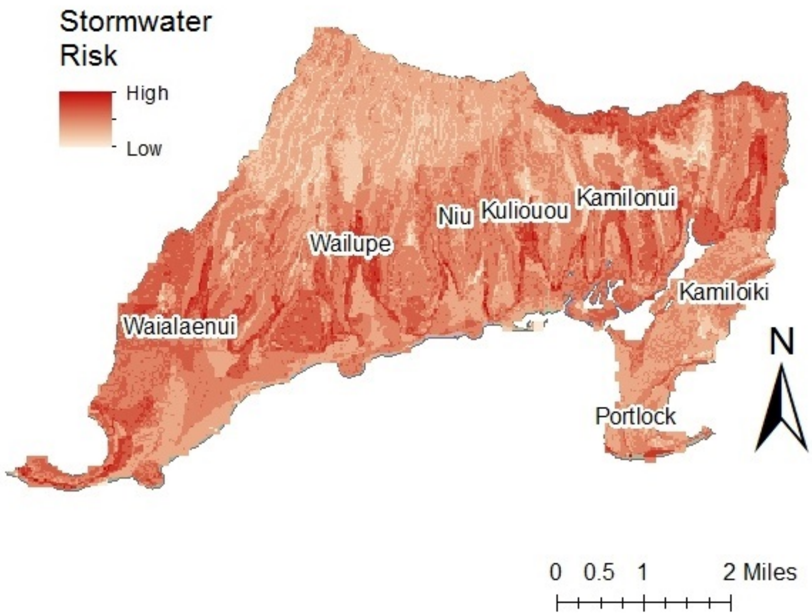

Figure 2: *Stormwater suitability map for Maunalua Bay using model weighted importance "Permeability."*

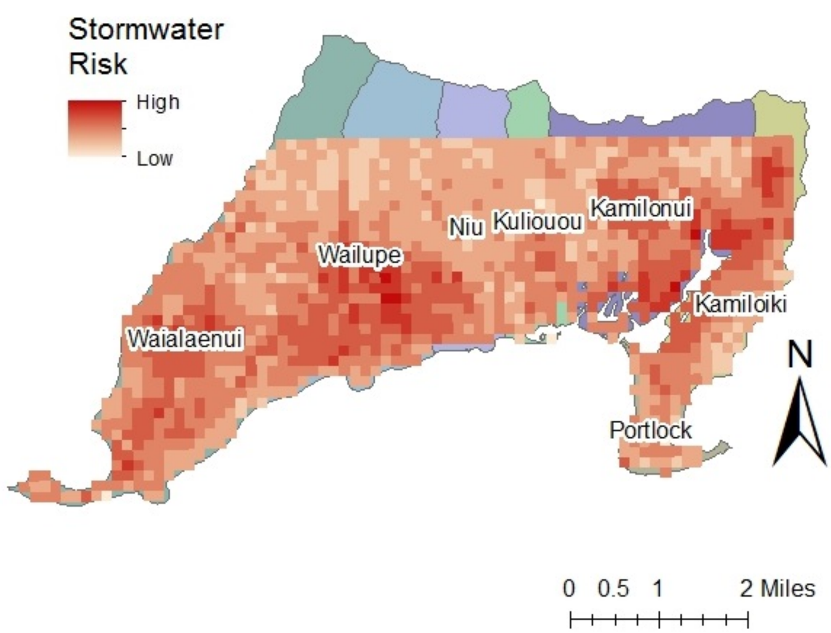

Figure 3: *Stormwater suitability map for Maunalua Bay using model weighted importance "Storm Drain."*

III. Green Infrastructure Management Plan: Case Study Results

After producing our three suitability maps, we compared their results to identify areas that consistently showed high stormwater risk across all three modeling schemes. We identified one such area to be the back of Kamilo Iki valley, west of the inland extremity of Koko Marina and seaward of some of the only remaining agricultural land in the Maunalua region. While surveying this vicinity for an appropriate case study site, we located a townhouse subdivision, which we refer to as Critical Source Area 1 (CSA 1) at the base of a nearby gulch (Figure 4). Upon closer inspection of this site, we noticed a large rainwater catchment system already constructed above the property. This finding suggests that the area had a recognized need for stormwater management, validating our model's efficacy. Because this community had already implemented a stormwater mitigation intervention, our team decided to continue our search. We ultimately chose Critical Source Area 2 (CSA 2), a 15.0 acre, 64 home subdivision located in the aforementioned portion of Kamilo Iki (Figure 5), as our case study site.

Figure 4: *Critical Source Area 1 (highlighted) from Google Earth. Drainage basin is located in the middle of the image.*

Figure 5: *A satellite view of Critical Source Area 2 (highlighted): the Kamilo Iki watershed (Google Earth).*

Using aerial imagery and the area measurement tool available through Google Earth we determined the the average land cover of a house lot in this CSA 2 to be 15% concrete, 33% roof, and 52% lawn. It is important to note that this calculation only included land cover within the bounds of private properties, and excluded public roads and sidewalks, emphasizing the impacts that individual homeowners can have on stormwater mitigation. With this information, we were subsequently able to estimate the reduction in peak runoff resulting from implementing four predefined green infrastructure best management practices (BMPs) at CSA 2 using the free, online Green Values Stormwater Management Calculator (Table 2).[7]

Table 2. *Benefits of Implementing Various Green Infrastructure Interventions at Critical Site 1*

Green Infrastructure Intervention (from Green Values Stormwater Management Calculator)	Percent reduction in peak discharge for an average house in CSA 1
Half of Lawn Replaced by Garden with Native Landscaping	6%
Porous Pavement used on Driveway, Sidewalk and other non-street pavement	10%
Provide Tree Cover for an Additional 25% of Lot	17%
Roof Drains to Rain Gardens at All Downspouts	36%

IV. Discussion and Recommendations

[7] Center for Neighborhood Technology. Green Values Stormwater Management Calculator. http://greenvalues.cnt.org/calculator/calculator.php

The Green Values Stormwater Management Calculator (SMC) is the more user-friendly of two such tools made available by the Center for Neighborhood Technology (CNT), a national environmental non-profit organization. Although limited in its settings compared to CNT's more robust National Stormwater Calculator,[8] the SMC provides a valuable initial estimate of the relative impact of green infrastructure implementation on a household or neighborhood scale. The SMC's simplicity also makes this type of tool accessible to the average homeowner who may not be capable or inclined to complete the NSC's lengthy list of input fields. In the case of CSA 2, the SMC illustrated how substantial reductions in peak stormwater discharge can be achieved via relatively inexpensive landscape modifications, and further reduced by directly diverting roof runoff to such permeable areas for infiltration. Replacing existing driveways with permeable pavement is another effective, albeit much more expensive, way to increase stormwater infiltration. Given these findings, we recommend the establishment of native rain gardens as miniature infiltration basins for as the most cost effective and least intrusive way to mitigate stormwater runoff in this scenario. We have included an additional explanation of the advantages of various green infrastructure technologies in Appendix E.

V. Conclusion

Conventional stormwater management infrastructure needs to be adapted to accommodate for rapid urbanization and impervious surfaces. However, large scale changes to infrastructure cost time and money. Therefore, the creation of a suitability map of stormwater CSA can help pinpoint areas of priority for stakeholders who want to promote green infrastructure and assess the most appropriate options. Our project provides a preliminary map and model for use in the Maunalua Bay Watershed. These maps provide critical knowledge and insight into the drivers of storm water issues throughout the watershed.

Enhancing the infrastructure of Maunalua Bay will lessen the amount of stormwater that is discharged into the bay and increase ecosystem health. Currently, the watershed is vulnerable to pollutants such as sediment, chemicals, organic materials (plants, animal wastes, and animal remains), and inorganic materials (plastics, metals, and domestic rubbish). Reduction of these pollutants will increase water quality and species diversity and thus, the overall health of the bay and associated practices. The reduction and treatment of stormwater is possible through green infrastructure. This has several benefits for watershed residents and the environment. Firstly, stormwater treatment allows for more available freshwater in the watershed for domestic and private use. Secondly, freshwater enters the coastal environment at a slower rate decreasing the negative effect on the chemistry and physical structure of the coast, improving marine life and mitigating coastal erosion. Finally, increased water flow creates better circulation throughout the watershed, potentially improving water quality and ecosystem function.

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[8] Center for Neighborhood Technology. Green Values National Stormwater Calculator. http://greenvalues.cnt.org/national/calculator.php

This proposal has potential collaboration between multiple groups as well as applications in grant writing. This map allows residents, business and government officials to pinpoint most vulnerable areas to stormwater to focus limited resources. By demonstrating a need for green infrastructure through critical source area mapping, funding opportunities are widened through evidence based need. If the modeling is successful in locating these CSAs and the application of green infrastructure techniques reduces stormwater entering the Maunalua Bay, then the methods of this study may be applied to other areas that have flooding and sediment problems due to current infrastructure. This could make Maunalua Bay a model for watersheds within the Hawaiian archipelago as a way for small watershed monitoring groups to focus their limited resources.

Appendix A: *Critical Source Areas (CSA) Map Layers*

Category	**Layer Name**	**Source**	**Metadata Description**
Topography	Digital Elevation Models (DEMs) for the main 8 Hawaiian Islands	Department of Commerce (DOC), National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Center for Coastal Monitoring and Assessment (CCMA), Biogeography Branch	Digital elevation model (DEM) data are arrays of regularly spaced elevation values referenced horizontally either to a Universal Transverse Mercator (UTM) projection or to a geographic coordinate system. The grid cells are spaced at regular intervals along south to north profiles that are ordered from west to east. The U.S. Geological Survey (USGS) produces five primary types of elevation data: 7.5-minute DEM, 30-minute DEM, 1-degree DEM.
Soil	Soil Permeability	Hawaii Soil Atlas	Water permeability describes the ease with which water can drain through a soil profile. Saturated hydraulic conductivity (Ksat) is a numerical property that describes water permeability. Soils that permeate water slowly (Ksat < 3μm/s) are prone to ponding, flooding,

			and runoff, while those that permeate very quickly (Ksat > 100µm/s) may drain water too quickly resulting in water not being retained for plant use. Moderate and fast permeating soils provide naturally balanced levels of water drainage and retention. Ksat data from the SSURGO database was used to classify permeability based on modified classes from the NRCS Field Book for Describing and Sampling Soils (Slow < 3, Moderate =3 to <10, Fast = 10 to <100, and Very Fast ≥ 100 µm/s).
Hydrology	Watersheds - (CWRM)	State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management, 2008	Surface water hydrologic unit boundaries for the 8 major Hawaiian Islands
Infrastructure	Land Cover Analysis: Impervious Surface and Land Cover Data (C-CAP)	NOAA, 2005	Land Use and Land Cover (LULC) data consists of historical land use and land cover classification data that was based primarily on the manual

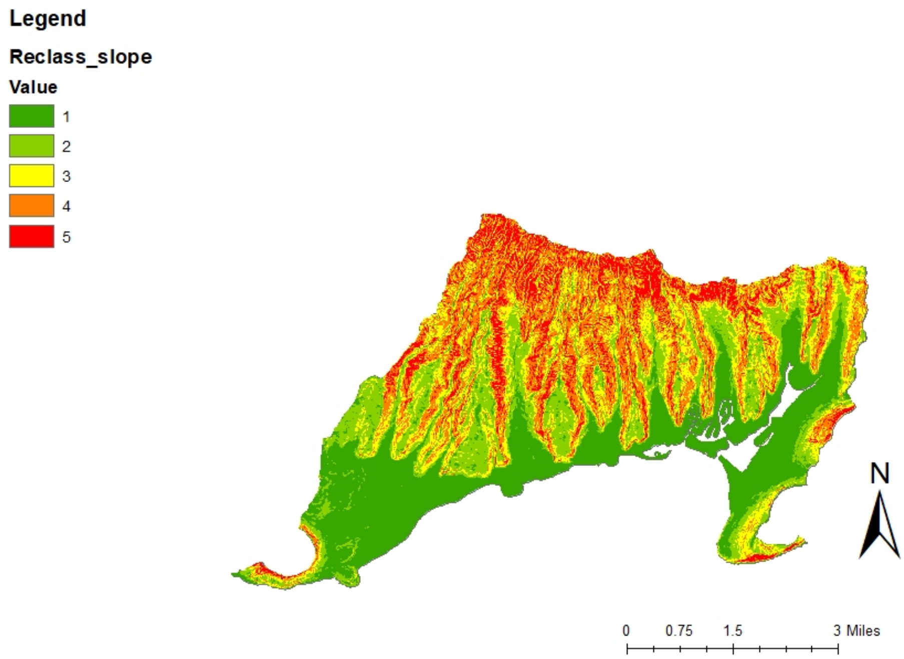
			interpretation of 1970's and 1980's aerial photography. Secondary sources included land use maps and surveys. There are 21 possible categories of cover type The spatial resolution for all LULC files will depend on the format and feature type. Files in GIRAS format will have a minimum polygon area of 10 acres (4 hectares) with a minimum width of 660 feet (200 meters) for manmade features. Non-urban or natural features have a minimum polygon area of 40 acres (16 hectares) with a minimum width of 1320 feet (400 meters). Files in CTG format will have a resolution of 30 meters.
Infrastructure	Stormwater Drain System	Hawaii Department of Transportation, 2008	Stormwater drain system for Oahu

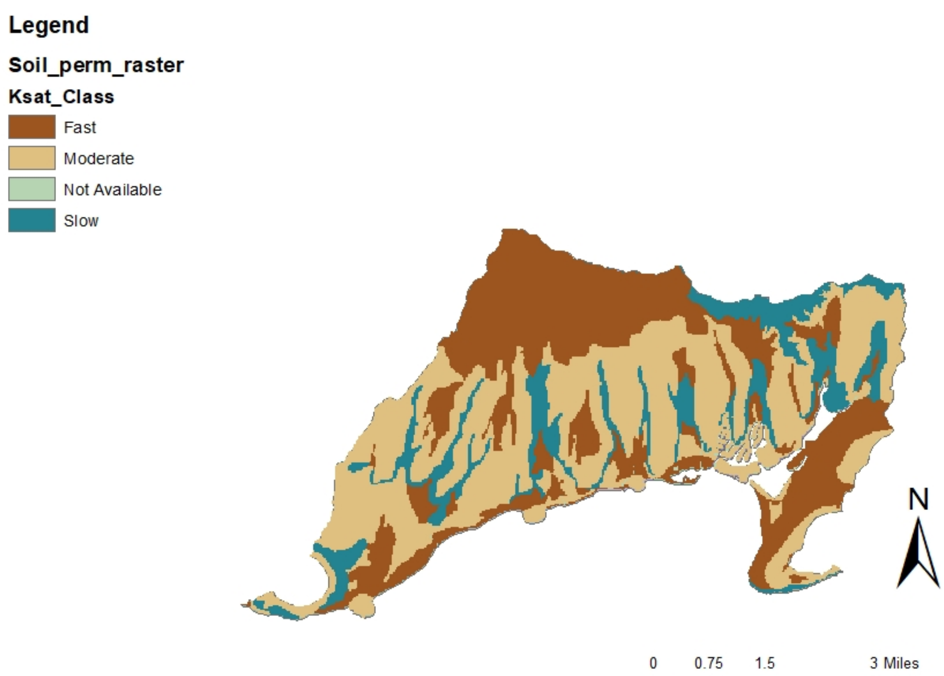
***Data layers chosen for the CSA Map production are based of the EPA National Pollutant Discharge Elimination System (NPDES) manual, discussions with members of Malama Maunalua, and several CSA maps developed for watershed plans included in the literature review. [4,5,6]

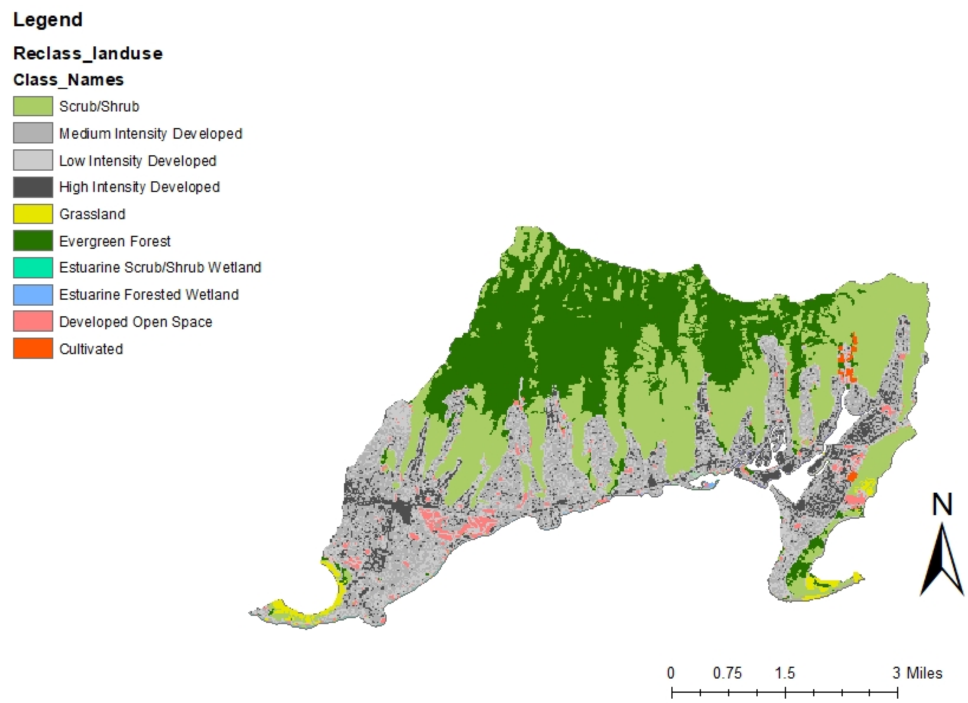
Appendix B: *Ranking Assignments for each GIS layer (all layer attributes homogenized to a 5 point ranking scale, with 5 being highest stormwater risk and 1 being lowest stormwater risk).*

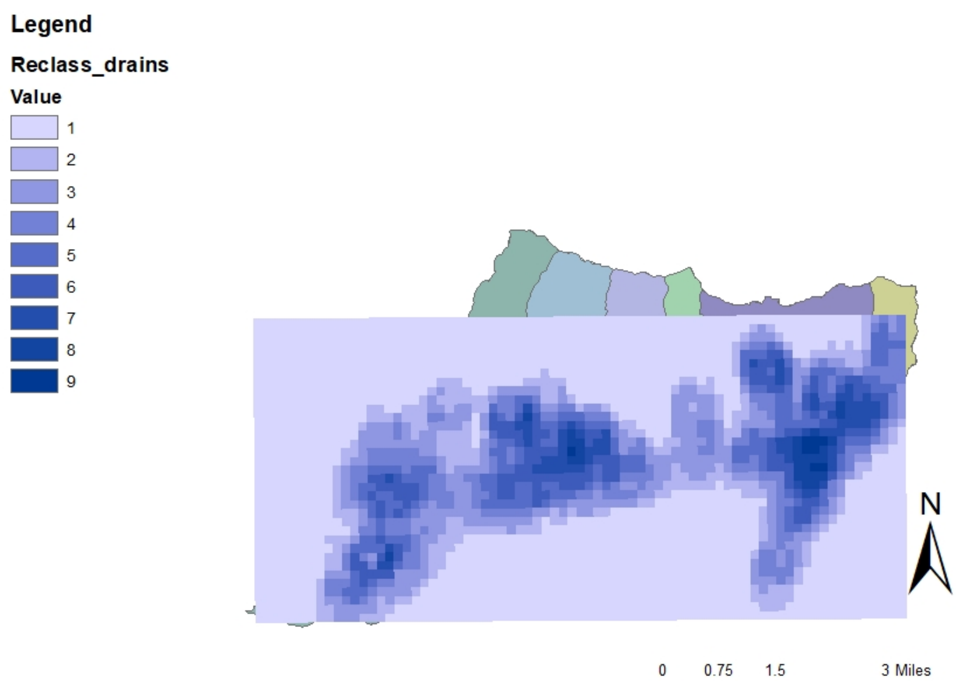
Layer Name	Attribute Metadata	Attribute	Assigned Ranking
Digital Elevation Models (DEMs) for the main 8 Hawaiian Islands	Contour line every 10m converted using slope function to slope, class breaks identified using classify tool to assign qualitative ranking terns	High Moderate-High Moderate Moderate-Low Low	5 4 3 2 1
Soil Permeability	Drainage capabilities of stormwater for the given soil	Fast Moderate Slow Not Available	1 2 3 0
Land Cover Analysis: Impervious Surface and Land Cover Data (C-CAP)	Land type from impervious surface density development to natural systems	High Intensity Devel. Med. Intensity Devel. Low Intensity Developed Open Cultivated Grassland Estuarine Scrub Estuarine Forest Scrub/Shrub Evergreen Forest	5 5 4 3 3 2 2 2 2 1
Stormwater Drain System	Transformed drain density values outputted from prominity analysis tool results (map developed by project team)	1 2 3 4 5 6 7 8 9	1 1 2 2 3 3 4 4 5

Appendix C: *Rasterized and reclassified map layers for the four layers going in the suitability map. Top figure to bottom: Slope, soil permeability, land cover, storm drain density.*

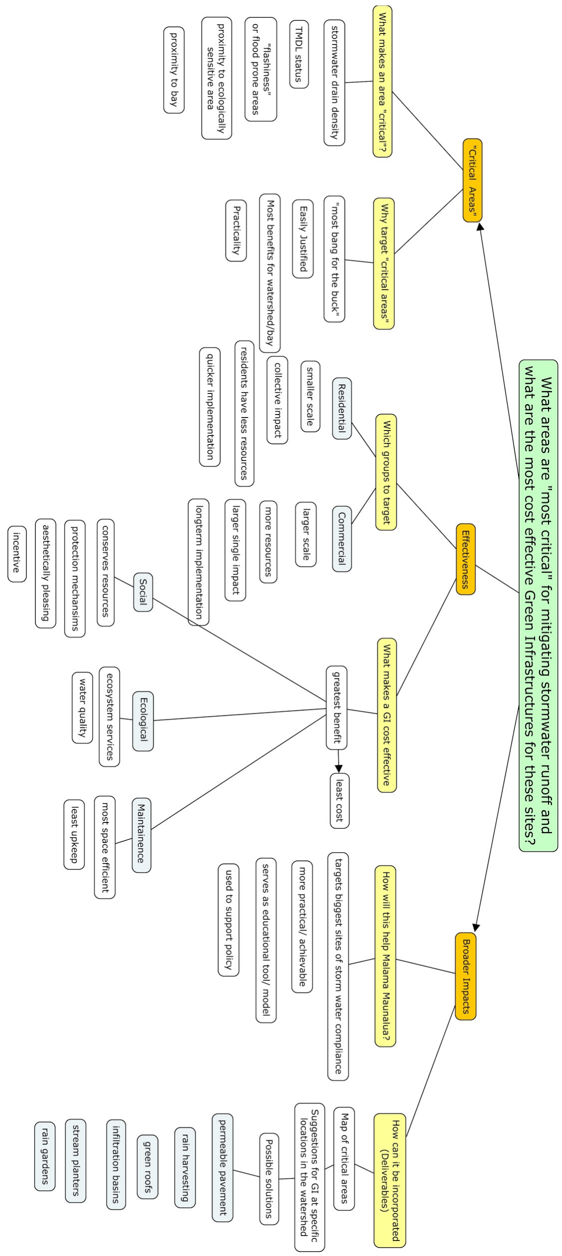





Legend
Reclass_landuse
Class_Names
Scrub/Shrub
Medium Intensity Developed
Low Intensity Developed
High Intensity Developed
Grassland
Evergreen Forest
Estuarine Scrub/Shrub Wetland
Estuarine Forested Wetland
Developed Open Space
Cultivated
N
0 0.75 1.5 3 Miles


Legend
Reclass_drains
Value
1
2
3
4
5
6
7
8
9
N
0 0.75 1.5 3 Miles

Appendix D: *Concept Map for Malama Maunalua Green Infrastructure project*



Appendix E: *Additional Explanation of Various Green Infrastructure Technologies*

The first least expensive and labor intensive green infrastructure intervention recommended by the Green Values SMC is simply planting more native vegetation and trees in one's yard. Native plants are adapted to their respective environments and naturally take up more water and retain more moisture in the soil than turf grass. Trees, whether native or non native, similarly absorb more water because of their deep roots, slowing runoff and expediting infiltration.

The next option, constructing a rain garden, is intermediate in cost and labor. Rain gardens come in many different sizes and designs. This option is flexible because there is no one way to construct and to design a rain garden. The only requirements are a permeable soil mixture and a concave shape, maximizing stormwater capture and drainage. The design can mimic either a wetland or a dry riverbed. From there, a variety of desired plants can be added to the garden. If native plants are chosen, this option can be further enhanced by the benefits discussed in the previous example (Figure 6).

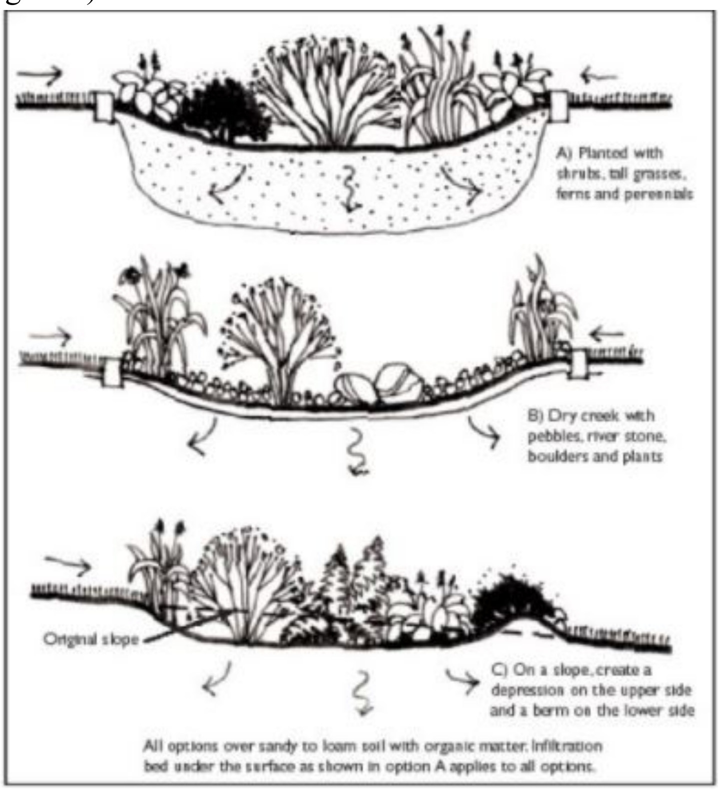


Figure 6. *How to design a rain garden*[9]

The most expensive and labor-intensive green infrastructure method is permeable pavement. The purpose of this method is that during a wet weather event, some of the water is absorbed by the pavement and back into the watershed instead of being runoff into rivers, lakes, and the ocean. The three options of permeable pavement are: porous asphalt, porous concrete,

[9] "Rain Gardens: A Way to Improve Water Quality". University of Massachusetts Amherst. 2011

and interlocking pavers. Each option has the durability to last at a minimum of 20 years, which is comparable to that of conventional impervious pavement (Table 3).

Table 3. Comparison of the Three Major Types of Permeable Pavements.[10]

Design Factor	Porous Concrete (PC)	Porous Asphalt (PA)	Interlocking Pavers (IP)
Scale of Application	Small and large scale paving applications	Small and large scale paving applications	Micro, small and large scale paving applications
Pavement Thickness1	5 to 8 inches	3 to 4 inches	3 inches 1, 8
Bedding Layer 1, 8	None	2 inches No. 57 stone	2 inches of No. 8 stone
Reservoir Layer 2, 8	No. 57 stone	No. 2 stone	No. 2 stone 3-4 inches of No.57 stone
Construction Properties 3	Cast in place, seven day cure, must be covered	Cast in place, 24 hour cure	No cure period; manual or mechanical installation of pre-manufactured units, over 5000 sf/day per machine
Design Permeability4	10 feet/day	6 feet/day	2 feet/day
Construction Cost 5	$ 2.00 to $6.50/sq. ft.	$ 0.50 to $1.00/ sq. ft.	$ 5.00 to $ 10.00/ sq. ft.
Min. Batch Size	500 sq. ft.		NA
Longevity 6	20 to 30 years	15 to 20 years	20 to 30 years
Overflow	Drop inlet or overflow edge	Drop inlet or overflow edge	Surface, drop inlet or overflow edge
Temperature Reduction	Cooling in the reservoir layer	Cooling in the reservoir layer	Cooling at the pavement surface & reservoir layer
Colors/Texture	Limited range of colors and textures	Black or dark grey color	Wide range of colors, textures, and patterns
Traffic Bearing Capacity 7	Can handle all traffic loads, with appropriate bedding layer design.		
Surface Clogging	Replace paved areas or install drop inlet	Replace paved areas or install drop inlet	Replace permeable stone jointing materials
Other Issues		Avoid seal coating	Snowplow damage
Design Reference	American Concrete Institute # 522.1.08	Jackson (2007) NAPA	Smith (2006) ICPI
1 Individual designs may depart from these typical cross-sections, due to site, traffic and design conditions. 2 Reservoir storage may be augmented by corrugated metal pipes, plastic arch pipe, or plastic lattice blocks. 3 ICPI (2008) 4 NVRA (2008) 5 WERF 2005 as updated by NVRA (2008)	6 Based on pavement being maintained properly, Resurfacing or rehabilitation may be needed after the indicated period. 7 Depends primarily on on-site geotechnical considerations and structural design computations. 8 Stone sizes correspond to ASTM D 448: *Standard Classification for Sizes of Aggregate for Road and Bridge Construction.*		

[10] "Permeable Pavement Fact Sheet. Information for Howard County, Maryland Homeowners" University of Maryland Extension. 2016

Lastly, rain barrels are another effective green infrastructure option that was not available through the Green Values SMC. They are essentially a catchment system for roof runoff ranging from dozens to hundreds of gallons in capacity. Although rain barrels have a storage limit, and may not be able to retain all runoff from storm event, their overflow can be diverted to permeable surfaces or even rain gardens minimize runoff. The captured water offers cost savings and environmental benefits as a water source for landscape care and other household maintenance that can be accomplished with non-potable water. The below table lists several commercially manufactured rain barrels currently available through well known retailers (Table 4). Rain barrels are also relatively simple and can be constructed as a DIY project with affordable, readily available, and often repurposed household items.

Table 4. Cost comparison of commercially available Rain Barrels (May 2018).

Rain Barrel	**Cost ($)**
Home Depot (online)	
RTS Home Accents 50 gal w/ brass spigot	$88.99
Earth Minded 45 gal recycle w/diverter	$79.99
Good Ideas 42 gal rock shape	$94.76
Algreen 80 gal brownstone	$147.04
Beckett 16 gal rain garden	$41.84
Lowes (online)	
Rain Wizard 40 gal black recycled plastic	$77.89
Rain Wizard 50 gal terra cotta plastic	$104.37
Real Wood Products 59 gal	$142.86
Ace Hardware (online)	
Fiskars Salsa Spice 58 gal	$139.99
Suncast Light Taupe 50 gal	$79.99
EarthMinded Gray Rain Barrel 50 gal	$119.99
EarthMinded Charcoal Rain Barrel 45 gal	$89.99
EarthMinded Black Industrial Drum no hole	$69.99