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FROM MAUKA TO MAKAI

Reducing Stormwater Runoff Pollution in Maunalua Bay, O'ahu, Hawai'i

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Kahuwai

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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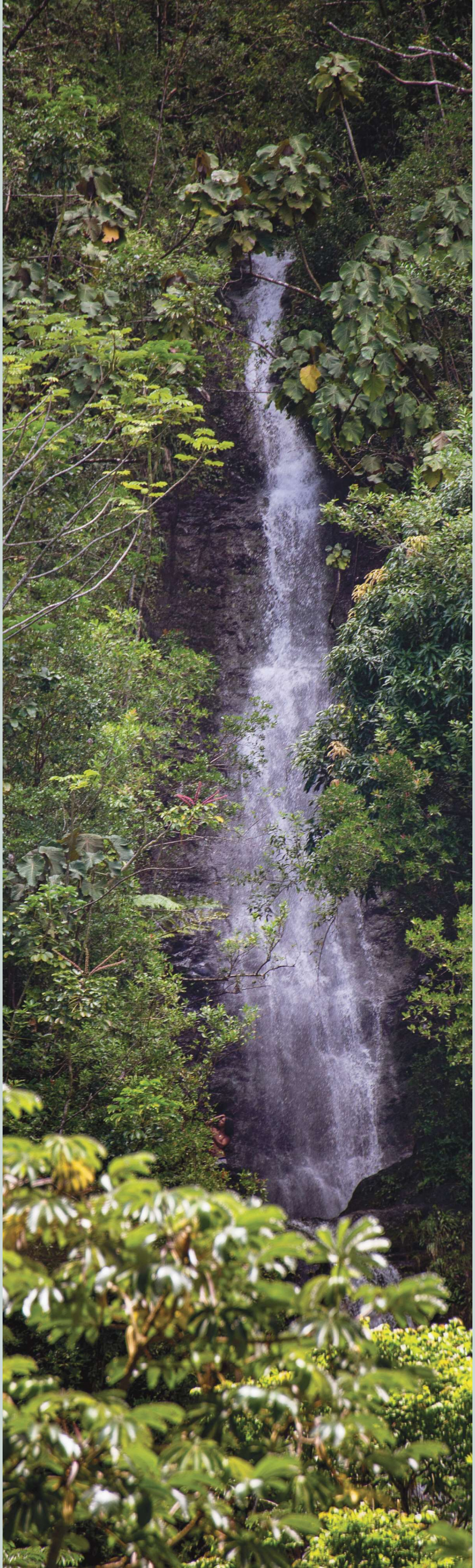

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mālama maunalua

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Abstract

A topic of contemporary interest in watershed management is the mitigation of polluted urban stormwater runoff into riparian and coastal ecosystems. Stormwater pollutant loading is exacerbated in watersheds with short and steep drainage basins and variable precipitation, such as in the Hawaiian Islands. This project explores spatial differences in the origins of polluted stormwater runoff and the potential for strategically placed green infrastructure to reduce runoff in Maunalua Bay, a region located on the southeastern coast of the Island of Oʻahu. The ten watersheds surrounding Maunalua Bay have undergone extensive development since the 1950s, and stressors such as stormwater pollution and sediment loading have negatively impacted the ecological integrity and reef community structure of Maunalua Bay. To understand how to effectively reduce polluted stormwater runoff, we employed the Environmental Protection Agency's Storm Water Management Model 5.1 to simulate the hydrology of the region. Using best available precipitation data, we calibrated our model within 15% of the observed discharge data (R2 = 0.80, NSE = 0.65). Individual subcatchments within the Wailupe watershed with high stormwater runoff coefficients (0.64-0.80) were identified as "hotspots" of total volume runoff. A positive, linear trend was found between runoff and percent impervious cover, supporting our hypothesis that the lack of infiltration in urbanized areas leads to greater runoff. Subcatchments with high peak flow were also identified and occurred mostly in the upper regions of the Wailupe watershed, suggesting a potential source of sediment. Results from our model help to identify priority areas for watershed managers to target stormwater reduction efforts. Furthermore, the calibrated model is a tool with which researchers in the Maunalua region can use to perform more comprehensive analyses of all ten watersheds to inform regional management decisions.

Executive Summary

The Maunalua Bay region is located on the southeastern coast of the Island of Oʻahu in Hawaiʻi, United States**.** It is composed of 10 watersheds that extend from the Koʻolau Mountain Range to the coastal waters that feed into Maunalua Bay. Since the 1950s, changes in land use combined with increased recreational activity and tourism have impacted the natural health and function of the bay ecosystem (Wolanski *et al.,* 2009). The Hawaiian Islands are naturally subject to flashy stream flows due to steep terrain and high rain intensity (Lau and Mink, 2006). Urban development has led to the channelization of streams and increased runoff from impervious surfaces that has exacerbated this flashiness, leaving the marine ecosystem in receiving waters vulnerable to loading of sediment and land-based pollutants. Urban-derived stormwater pollution contributes to the degradation of the ecologically important coral reef habitat, fosters the colonization of invasive species (Muthukrishnan and Fong, 2018), and alters the ecosystem dynamics of Maunalua Bay (Miller *et al.*, 2009).

Mālama Maunalua is a local non-profit organization committed to restoring Maunalua Bay. Traditionally, Native Hawaiian resource management followed *ahupuaʻa* – a holistic management of resources from the mountains (*mauka*) to the sea (*makai*). Embedded in this practice was an understanding that upland activities have an impact on the health of marine organisms in the receiving waters downstream. Driven by these principles, Mālama Maunalua is invested in implementing a watershed-based management approach to improve the health of the Bay. A team of four Master's students from the Bren School of Environmental Science & Management collaborated with Mālama Maunalua to develop a holistic, watershed-level approach that couples ongoing ocean restoration efforts in the Bay with improved land management upstream in the watershed.

One strategy to reduce stormwater runoff in urban areas is to incorporate green infrastructure (also known as Low Impact Development, LID) into land management. Green infrastructure projects are designed to increase infiltration of water into natural soils from a surrounding drainage area. This can be done by creating depressions in the land surface and vegetating them, using highly permeable materials on the surface, and/or collecting and storing rainfall. In order to provide recommendations on green infrastructure placement, it is important to understand the baseline conditions for runoff in upstream areas. The Maunalua Bay region lacks comprehensive observational hydrologic data throughout each watershed, and Mālama Maunalua has limited staff, time, and funding to collect such data. Without a comprehensive assessment of the region, organizations like Mālama Maunalua are prevented from effectively targeting their management efforts. We therefore decided to employ a hydrologic model that uses best available data to understand which areas of the urban and natural watershed produce the highest total runoff volumes and peak discharge. This model will serve as a tool for Mālama Maunalua and other regional stakeholders to inform management decisions.

The overall objective of this project is to analyze the potential for reducing stormwater runoff into Maunalua Bay through the use of strategically placed green infrastructure. There are four key phases in addressing this objective:

1. **Create a reproducible hydrologic model for the Maunalua Bay Region** that identifies management areas or “hotspots” in the watershed based on total stormwater volume and peak discharge.
2. **Characterize data availability and limitations** for each of the ten watersheds in the region.
3. **Synthesize a spatial map of viable locations to implement green infrastructure projects** that would reduce stormwater and sediment loading from hotspots.
4. **Recommend management scenarios** that optimize between financial costs and mitigation from green infrastructure.

This project investigates the first two phases. Our client, Mālama Maunalua, will use our work to continue answering phases three and four. The deliverables of this project will serve to guide Maunalua Bay stakeholders in identifying priority areas for management within each watershed. Additionally, this project will provide insight into the viability of green infrastructure as a stormwater management solution for the region. This work will aid Mālama Maunalua in their mission to restore the health of the locally important Maunalua Bay ecosystem, as well as add to the knowledge of urban stormwater runoff reduction in other island states and nations.

Phase 1: Hydrologic Modeling

To accomplish the goals of this project, we chose to model the hydrology of the Maunalua Bay region using the U.S. Environmental Protection Agency (EPA) Storm Water Management Model 5.1 (SWMM). SWMM is a dynamic model that simulates both hydraulic flows and hydrologic processes to predict stormwater runoff and pollutant loading. The model also has the capacity to predict reductions in runoff from the implementation of specific green infrastructure designs. SWMM was selected due to its ability to represent features of both natural and urbanized watersheds, encompassing the unique characteristics of the Maunalua Bay region.

Hydrologic modeling requires a degree of empirical precipitation and stream discharge data. These data are limited in the Maunalua Bay region: only two of the ten watersheds (Wailupe and Kuliʻouʻou) have stream gauges and only one has a precipitation gauge recording at 15-minute intervals (Wailupe). Calibration of SWMM therefore was conducted using the available data for the Wailupe watershed. Some specific tuning of the model was required, such as the capping of subcatchment widths, the use of different soil curve numbers for antecedent wet or dry conditions, and the adjustment of Manning’s N values based on land use.

Our initial model results indicate that total volume runoff is higher in the urban areas of the watershed where impervious cover is highest. This observation validates the need for increased vegetation in specific urban areas. However, we also found that peak flow is higher in the upper watershed where no urbanization has occurred. Based on previous studies confirming the positive relationship between peak flow and suspended sediment concentrations, our results suggest that the sources of sediment are in the upper, vegetated watershed. Therefore, reducing sediment concentrations at the source may require restoration efforts in the upper watershed where erosion is highest. Nonetheless, green infrastructure in the urban watershed can still be an important mitigation tool. Capturing sediment before it enters the built stormwater conveyance network through bioretention will prevent stormwater from carrying sediment into the Bay.

Phase 2: Characterizing Data Availability

In developing our model, we were able to thoroughly investigate the relevant hydrological data available throughout the region. Data availability is a limiting factor for being able to use SWMM. We therefore believed that a comprehensive review would be a helpful tool for anyone working in the Maunalua Bay region using SWMM. A table of relevant available data for each of the ten watersheds was thus compiled to help future users easily identify data and navigate our calibrated model. Included in this table is a list of data gaps for each watershed. This will inform future studies and indicate data that must still be collected to increase the accuracy of SWMM use across the Maunalua Bay region.

Phase 3 & 4 Recommendations

A key function of SWMM is its ability to assess the reduction in stormwater runoff given changes in watershed management. Although our project did not carry out phases 3 and 4, we did identify a tool that can be paired with SWMM to assess specific green infrastructure implementation in the hotspots we previously identified. For future studies we therefore recommend coupling SWMM results with the San Francisco Estuary Institute's GreenPlan-IT Toolkit. This tool determines the optimal spatial placement of different green infrastructure designs based on soil hydrology, watershed characteristics, and developable land.

It can also be used to optimize the mitigation of runoff per dollar spent by considering runoff reduction potential and costs of implementation and maintenance of different green infrastructure designs. The output of this tool is an ideal spatial distribution of green infrastructure based on runoff reduction and cost. SWMM coupled with the GreenPlan-IT toolkit is therefore a powerful tool that managers in the region can use to identify stormwater hotspots, suitable areas for green infrastructure placement, and the approximate costs associated with implementation.

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Objectives

Research Objective

The overall objective of this project is to analyze the potential for reducing stormwater runoff into Maunalua Bay using strategically placed green infrastructure. We have identified four key phases which will allow this objective to be met:

1. **Create a reproducible hydrologic model for the Maunalua Bay Region** that identifies management areas or "hotspots" in the watershed based on total stormwater volume and peak discharge.
2. **Characterize data availability and limitations** for each of the ten watersheds in the region.
3. **Synthesize a spatial map of viable locations to implement green infrastructure projects** that would reduce stormwater and sediment loading from hotspots.
4. **Recommend management scenarios** that optimize between financial costs and mitigation from green infrastructure.

For the purposes of this project, we focused on completion of phases 1 and 2. This will enable our client and other stakeholders to carry out phases 3 and 4 in future work.

Significance of the Project

Background

Land acknowledgement

We acknowledge that the land in which our project takes place was home to and is still home to Native Hawaiians who were the original stewards of the land and many of whom were displaced from their unceded ancestral lands.

The Maunalua Bay Region

The Maunalua Bay region is located on the southeastern coast of the Island of Oʻahu in Hawaiʻi (Figure 1). For hundreds of years, Maunalua Bay (the Bay) has been an important ecological, economic, and cultural feature for the people of this region. The Bay's 8 miles of shoreline and 6.5 square miles of submerged waters stretch between the volcanic cones of Diamond Head (*Leahi*) and Koko Head (*Kawaihoa*), granting the Bay its name *Maunalua* (two mountains). Extending from the southeastern shore of Oʻahu to the southern summit of the Koʻolau Mountains is the greater Maunalua region. This area encompasses 28 square miles of land which is composed of 10 *āpana* (watersheds) that feed directly into the bay (Figure 1, Miller *et al.*, 2009). The region is characterized as semi-arid, and climate varies over short distance. There is a warm and dry season from May through September, and a cooler, wet season that occurs from October through April. Rainfall in the region varies not only temporally with the seasons, but spatially throughout the region. Annual rainfall has a range of between 20 inches per year in the coastal regions, to up to 100 inches per year in the higher elevations of the Koʻolau Mountain Range (Miller *et al.*, 2009). This creates spatial rainfall gradients that, even within a single watershed, exceed 80%.

Natural History

The Hawaiian Islands are volcanic in origin, and the Maunalua Bay region is derived from the fragmented remains of the Koʻolau shield volcano that erupted between 2.2 and 2.5 million years ago (Lau and Mink, 2006). Since the end of the initial volcanism stage, rapid erosional processes driven by wind, precipitation, and the sea developed the landscapes that give the Islands their unique characteristics (Lau and Mink, 2006). Situated in the middle of the North Pacific Subtropical Gyre, prevailing northeastern trade winds create orographic precipitation along the eastern coasts of the Islands. In the high elevations along volcanic ranges such as the Koʻolau, this precipitation contributed to the chemical and physical erosive processes that shaped the steep ridges and deep valleys that are characteristic of Hawaiian watersheds (Lau and Mink, 2006). The watersheds of Maunalua continue to be altered from natural erosive processes in addition to anthropogenic changes in land use.

Native historic vegetation zones in the Maunalua Bay region consist of lowland wet forest and shrubland in the upper elevations, lowland mesic forest and shrubland in the mid-elevations, and lowland dry forest, shrubland, grasslands, and wetlands in the mid-to-low elevations (Atkinson, 2007). It is well accepted that currently, the mid- and lower-watershed areas have been colonized by invasive alien species, however some native forested area is intact in the highest elevations. Historically, streams in the region provided perennial baseflow and there were numerous freshwater springs present in the lower elevations. These have been severely modified by urbanization of the region, which has channelized the major streams that now flow intermittently throughout the year (Miller *et al.*, 2009).

Maunalua Bay itself is composed primarily of expansive reef flats that extend from the coastline to a fore-reef that drops to a depth of 15-20 feet (Miller *et al.*, 2009). The Bay is home to an array of native Hawaiian reef fauna. The fore-reef has substantial coral reef growth and is the most conspicuous habitat for a diversity of marine life that ranges from native *limu* (algae) to reef fishes, invertebrates, and marine turtles and mammals. Maunalua Bay's beaches, reef flats, and marine life make it a desirable for recreational activities for tourists and residents alike. The

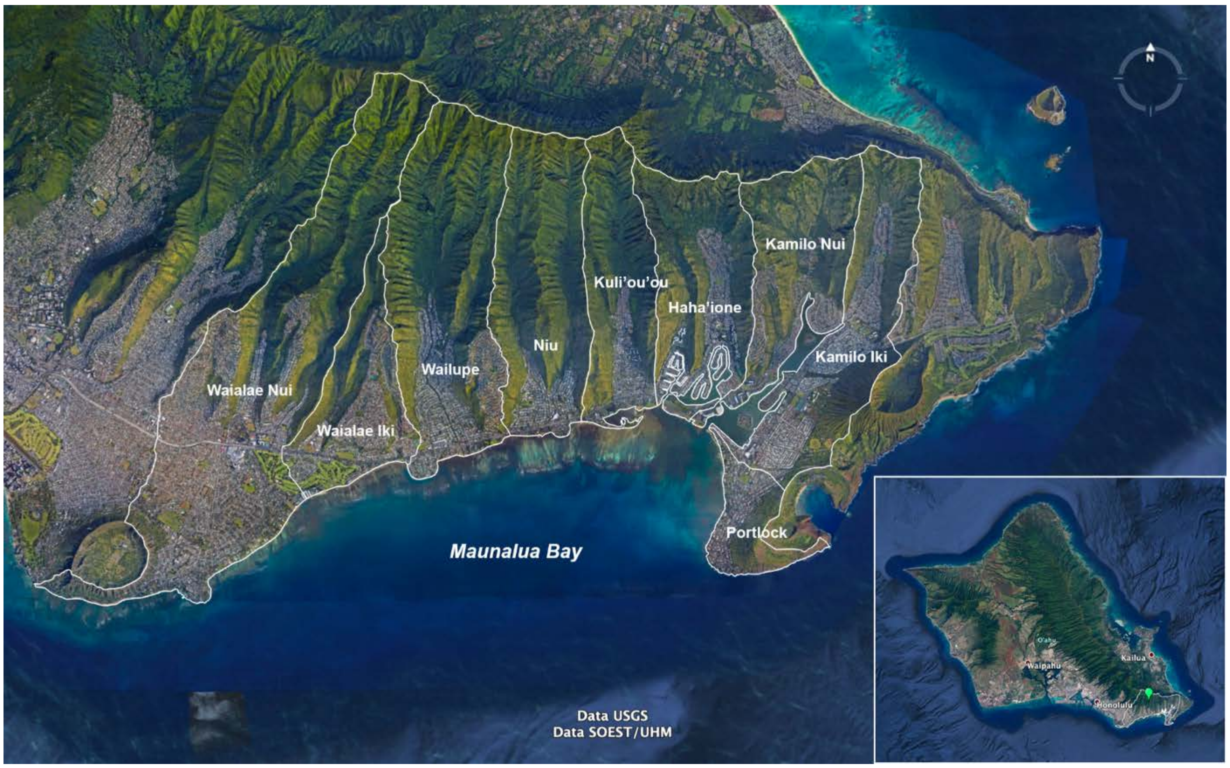


Figure 1: The Maunalua Bay Region, Oʻahu, Hawaiian Islands, U.S.A. Data provided by the U.S. Geological Survey and the University of Hawaiʻi at Mānoa School of Ocean, Earth, Science, and Technology (SOEST).

area is known to be a destination for surfers, outrigger canoe paddling, fishing, jet skiing, boating, and SCUBA diving.

Cultural Significance

Prior to Western contact, *kanaka maoli* (indigenous Hawaiians) believed in coexistence between people and nature and its *mana* (spiritual power) (Blaisdell *et al.*, 2005). As Blaisdell *et al.*, 2005 eloquently states:

> "Kanaka maoli *believed that our siblings are the plants and animals in nature. Therefore, through these relationships, it was everyone's responsibility to* mālama ʻāina, *care for the land and all her natural resources. These were collective relationships with all in the cosmos. The early kanaka maoli had a saying,* ''He aliʻi no ka ʻāina; he kauwa wale ke kanaka,'' *the land is chief; the human is but a servant.*"

Pre-Western management of natural resources in Hawai'i centered on that of *ahupua'a*, which embodies this ideology of interconnectedness. *Ahupua'a* were a series of land divisions in which all resources were holistically managed (Figure 2, Blaisdell *et al.,* 2005). Central to *ahupua'a* land management was the protection of *wai* (freshwater) from the uplands, down the rivers, to the *kai* (sea). In early Hawai'i, *wai* was believed to be a gift from the gods in the uplands for human use such as agri- and aquaculture, and its protection ensured the sustaining of life for the people of Hawai'i (Blaisdell *et al.*, 2005). This is representative of the understanding of Native Hawaiians that management decisions made in the upper watershed ultimately have downstream impacts.

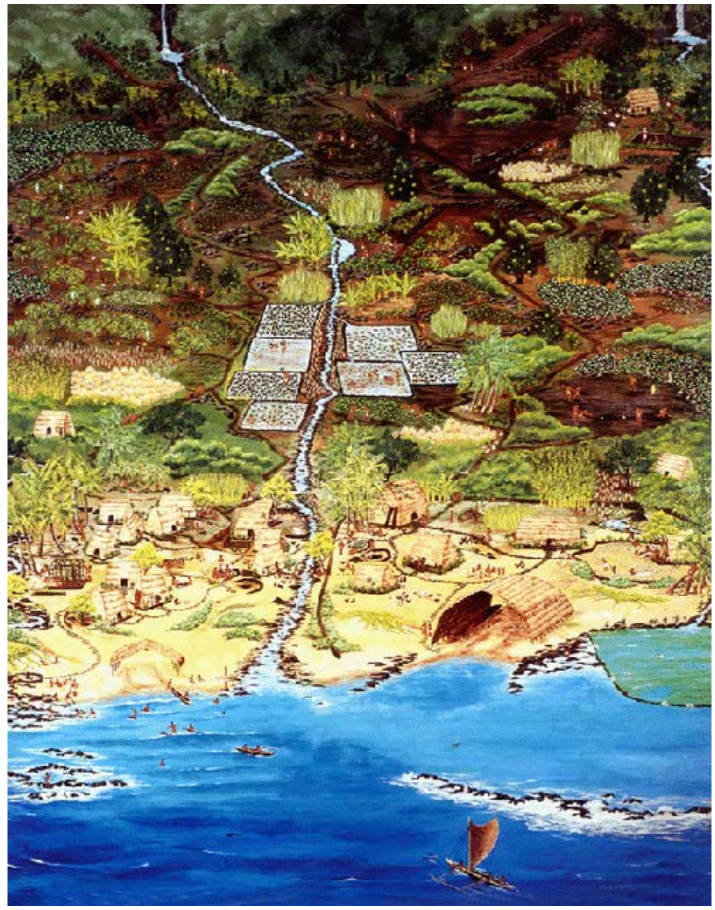


Figure 2. Ahupua'a. Artist – Marilyn Kahalewai

In the coastal waters of *ahupua'a*, Native Hawaiians developed *loko i'a*, or fishponds to allow for the rearing of juvenile fish and create a sustainable source of fish throughout the year. O'ahu was known to have roughly half of all the fishponds of all the Hawaiian Islands, which is a testament of the reliance on this resource for subsistence (Costa-Pierce, 1987). Historically, Maunalua Bay was home to six *ahupua'a* (Waiʽalae Nui, Waiʽalae Iki Wailupe, Niu, Kuliʽouʽou, and Maunalua) and at least four fishponds, including the largest in the Hawaiian Islands (Figure 3, Atkinson, 2007; Summers and Sterling 1962; Erlens and Athens, 1994). Kuapā Pond, which is now the current location of the Hawai'i Kai residential district and marina, was known for its abundance of mullet and shrimp (Coleman, 2014). The importance of Kuapā Pond is emphasized by its presence in Native Hawaiian history. Stories about the pond include visitation by Native Hawaiian monarchs, origin stories, and oral interviews by *kupuna* (elders) and *konohiki* (fish wardens) (Atkinson, 2007; McAlliser 1933 in Takemoto et al. 1975). This brief overview of the cultural history of the Maunalua region highlights its unique cultural value – a value that is embedded within the lives of the people who live there today.

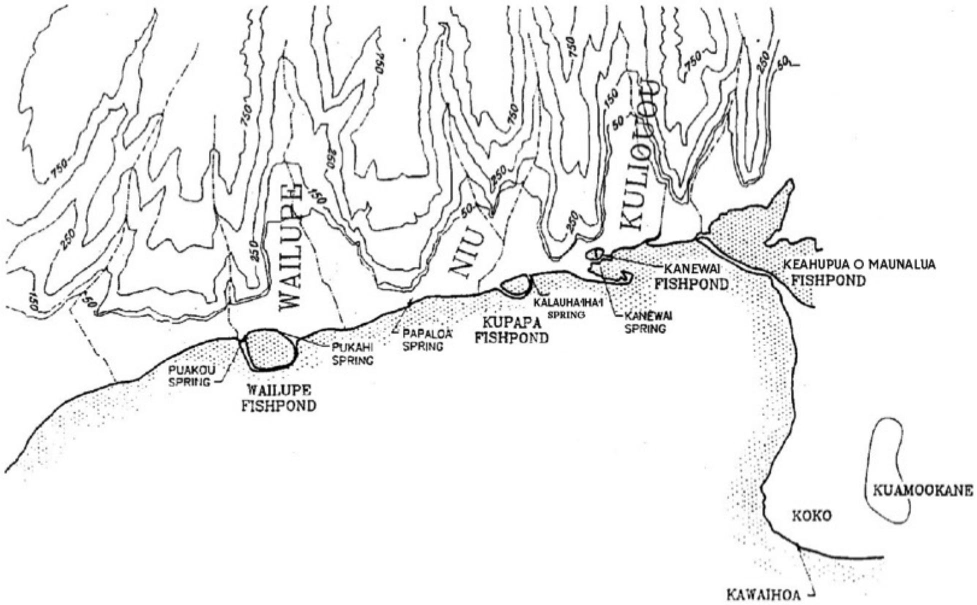


Figure 3. Historical Locations of Hawaiian Fishponds and Springs of Maunalua Bay, Oʿahu. Source: Erlens and Athens, 1994.

Problem

As a volcanic island with limited land area, land-based activities on Oʿahu have a significant impact on the water quality and overall health of Maunalua Bay (State of Hawaiʻi DOH CWB, 2015). In 1954, Henry Kaiser initiated a high value residential development that significantly altered the Maunalua Bay region (Coleman, 2014). Since then, continued urbanization of the surrounding watersheds coupled with increased tourism and recreation activities have resulted in pollutant loading, introduction of invasive species from vessels, trampling by snorkelers and divers, and anchor damage on the coral reef flats of the Bay (Weiner *et al.,* 2009; Dinsdale and Harriot, 2004; Kay and Liddel, 1989). Urban land cover estimates from a previous assessment provided a range of 18-65% for each of the ten watersheds in Maunalua Bay region (Miller *et al.*, 2009). In the watersheds, the transport of polluted water is accelerated by the channelization of all ten major streams in the region, nine of which are fully lined with concrete (Atkinson, 2007). Due to high pollutant loading, Maunalua Bay was declared an impaired body of water by the State of Hawaiʻi Department of Health (DOH) in 2004 for enterococcus levels, suspended solids, and nutrients (USDA NRCS, 2004; Miller *et al.,* 2009). Maunalua Bay watersheds have also been designated as priority watersheds by the State of Hawaiʻi for remedy and preservation in 2008 (State of Hawaiʻi DOH CWB, 2008). However, as of 2018, Maunalua Bay is still in non-attainment for total nitrogen, nitrate, nitrite, ammonium, and turbidity (State of Hawaiʻi DOH CWB, 2018).

The Bay has seen negative impacts on marine biodiversity, fisheries, and recreation (State of Hawaiʻi DOH CWB, 2018) due in part to land-based pollutant loading and impaired ocean conditions that promote the success of invasive species which outcompete native corals and algae for benthic substrate (Muthukrishnan and Fong, 2018). This result is similar to other coral reef communities and has led to a distinctive shift in community structure from coral dominated to invasive algal dominated (Miller *et al.*, 2009; Muthukrishnan and Fong, 2018). This is compounded by the overfishing of native reef fish and preference for herbivorous fish for native algal species, diminishing their impact on algae removal (Stamoulis *et al.*, 2017). Historical coral cover in Maunalua Bay was estimated to be about 20-60% in the 1960's (Wolanski *et al.*, 2009); however more recently in 2013 coral cover was estimated to be between 5-10% in most of the Bay (Franklin *et al.*, 2013).

Hoping to improve the health of Maunalua Bay, community members in the region founded a non-profit organization called Mālama Maunalua in 2005; *mālama* in Native Hawaiian means to care for or nurture. The organization has garnered widespread community support to address and resolve the issues facing Maunalua Bay (Weiant *et al.*, 2019). Wide-scale restoration would allow the Bay to continue supporting local fishing, food gathering, recreation, and the preservation of Native Hawaiian culture (Kittinger *et al*., 2013). For the past 14 years, the organization has been implementing restoration projects in collaboration with the local community, including sediment removal in stream channels, native tree planting, seagrass planting, sea urchin seeding, and invasive algae removal. Due to data and funding limitations, these projects have sought to address the issue mostly through postliminary mitigation and have not comprehensively addressed the land management conditions that lead to environmental degradation of the Bay. A holistic, watershed-level approach coupling downstream restoration with management that targets runoff reduction is necessary to effectively conserve Maunalua Bay now and for the future (Wolanski *et al.,* 2009).

Purpose

Mālama Maunalua reached out to the Bren School to collaborate on a management project with the goal of identifying management areas or "hotspots" in the watershed in which land-based pollution could be reduced through the use of green infrastructure. This project contributes to their mission of Maunalua Bay's restoration by modeling the hydrology of the region to predict stormwater runoff and identify hotspots where Mālama Maunalua can target their management efforts. Our approach is informed by the ideology of *ahupua'a* – that the health of Maunalua Bay can be protected through solutions that manage freshwater resources holistically across the entire watershed. This project, coupled with Mālama Maunalua's recent stormwater management campaign, will help improve the water quality of Maunalua Bay and support our client's plans introduce climate-adaptive native corals back into the Bay in 2020.

We also hope that our project will aid others seeking to restore their own watersheds. Across the entire Hawaiian islands fragile coral ecosystems are increasingly threatened by urbanization (State of Hawaiʻi DOH CWB, 2015); a fate that is shared by other regions which experience reef degradation due to urbanized waterfronts such as Australia, Africa, Indonesia, Madagascar, the Pacific Islands, and the meso-American reefs (Bartley *et al.*, 2014). In addition to the major local significance of this project, our work will be applicable to other coastal communities in the Hawaiian Islands and around the world which face similar issues. Development of management solutions for stormwater runoff in Maunalua Bay serves as a blueprint for other island communities which face similar threats to the marine environments they depend upon.

Approach

Previous studies and assessments in the Maunalua Bay region indicate that there are multiple factors that contribute to the environmental degradation of Maunalua Bay (Wolanski *et al.*, 2009; Miller *et al.*, 2009; Weber *et al.*, 2006; Richardson *et al.*, 2015). Findings from a 2009 study that investigated the impact of urbanization on coral reef flats in the area concluded that a holistic approach was required for the Bay to be able to recover and identified 8 management goals that need to be addressed (Wolanski *et al.*, 2009). These include:

1. Proper land use management in the surrounding catchment to reduce pollutant loading from land runoff.
2. Recovering the groundwater storage to decrease peak stormwater flows.
3. Replenishing herbivorous fish populations.
4. Removing the marina induced recirculation by cutting new outlets through the peninsula.
5. Physically removing the recent sediment deposits on the east side of the Bay.
6. Re-establishing coastal wetlands.
7. Redirecting the Kuliʻouʻou stream to flow into Paiko Lagoon as it did historically to trap sediment.
8. Re-establishing native seagrass and corals.

This project addresses the first two listed management goals of improving land management and reducing peak stormwater flows. Research has shown that areas of high stormwater flow volume also transport larger loads of sediments and other pollutants (Sustainable Resources Group Intn'l, Inc., 2010). This study also characterized the Wailupe Gulch ravine in the Wailupe watershed and noted that the downstream reaches in the urban corridor transport sediment out of the reach compared to sediment delivered into the reach, eventually depositing sediment into the ocean (Sustainable Resources Group Intn'l, Inc., 2010). This positive net transport of sediment into the Bay is a major concern because ecological studies of the Bay indicate that the most harmful source of pollution to the ecosystem is sediment (Williams *et al.*, 2009; Wolanski *et al.*, 2009). Bothner et al., 2006 discuss the extensive scientific literature investigating the degradation of coral reef health due to sedimentation, including smothering and burial, decreased irradiance from high turbidity, and larval settlement inhibition, among others. Furthermore, other contaminants such as nutrients and endocrine disruptors have the potential for sorption to sediment particles, and as such sediment can serve as a transport mechanism for other contaminants to coastal waters (Kronvang *et al.,* 2006). As such, we primarily investigate the dynamics of stormwater runoff in this region and its relationship to sediment loading for this study.

Although it is well-accepted that sedimentation is a critical stressor for coral reefs, coral recovery from sedimentation events is not well studied and coral response to sediment stressors vary widely by species. As such, it has been a challenge for Mālama Maunalua to establish recovery thresholds and goals. In field and laboratory studies, burial of some coral species has led to death in just a few hours, while other species survived (Rogers 1990). A study by Rodgers in 1983 of

Caribbean reef corals study suggests chronic rates of sediment greater than 10 mg/cm^2 per day are considered high; however, the study but was not able to determine sedimentation rates that can be associated with recovery. More recently, Bessell-Browne *et al.* conducted a laboratory study manipulating light and suspended sediments to various coral species finding that although mortality was high (65%) in conditions that simulate dredging operations (low light, high sediment concentrations), no full colony mortality was observed for any experiment (Bessell-Browne *et al.* 2017). This indicates the potential for recovery of corals from sedimentation events. There are other factors that determine stress in corals when exposed to sedimentation, such as nutrients and co-pollutants, that is little understood and make it hard to determine potential harm to corals (Weber *et al.*, 2006). Large freshwater inputs can also harm coral due to drops in salinity, which alone can prevent the healthy growth of corals (Wolanski *et al.*, 2009). Further research needs to be done to understand how impervious surfaces have changed freshwater inputs into the Bay and the subsequent effect on corals. Further research is also needed to understand how much sediment loading reduction is required to improve conditions for coral. For these reasons, there is no sedimentation pollution or runoff reduction threshold we will use for this analysis, and our focus will be to use reductions in stormwater runoff as a proxy for reducing sediment pollution into Maunalua Bay.

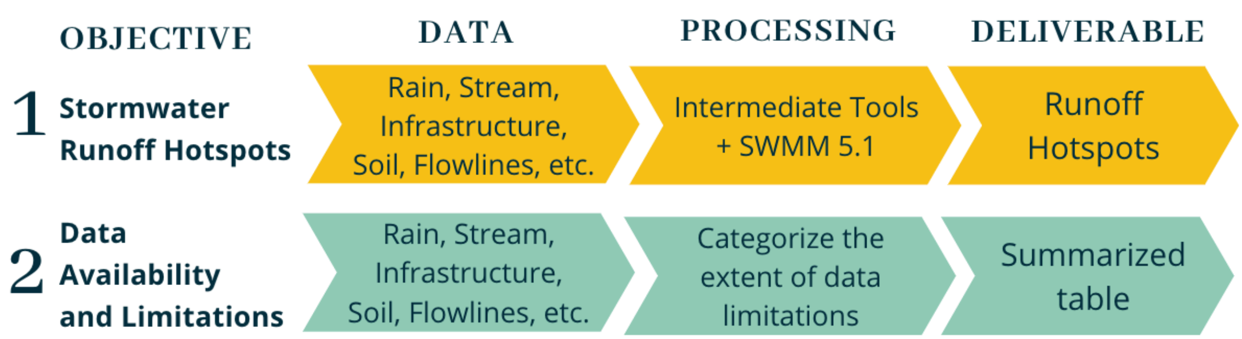


Figure 4. Conceptual Diagram of Project Approach to Stormwater Hotspot Identification and Data Availability and Limitations

To reduce stormwater runoff and thus pollutant loading into Maunalua Bay, it is necessary to identify the sources in the watersheds above the Bay. Due to the heterogeneity of the natural and built environment in watersheds, we can delineate watersheds into subcatchments that allow for increased resolution of watershed characteristics. Based on their features, subcatchments will contribute different volumes of runoff and pollutant loading, making it easier for managers to prioritize their efforts on areas that contribute the most to stormwater runoff, designated as hotspots. A stormwater hotspot is defined as a subcatchment within a watershed which has higher stormwater volume and runoff relative to the surrounding areas. The workflow for characterizing the watershed, delineating subcatchments, and modeling for hot spots can be seen in Figure 4, Objective 1 (Figure 4).

Identifying stormwater hotspots is difficult due to regional limitations. These limitations include, but are not limited to, lack of available high-resolution data as well as limited staff and monetary resources for sampling in the watershed. These limitations make it difficult for managers to know where in the region to target restoration efforts. To address these limitations, this project used a hydrological model to obtain a baseline estimate of runoff and pollutant loading in Maunalua region. The model of choice for this study is the EPA Storm Water Management Model 5.1 (SWMM) (Figure 5; US EPA, 2019 [SWMM 5.1.013]). This is because SWMM is capable of simulating hydrologic processes across different subcatchments that represent both natural and urbanized areas within the watershed - flow through the natural upper watershed and flow through the urban stormwater drainage system. The model can also be used to model reductions in flow for green infrastructure implementation in the watershed. While searching for the appropriate data for the model, we will compile data for the region and assess the extent of data limitations to be summarized in a table for future studies (Figure 4, Appendix A).

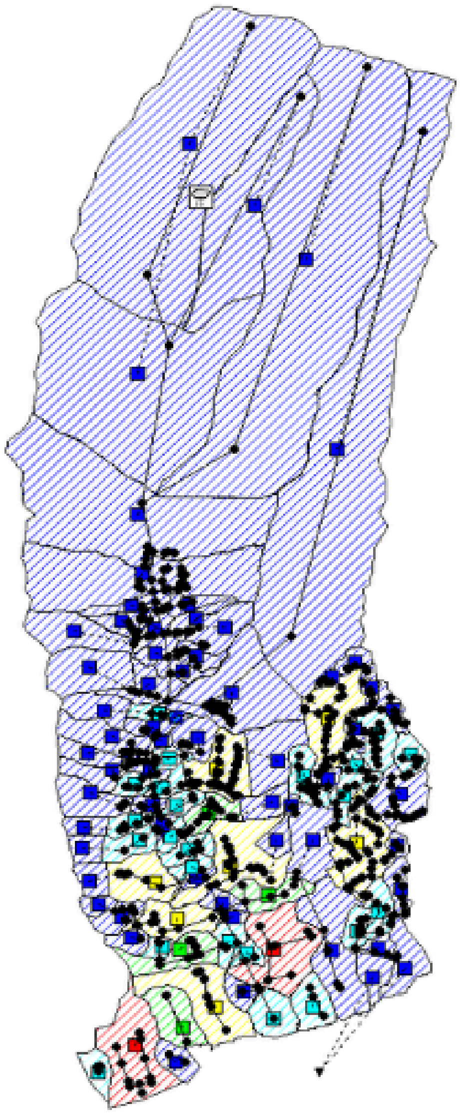


Figure 5. Diagram of the EPA Storm Water Management Model 5.1 Setup for the Wailupe Watershed

SWMM's many applications motivated the San Francisco Estuary Institute to build a green infrastructure software toolkit that interacts with the model, called the GreenPlan-IT. The software consists of multiple tools to aid municipal managers in green infrastructure placement (San Francisco Estuary Institute [GreenPlan-IT Tool Kit v2.2]). We have explored using the toolkit, which requires runoff values from business as usual and green infrastructure implementation scenarios from SWMM. The toolkit employs ArcMap for a spatial analysis on green infrastructure placement based on soil and landscape conditions, as well as the built environment. The toolkit also provides a cost effectiveness analysis by using the Non-dominated Genetic Sorting Algorithm II, which uses mathematical equations to optimize two or more competing objectives that are of equal value, in this case runoff mitigation and dollars spent. Managers will have the flexibility of providing regional data sets, placement criteria, and cost for the tool, which makes the toolkit region specific. The combination of the model and toolkit has the potential to provide our client and/or stakeholders with cost effective options for green infrastructure placement, as well as runoff value for business as usual and green infrastructure placement scenarios. Figure 6 displays the approach of the project in a visual format.

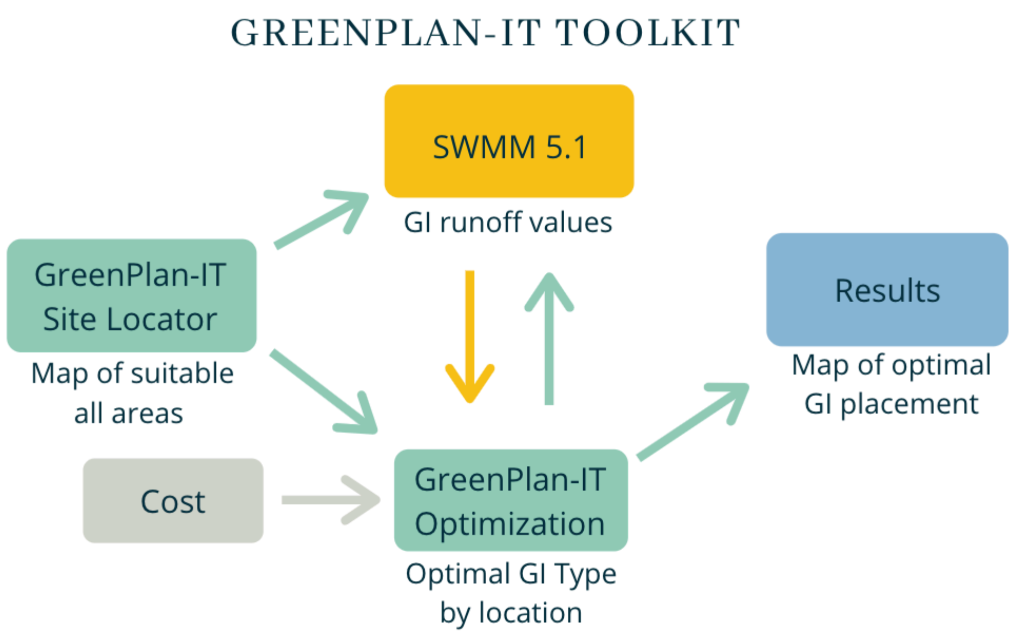


Figure 6. Conceptual Overview of GreenPlan-IT Toolkit Interaction with the EPA Storm Water Management Model 5.1

Priority Watersheds

In the most recent State of Hawai'i Water Assessment Report, Kuli'ou'ou was in non-attainment for enterococcus levels, while all other watersheds were in attainment for water quality parameters or no data was available for the parameters (State of Hawaii DOH CWB, 2018). According to a community water quality monitoring report from 2011, Wailupe and Kuli'ou'ou share the lowest pH readings as well as the highest nitrate and turbidity reading for the watersheds in the region (Watershed/Mauka Watch, 2011). From the same report, Kuli’ou’ou had the highest phosphate readings (Watershed/Mauka Watch, 2011).

Of the two watersheds identified as priority watersheds, we have selected Wailupe watershed as the representative watershed to build in SWMM (Figures 5 and 7). Wailupe has high turbidity levels, indicating sediment transport which is one of the pollutants we would like to address in the study. Wailupe also has the most ideal precipitation data (15-minute intervals) to run the model with and associated stream discharge data to calibrate with. Lastly, multiple assessments have been conducted in years past in the watershed (Sustainable Resources Group Intn’l, Inc., 2010; USACE, 1974) that allow for reference to ensure that we have a more complete understanding of watershed dynamics, and supplementation of missing data parameters with literature.

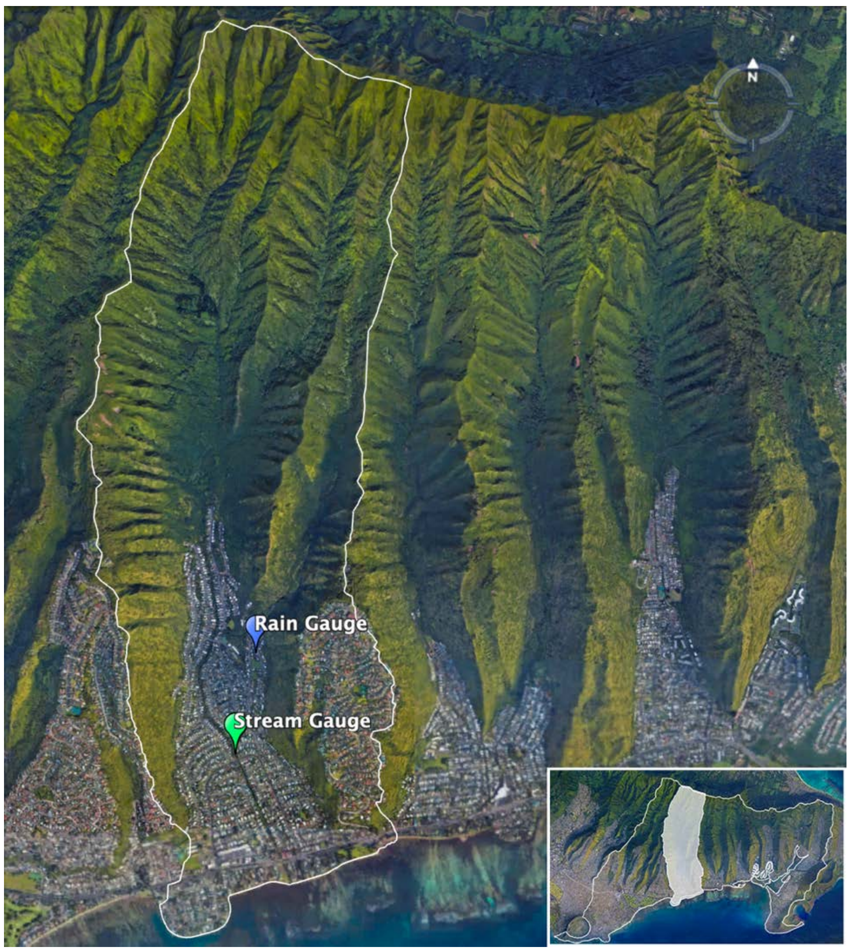


Figure 7. Wailupe Watershed in the Maunalua Bay Region. Blue icon indicates location of NOAA precipitation gauge COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US). Green icon indicates location of USGS stream gauge 16247550 (Wailupe Gulch at E. Hind Dr. Bridge).

Hotspot Definition

A stormwater hotspot is defined as a subcatchment within a watershed which has higher stormwater volume and runoff relative to the surrounding areas. We have chosen stormwater flow volume as the variable of comparison because mountain and urban sediment is flushed into the Bay primarily during rain events, leading to high loading of harmful pollutants. During these events, suspended sediment is transported with stormwater, thus the higher flow of stormwater, the greater the amount of sediment that is suspended (USGS, *Sediment and Suspended Sediment*). Other studies have researched the relationship between sediment transport and flow, finding that higher flow is linked to higher rates of transport (Waters and Crowe Curran, 2015). An example of this is shown in Figures 8 and 9, that show the increase in suspended sediment concentrations with increases in discharge during a 2.8 inch rain event in the Wailupe watershed on March 14, 2009. It is likely that these flows and sediments will pick up other pollutant that area characteristic with the surrounding land use.

It is difficult to accurately model sediment loading and transport due to the number of variables involved in sediment routing, including Manning's N, initial sediment concentration, morphology of channel, intensity and velocity of flow, and slope among others (US EPA, 2019 [SWMM 5.1.013]). Given the time frame of the project, we have decided not to attempt sediment modeling, and instead focus on stormwater flow as a proxy for sediment transport. The concurrent peaks in suspended sediment concentration and peak flow of the 2.8 inch storm in March 2009 shows this relationship (Figures 8 and 9). Given the relationship between flow and sediment described previously, we can safely assume that modeling stormwater volume will also have implications for sediment.

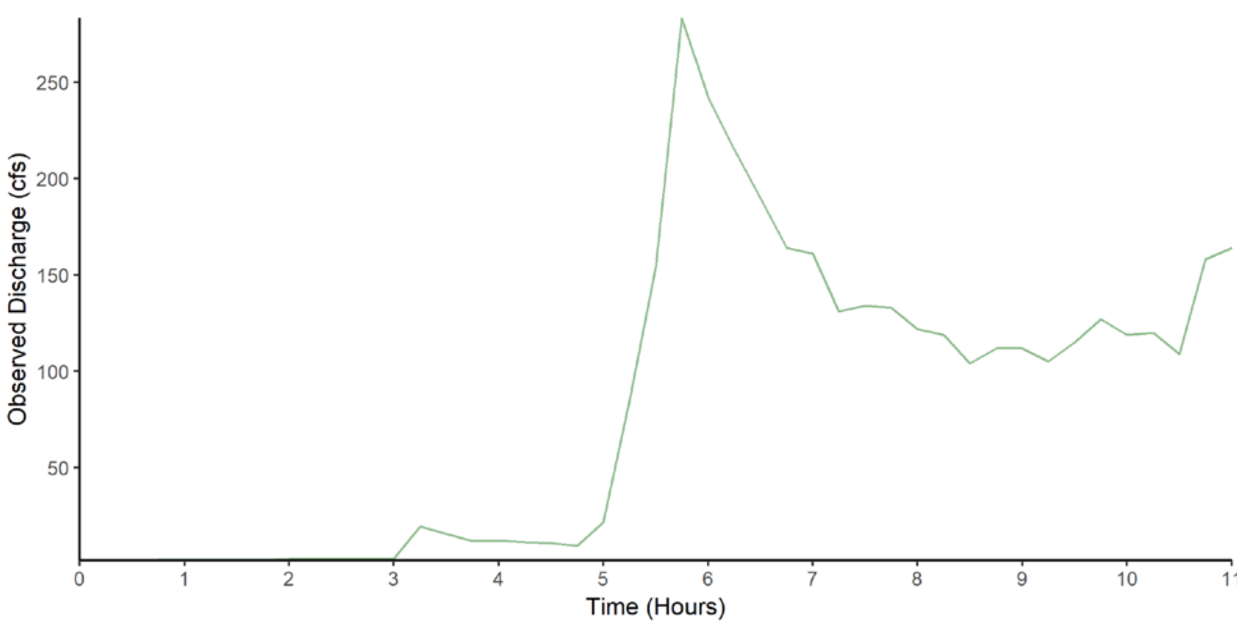


Figure 8. Timeseries of Observed Discharge (cfs) During a 2.8 inch Storm on March 14, 2009, 12:00am to 11am. Data from USGS stream gauge 16247550 (Wailupe Gulch at E. Hind Dr. Bridge).

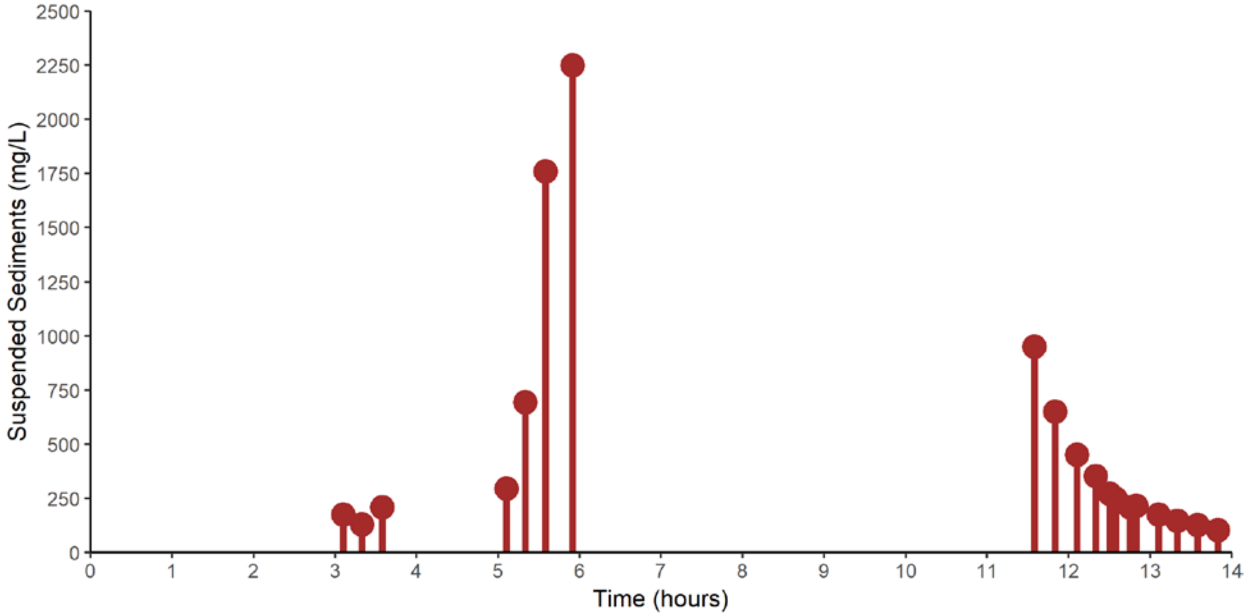


Figure 9. Timeseries of Suspended Sediment Concentrations (mg/L) During a 2.8 inch Storm on March 14, 2009, 3:00am to 2:00pm. Data from USGS stream gauge 16247550 (Wailupe Gulch at E. Hind Dr. Bridge).

United States Environmental Protection Agency Stormwater Management Model 5.1 (SWMM)

To analyze the hydrology of the Maunalua Bay Region, we used the U.S. Environmental Protection Agency (EPA) Storm Water Management Model 5.1 (US EPA, 2019 [SWMM 5.1.013]). SWMM is an open source tool that is available for download with associated manuals from the EPA's online platform. SWMM is a dynamic model that simulates both hydraulic flows and hydrologic processes to predict stormwater runoff and pollutant loading. It can also be used to predict the reduction in runoff from the implementation of specific green infrastructure designs. We chose this model for its ability to represent both natural and urbanized watersheds, a key characteristic of the Maunalua Bay region. The model can also be paired with the San Francisco Estuary Institute's GreenPlan-IT toolkit which can aid us in green infrastructure placement and evaluate green infrastructure performance (San Francisco Estuary Institute [GreenPlan-IT Tool Kit v2.2]).

SWMM requires several key inputs, for which we have gathered and prepared data into the appropriate format with intermediate tools. Primarily, precipitation data is required to generate the stormwater flow. We found a 2-year 24-hour storm typical for the region for our model simulation and initial calibration. In SWMM, watersheds are delineated into subcatchments such that there is one way in and one way out for discharge accumulated on the subcatchment. This could be one input node and one output node for a conduit or stream. Each subcatchment must have information that characterizes it, such as infiltration (soil curve numbers), percent imperviousness, roughness, slope, and size. These allow the model to calculate volume of stormwater, volume infiltrated, volume runoff, and generate a hydrograph. Then the model requires the stormwater network and direction of flow. For our region, stormwater conduits start in the upper watershed as natural streams that are then channelized in the urban area. Stormwater pipes, ditches, and culverts generally transport water toward the channelized stream or directly toward the ocean for flood control.

See the preceding sections for details on data, data preparation and tools, and then the model simulation and calibration. SWMM can be downloaded for free at the EPA Storm Water Management Model website. For information on how to set up the model, see the SWMM manuals which can be downloaded from the same source. For specific steps we took to set up SWMM, see Appendix B.

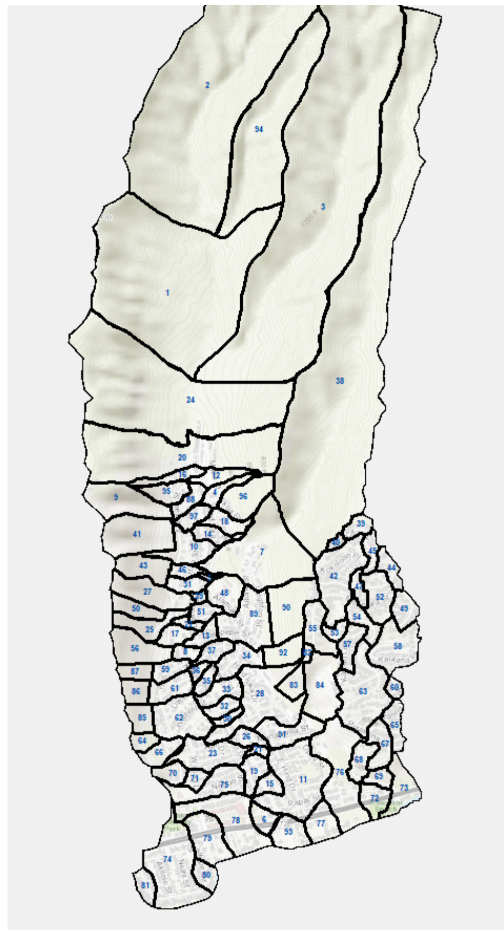
Data Processing Methods (Wailupe Watershed)

All data used in this project are publicly available from various sources (Appendix A). Metadata was created during the data cleaning and analysis phases of the project. Metadata includes data sources, documentation of data analysis process and steps, as well as any other information needed to properly interpret the data. A table with links and description of these data can be found in Appendix A.

Subcatchment Delineation

SWMM requires that the watershed of interest be divided into smaller "subcatchments" between which water and pollutants flow. Subcatchment delineation traditionally involves separating watersheds based on the direction that water flows and accumulates using Digital Elevation Models (DEM) (Jenson, 1991). These methods commonly use algorithms such as the D8 Flow Direction which models flow as a vector following topographic gradients (O'Callaghan and Mark, 1984). Although these methods are widely used across natural watersheds, delineating urban catchments is challenging (Kayembe and Mitchell, 2018). In urbanized watersheds, the natural topography is altered such that water no longer simply flows according to topography but is also directed by infrastructure such as roads and pipes. The watersheds of Maunalua Bay are distinctly divided between these two characteristics, with vegetated land in the upper regions and urban land in the lower regions. As our goal is to determine where in the built landscape green infrastructure should be placed to return the greatest reduction in stormwater, we determined that a higher resolution of subcatchments was required to better understand flow in urban areas. As such, several different methods were combined to achieve subcatchment delineation.

Figure 10. Wailupe Subcatchments



Upper Watershed

The upper region of the watershed has a very steep topographic gradient with well-defined peaks and valleys. There is no urban development here, so water flows entirely based on topography and vegetation. For these areas, we used subcatchments that had been previously delineated by the USGS National Hydrology Dataset using standard flow direction methods.

Lower Watershed

The lower region of the watershed is completely opposite to the upper region. With the exception of a steady downward slope, the region is almost entirely flat. Water is instead directed by roofs, driveways, roads, and underground pipes. Traditional methods of delineation are therefore unsuitable. To address this problem, we looked to other urban watersheds and combined two different methods.

The first method we used involved reconditioning the Digital Elevation Model (DEM) to consider the built environment. The stormwater network – consisting of pipes, outfalls, and streams – were "burned" into the DEM. Some manual editing of pipes was done prior to this, as the pipe data does not perfectly align with the stream data and some outfalls were missing. All manual editing was verified with Google Earth or prior in-person site visits. Once the DEM was reconditioned, standard flow direction methods were then applied. This process was built into a single ArcGIS model (Appendix C). This method was enough to delineate the majority of the urban regions of the watershed. However, in some areas these tools were unable to delineate subcatchments into the small size that our analysis in SWMM requires. For these regions, we decided to use a different method to delineate further.

The second method was modeled after the approach of the Pennsylvania Department of Environmental Protection ("Consideration in Using GIS"). In this approach, inlets for water into the sewer system are treated as separate polygons which water can flow into. Subcatchments are then defined as the area that drains into a particular polygon. We used this approach to increase the resolution of subcatchments in specific areas of the watershed for which the previous method was insufficient. A second ArcGIS model was built to automate this process (Appendix D). We performed this analysis on the entire watershed to verify its consistency with the first method, finding that watersheds were delineated within similar boundaries for each method, albeit at a higher resolution for this second method.

Final Subcatchment Processing

Once all three methods for delineation were complete, the subcatchments were combined into a single layer (Figure 10). This entire analysis was performed for the Wailupe watershed. Although the original Wailupe watershed boundary extended further West, the final Wailupe outline was altered to better account for the built stormwater network. The new outline included only those subcatchments which were not cut off by the original boundary and that drained specifically into Wailupe outfalls. Finally, the subcatchment boundaries were converted to points with XY coordinates and exported as a .csv suitable for the SWMM input file.

Impervious Surface Cover (Land Use)

SWMM requires a percent imperviousness value for each delineated subcatchment. To obtain this information, the spatial layer for roads and bike paths were clipped to the Maunalua Bay region and buffered to account for sidewalks. All bike paths were assumed to be paved, and all streets were assumed to have sidewalks. This layer was then overlaid on top of the building footprints layer using ArcGIS' intersection tool, accounting for impervious buildings.

The resulting layer was compared to high definition google earth images of Maunalua Bay to verify if any major impervious surfaces were missing, such as large parking lots or driveways. The few occurrences of these areas were then manually drawn into the layer.

The percent of imperviousness cover in each subcatchment was then calculated using the "Tabulate Area Intersection" tool* in ArcGIS. The results can be found in Appendix E.

Curve Numbers (Soils)

SWMM can account for infiltration of stormwater into soils using soil curve numbers. A soil curve number is a metric that represents the amount of runoff that infiltrates the soil. Curve numbers range from 0 to 100, with 0 representing completely saturated wet surfaces (such as lakes or oceans) and 100 representing completely impervious surfaces (USDA, Soil Conservation Service). The Natural Resources Conservation Service's (NRCS) National Water and Climate Center provides a list of soil curve numbers based on land cover and hydrologic soil group and condition. Hydrologic conditions are classified as "poor", "fair" or "good" and are determined using visual descriptions in the NRCS' tables. The numbers are calculated for average antecedent moisture conditions.

Figure 11. Wailupe Impervious Cover

Hydrologic soil groups are soil classifications determined by the NRCS based on a soil's infiltration and runoff potential as well as measured rainfall. There are four classes of soil. Group A soils have the highest infiltration and lowest runoff potential when "thoroughly wet" (NRCS's Hydrology National Engineering Handbook, 7-2). These soils have little clay -less than 10 percent- and a saturated hydraulic conductivity of more than 40.0 micrometers per second. Group B soils have more runoff potential than group A soils, but water transmission through the soil layers is unrestricted. Group C soils have lower infiltration and higher runoff potential than the two previously mentioned groups. The soil material is permeable, but water transmission through the soil is impeded. Group D soils have the highest runoff and lowest infiltration potential when thoroughly wet. Water transmission is very restricted. Group D soils generally have a high clay component -over 40 percent clay. Group D also encompasses all soils with a water table within 60 cm. Some of these soils can still be adequately drained however, leading to a dual group - A/D, B/D or C/D- if the saturated hydraulic conductivity would place the soil in one of the previous groups.

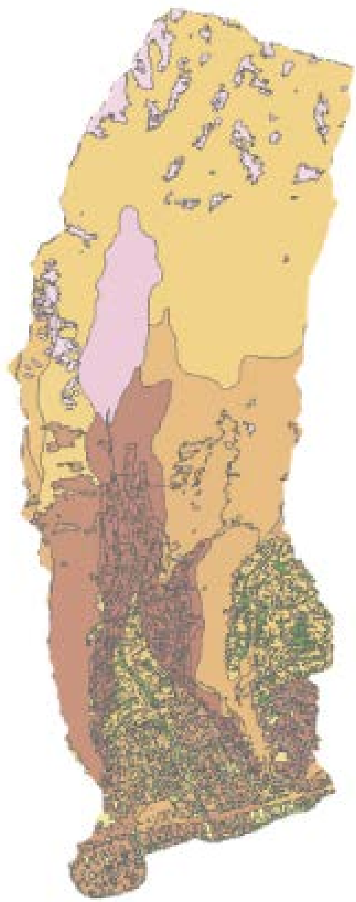


Figure 12. Wailupe Soil Curve Numbers

Curve numbers for residential and commercial areas include a consideration of the percentage of impervious land cover. As SWMM applies soil curve numbers only to the pervious area of subcatchments, we made the decision to list the land cover of residential and commercial areas as "Scrub Shrub" -the closest natural land cover- to avoid double counting the effect of impervious land cover in a subcatchment. Dual soil groups were all considered group D because they were all classified as "poor drainage" in the Soil Survey Geographic Database (SSURGO).

To obtain curve numbers, the soil hydrologic group layer was merged with the land cover layer using ArcGIS' intersection tool. The resulting combinations of land cover type and hydrologic group were each paired with a curve number (Table 1).

One consideration was that the curve numbers taken from the NRCS' National Water and Climate Center do not assign a curve number for scrub shrub cover in areas with hydrologic group A. Water however still permeates the soil in these areas, so to account for this, the number 36 was applied to scrub shrub land cover in areas with hydrologic group A. This number was chosen by looking at the decreases in the curve number among each group and also taking into account that 36 is the lowest curve number in the data. Hydrologic condition was estimated using Google Earth imagery.

The percent area of each curve number within each subcatchment was then calculated using the "Tabulate Area Intersection" tool in ArcGIS. The resulting attribute table was exported to R to create a new column with an average curve number per subcatchment using a weighted average method. A final shapefile with the curve numbers for the Maunalua Bay Region was assembled during this project and will be made available to the client for future use.

The model also required % slope for each subcatchment. For this attribute, the 10 meter DEM layer used in the Subcatchments method was used. A weighted mean slope was calculated for each subcatchment. The results for this can be found in Appendix E. Processing for imperviousness, Curve Number, and slope were completed using Arc GIS and calculations completed in R (Appendix H).

Table 1. Soil Curve Numbers by Land Cover and Hydrologic Groups found in the Maunalua Bay Region, O'ahu.

Land Cover	Hydrologic Group A	Hydrologic Group B	Hydrologic Group C	Hydrologic Group D
Grassland: poor condition	68	79	86	89
Unconsolidated shore	0	0	0	0
Bare Land/Bare soil	77	86	91	94
Open Space Developed- good	39	61	74	80
Evergreen forest- fair	36	60	73	79
Scrub Shrub	36	42	55	62
Open Water	0	0	0	0
Impervious surface- like shrubland	36	42	55	62
Palustrine Scrub Shrub wetland (woody wetland)	86	86	86	86
Palustrine Forested wetland (woody wetland)	86	86	86	86
Palustrine Aquatic Bed	NA	NA	NA	NA
Estuarine Emergent wetland	80	80	80	80
Palustrine emergent wetland	80	80	80	80
Pasture/Hay	40	61	73	79
Unclassified - here: open water	0	0	0	0
Cultivated Land	62	74	82	86

Precipitation Events

The production of runoff in SWMM requires precipitation data for simulation of storm events. 15-minute interval precipitation data was provided by the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) for stations COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US) and COOP:511308 (HAWAII KAI G.C.724.19 HI US) between the years of 1977 and 2014 (NOAA NCEI, 2020). Data was downloaded and processed in R Studio using the tidyverse, lubridate, and tseries packages. The annotated R code can be found in the Kahuwai GitHub project repository in the file NOAA_Precipitation_Data.RMD (Dornan *et al.*, 2019).

Although precipitation data at the Wailupe Valley School gauge was collected over a long time period (1977-2014), many gaps exist within the dataset. The dataset was filtered to select the highest-frequency data for model simulations by investigating years which had the greatest number of days with the most data points. Once the year with the most data had been determined, the data were replotted for that year to observe patterns and locate storms to use for model simulations. The storm selected for calibration in SWMM was from December 19, 2010 and totaled 5.3 inches that lasted 21.5 hours (Figure 10). This storm event falls within the 2-year 24-hour return interval for the Wailupe watershed (NOAA NWS, 2020). This return interval was selected due to it being the EPA's bank full discharge volume criteria for new sediment basin construction requirements (EPA, 2017). The NOAA Atlas 14 Point Precipitation Frequency Estimates for the Wailupe watershed, Oʻahu, Hawaiian Islands, U.S.A. for a 2-year, 24-hour storm is 4.58 inches with a 90% confidence interval of 3.95-5.33 inches (NOAA NWS, 2020). The storm used to validate the model was a 2.8 inch storm from March 14, 2009 with a duration of 11 hours (Figure 11). Once storms were identified and selected, the data frame was exported as a .csv file and input into SWMM.

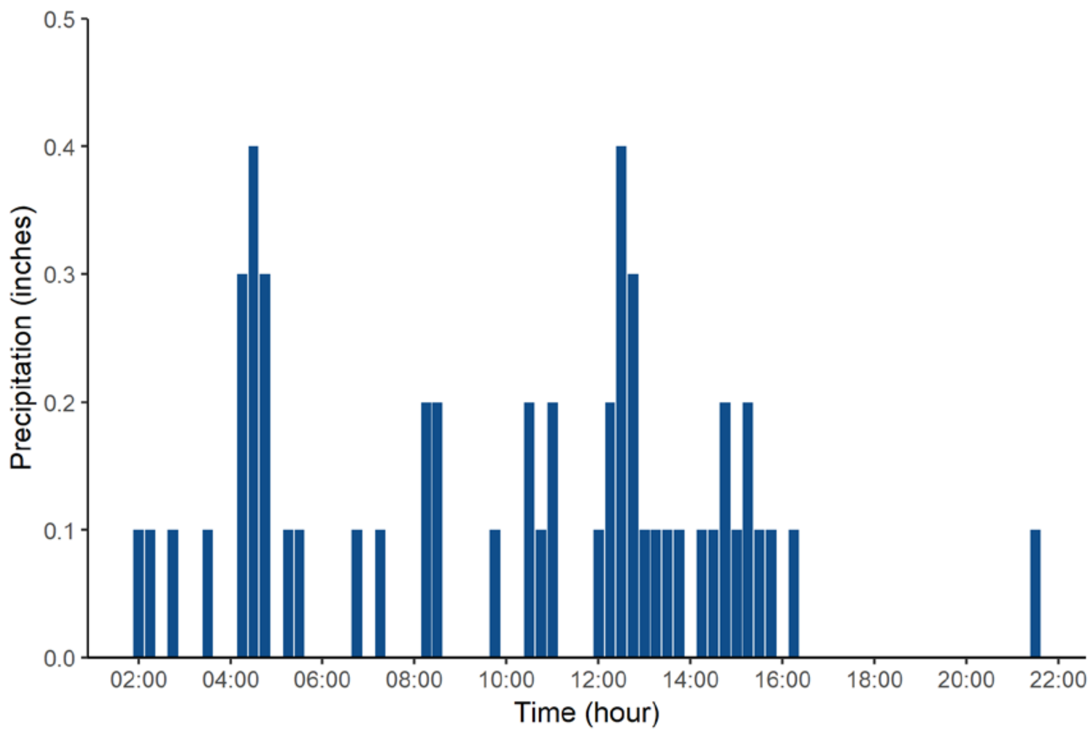


Figure 13. Precipitation Timeseries for the Storm Event Used for SWMM Calibration. Storm occurred on December 19, 2010 and totaled 5.3 inches over a 21.5-hour period. Data provided by NOAA precipitation gauge COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US).

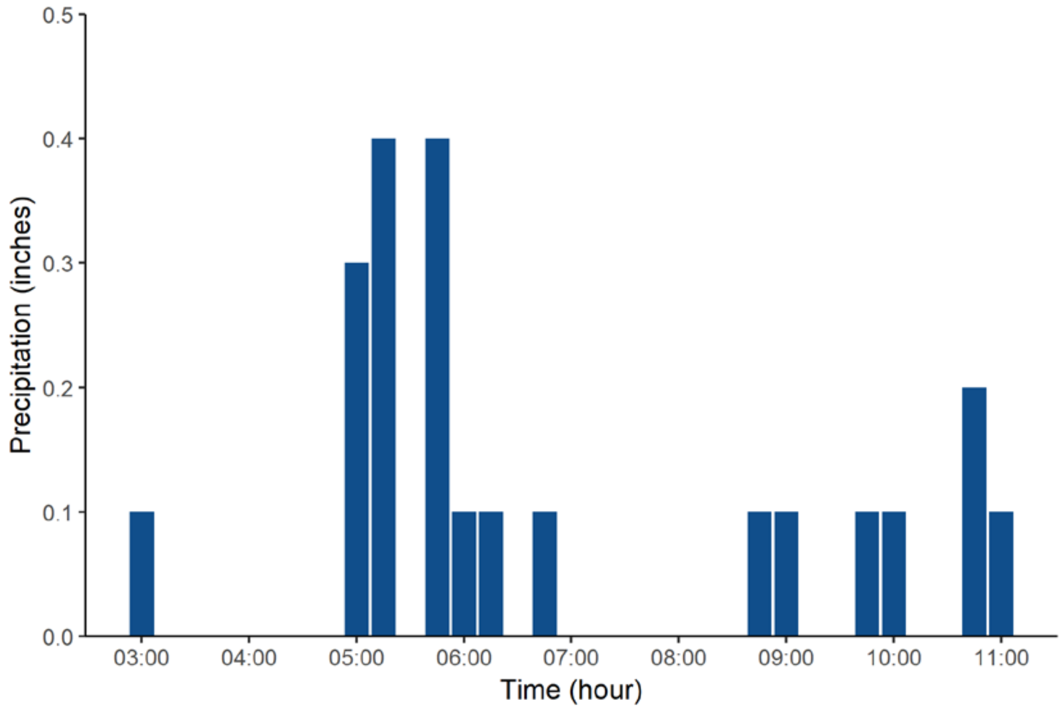


Figure 14. Precipitation Timeseries for the Storm Event Used for SWMM Validation. Storm occurred on March 14, 2009 and totaled 2.8 inches over a 11-hour time period. Data provided by NOAA precipitation gauge COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US).

Stream and Stormwater Network

SWMM requires stormwater network data to properly simulate and route runoff. The three elements of the stormwater network (conduits, structures, and streams) exist as separate data files and are obtained from the City and County of Honolulu public data. For the model to run, these elements must be connected to each other as they are in reality. Although the stormwater network was established in subcatchment methods, additional processing was necessary for SWMM-specific inputs.

Coordinates

To relate spatial model parameters, SWMM requires an input of decimal degrees for latitude and longitude as XY coordinates for each parameter. These were explicitly assigned to conduits, streams, and subcatchments in ArcGIS by first using the “Feature Vertices to Points” tool, which creates a new map layer of points that represent the original map layer. Then we use the “Add XY Coordinates Project Management" tool to include decimal degrees to each point in the attribute table of these layers.

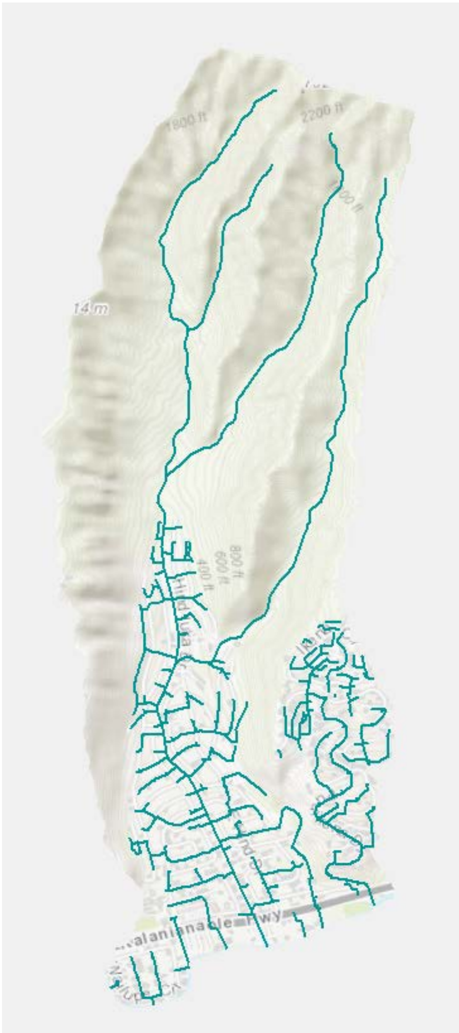


Figure 15. Wailupe Streams and Stormwater Network

Invert Elevations

The stormwater system of Wailupe is entirely gravity fed, indicated by the lack of pumps in the stormwater structure data. SWMM can easily represent these systems using invert elevations assigned to the end nodes of each conduit. Unfortunately, invert elevations are missing from the publicly available stormwater structure data from the City and County of Honolulu. We therefore relied on the surface elevations from the topographic data to represent invert elevations in the model. In the absence of actual invert elevations, we had to make some manual adjustments to the stormwater network. Any conduits that directed flow against the surface elevation gradient were removed from the network. We identified problematic conduits after getting the network into SWMM and adding directional flow arrows to the conduits. Any conduit arrow pointing in the opposite direction of flow (toward the ridges or opposite of the majority) should be reconnected to the next junction up/down stream or completely removed along with the segments upstream if it is on the fringes of the network. Removing a small number of conduits is not problematic for our purposes as SWMM can only route flow through one connected conduit segment, but not all of the branches. Smaller subcatchments are needed for that, however very small subcatchments around each branch may cease to be informative for large scale management.

We assigned surface elevations and subcatchment number to conduit and stream endpoints in the stormwater network, specifically the layer we converted to points. First, we converted 5ft contours topography map layer to a raster using the "Topo to Raster" tool, then converted the subcatchments map layer to a raster using the "Polygon to Raster" tool. Then we used the "Extract Multi Value to Points" via interpolation tool to assign elevation and subcatchment values to each element of the stormwater network which had previously been converted to points.

Exporting Data Tables

We then exported each elements' attribute table to a comma separated value (csv) file to be processed in R. To do this, we opened the attribute table, clicked the menu tab, and selected "Export data". When prompted to choose a file path and name to save the data table, we added ".csv" to the end to save as a csv file.

Data Processing

All data resulting from the above analyses were exported from ArcGIS Pro as csv files and organized in the tabular form required by SWMM. This included conduits, junctions, streams, and subcatchments as well as their essential attributes and spatial relationships. Data processing was largely done in R, with some manual inputting of values into SWMM. The annotated R code can be found in the Kahuwai github repo (Appendix H). The following methods are key components required by SWMM that needed to be calculated or organized in R.

Conduit Length

Conduit length is used by SWMM to calculate flow and is defined by the difference in elevation (height) and xy coordinate distance (width) between start and end points of the conduit. Although conduit length is provided in the stormwater structure data, we discovered that these lengths only consider the xy distance and do not represent the actual length of the conduit which is impacted by elevation. To better represent the actual system, we calculated the length of each conduit using the Pythagorean theorem. This process was automated using R code.

Conduit Dimensions

Most dimensions such as shape, width and height or diameter are provided, however some are missing. For concrete pipes, empty diameter columns replaced with average diameter of 23.1 ft calculated from conduits in the Wailupe watershed that do have diameters. For ditches with empty width and height columns, we used the measurement tool in google map satellite imagery. We measured the widths along the ditches behind homes in Hahaione and Kamilo iki watersheds. We chose these areas because we are certain that the conduits, we saw there were ditches given our previous visit to those areas. Using the measurement tool, the ditch widths were ~ 5ft in width. In the absence of a height measurement, we used 5 ft as well. This may be an overestimate of how deep most ditches are, so runoff near ditches may be underestimated, however the larger dimensions ensures the movement of flow through conduits without artificial stoppage or back flow.

Conduit Junctions

Every conduit (including streams) in SWMM requires a connecting junction or node. Our analysis uses the endpoints of each conduit to define a junction, the points inbetween as vertices, a stormwater structures, particularly “inlet/outlets” to define some of these junctions a outlets. The direction of flow were determined by extracting elevation to each of the conduit’s XY coordinates. These connections were specified by relating XY coordinates from one element to the other in R code. This system is not perfect, so some manual adjusting of the network conduits is necessary. One instance where you will need to manually adjust was described in the Invert Elevations subsection above. Other instances are in the urban subcatchments, where the stream becomes channelized. Although the junctions are located on or close to the stream path, each junctions must be connected to the stream or the model will not route the water from the stormwater infrastructure segments to the main channel (stream). This can be done in SWMM by using the tool to add a conduit in and drawing in the connection junction to junction. These connections essentially become conduits that make up the stream channel.

Characterizing Streams in SWMM

The spatial data for streams does not contain stream stage or width, and no dimensions are provided for the channelized portions of the stream in the conduit layer. To characterize Wailupe stream we looked to literature. Wailupe stream is unlined with concrete except for the bottom reach between Kalanianaʻole Highway and its mouth, “where both banks are hardened with rock, mortar, and concrete" and is about 60 ft wide with bank slopes varying from 1 vertical on 1 horizontal to 1 vertical on 2 horizontal (USACE, 1974). For this reason, we have made the cross-section of the channelized portion of the stream "trapezoidal". We used the measurement tool in google map satellite imagery to measure stream width in the channelized regions and measured between 20-30 ft wide between houses and 40-50 ft wide in the segment after Kalaniana'ole Highway to the mouth. The literature also estimates the bottom width of the stream to be between 15-20 feet in the upper reaches (USACE, 1974). No height or depth measurements were provided, so we used 10 ft from the land surface based on the general observation that the depth of the channel was at least a few feet "overhead" during a visit to some reaches along the stream. Stream cross-sections were coded to be 20 x 10 ft in the upper reaches, 30 x 10 ft in the urban reaches to account for the narrow sections in between houses for most of the channel in the urban subcatchments.

Characterizing Subcatchments in SWMM

Subcatchments were delineated and characterized in the Subcatchments methods of this document. Final data processing for these were organizing the XY coordinates of the subcatchment polygon vertices and the data that characterizes infiltration and overland flow in the subcatchments in SWMM format. The R code brings together the data from multiple sources including the attribute table exported in these methods.

Model Calibration and Validation

Calibration of SWMM for this project involved coupling observed stream discharge data from USGS station 16247550 (Wailupe Gulch at E. Hind Dr. Bridge) located at 21.2853º N, -157.7542º W in the Wailupe watershed to model simulation results (Figure 12). The observed stream discharge data used for calibration is from a 24-hour storm that occurred on December 19, 2010. Sensitive parameters such as curve numbers, depth of depression storage, and Manning's n were systematically tuned to fit the simulated discharge values to the observed data. To tune total runoff volume and flow peaks, the widths of large subcatchments were capped at 400 feet, soil curve numbers were adjusted to account for antecedent moisture conditions, and Manning's n were adjusted based on imperviousness of the subcatchment. The calculated soil curve numbers for this model assume average antecedent moisture conditions, which is a critical factor in estimating runoff. To account for dry antecedent moisture conditions, we increased all curve numbers by 25 percent directly in the SWMM input file. For wet antecedent moisture conditions, we increased all curve numbers by 25 percent directly in the input file.

The NOAA precipitation gauge for the Wailupe watershed is COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US), located at 21.2918º N, -157.7534º W (NOAA NCEI, 2020). To account for the spatial heterogeneity of rainfall within the watershed, we used estimated mean monthly rainfall information provided by the Rainfall Atlas of Hawai'i for the upper watershed, which does not have an installed rain gauge. These estimates are generated from nearby rain gauges and provide adequate estimates to increase the discharge volume entering lower regions of the watershed from the precipitation at higher elevations. Once the model was calibrated, we used data from the same gauge station from an 11-hour storm that occurred on March 14, 2009 to validate the model (Figure 13).

Results

SWMM Model Calibration Results

The storm chosen for calibration of SWMM lasted 21.5 hours and simulated a total discharge of 4,607.02 cfs, whereas the stream discharge gauge for that time period observed a total of 4,027.87 cfs (Figure 12). These simulated flows are 14.38% higher than observed flows. Over the course of the 11-hour validation storm on March 14, 2009, the model simulated a total discharge of 2,740.93 cfs whereas the stream discharge gauge observed a total of 3,622.74 cfs, a difference of 24% (Figure 13).

The model was assessed using the coefficient of determination (R^2) and the Nash-Sutcliffe model efficiency coefficient (NSE). The Nash-Sutcliffe coefficient is specifically used to assess the validity of hydrologic models and their ability to accurately predict flow (Ritter and Munoz-Carpena, 2013) For the December 19, 2010 calibration storm, the model's R^2 is 0.80 and the NSE coefficient is 0.65 (Figure 16). For the validation storm on March 14, 2009, the calculated R^2 is 0.89, NSE coefficient is 0.80, and overall discharge is lower than the observed by 24% (Figure 17). We hypothesize that the statistical regression metrics are higher for the validation storm because the overall shape of the observed and simulated hydrographs have a more consistent pattern than that for the 2010 storm.

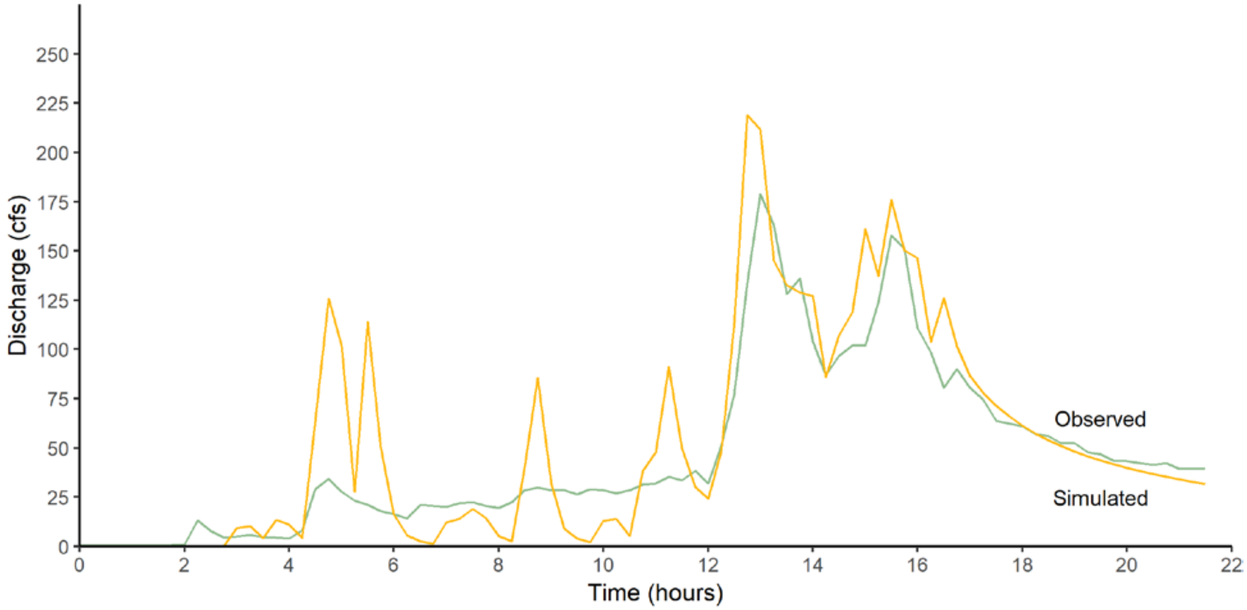


Figure 16. Timeseries of Observed and Simulated Discharge for the December 19, 2010 Precipitation Event. Observed data provided by NOAA NCEI precipitation gauge COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US). Performance: R^2 (0.80); NSE (0.65); Peak simulated discharge (+13%).

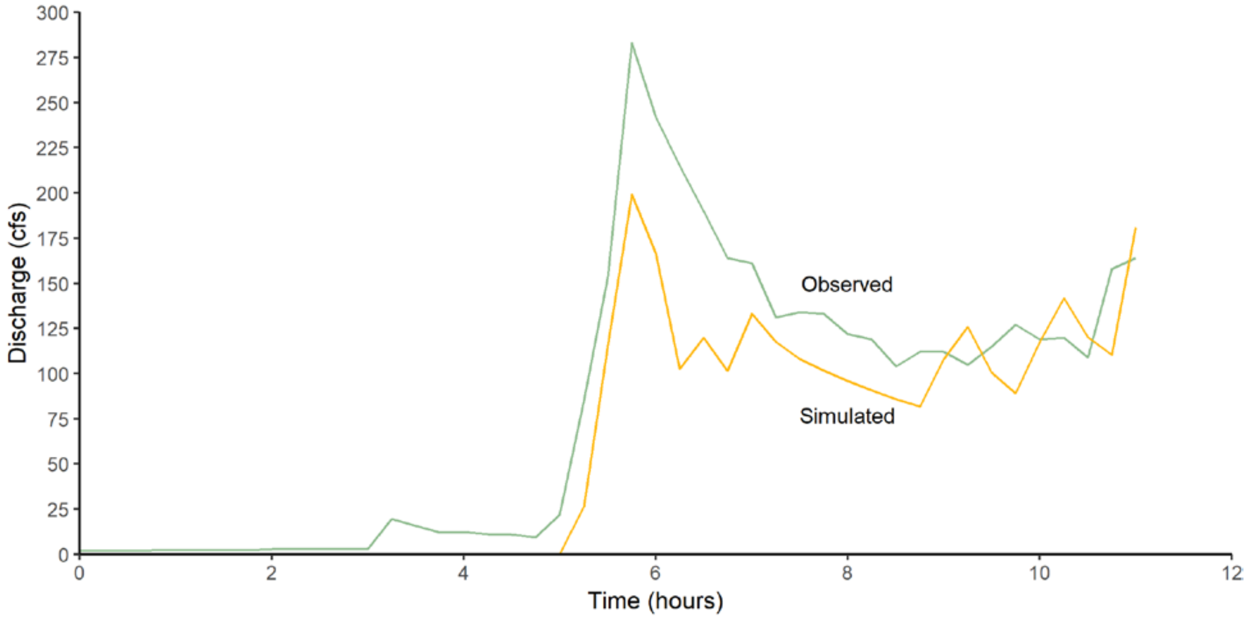


Figure 17. Timeseries of Observed and Simulated Discharge for the March 14, 2009 Precipitation Event. Observed data provided by NOAA NCEI precipitation gauge COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US). Performance: R^2 (0.89); NSE (0.80); Peak simulated discharge (-24%).

Model Results

SWMM output provides total precipitation (inches), total runon (inches), total evaporation (inches), total infiltration (inches), impervious runoff (inches), pervious runoff (inches), total runoff (inches, gallons), peak runoff (cfs), and runoff coefficient by subcatchment (Appendix F).

Runoff Coefficient Hotspots

Hotspots were determined first using the modeled runoff coefficients which represent normalized runoff volumes. The runoff coefficient is a ratio of the total volume of runoff relative to the total volume of rainfall that a subcatchment receives across its area (Ratzlaff, 1994). Runoff coefficients range from 0 to 0.79 for the December 19, 2010 storm and 0 to 0.72 for the March 14, 2009 storm (Appendix G). The spatial distribution of runoff coefficients for both can be observed in Figure 18. Hotspots were then compared across storm events, and the top 20 overlapping runoff coefficient hotspots were determined (Figure 19, Table 2). All 20 of these common hotspots occur in the urbanized areas of the watershed. Only one is associated with a notable landmark feature.

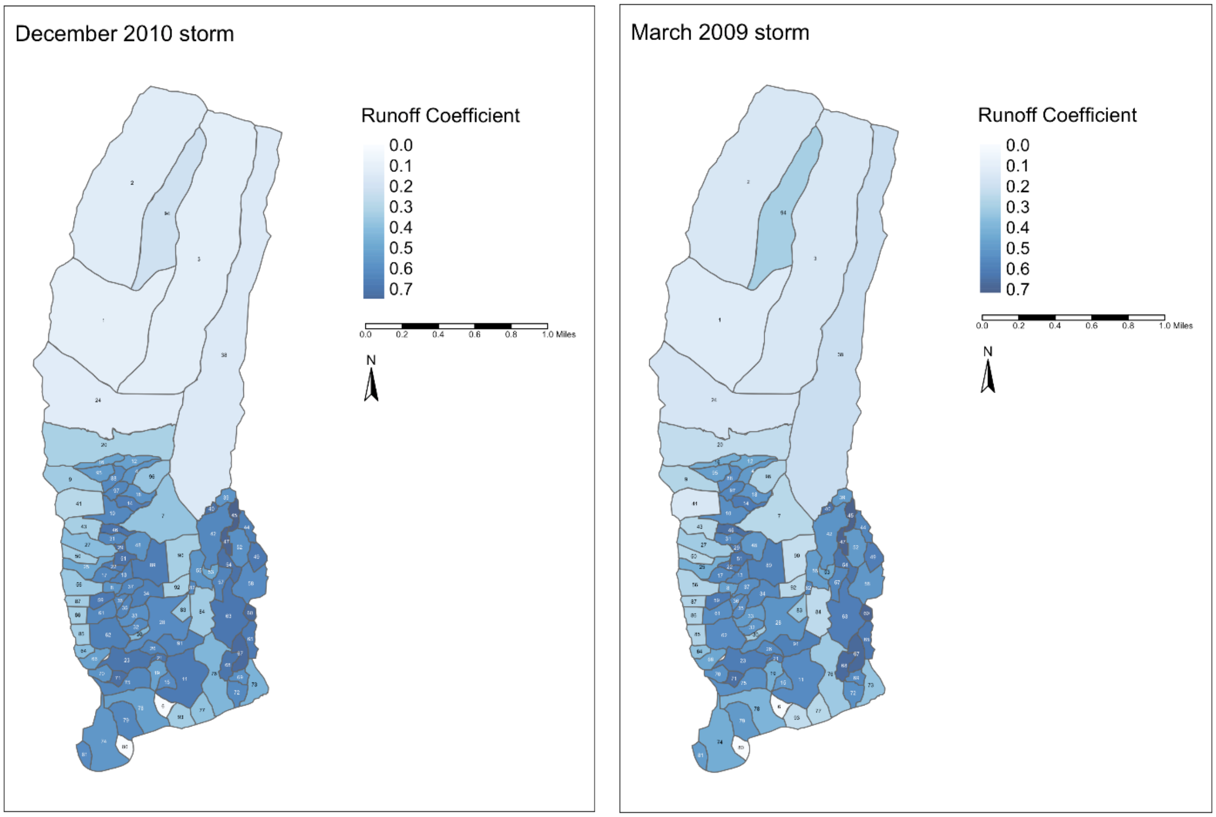


Figure 18. Modeled Runoff Coefficient Results for Wailupe Watershed. Left: December 19, 2010 storm used for model calibration. Right: March 14, 2009 storm used for model validation. Higher runoff coefficients indicate areas where more precipitation became stormwater runoff.

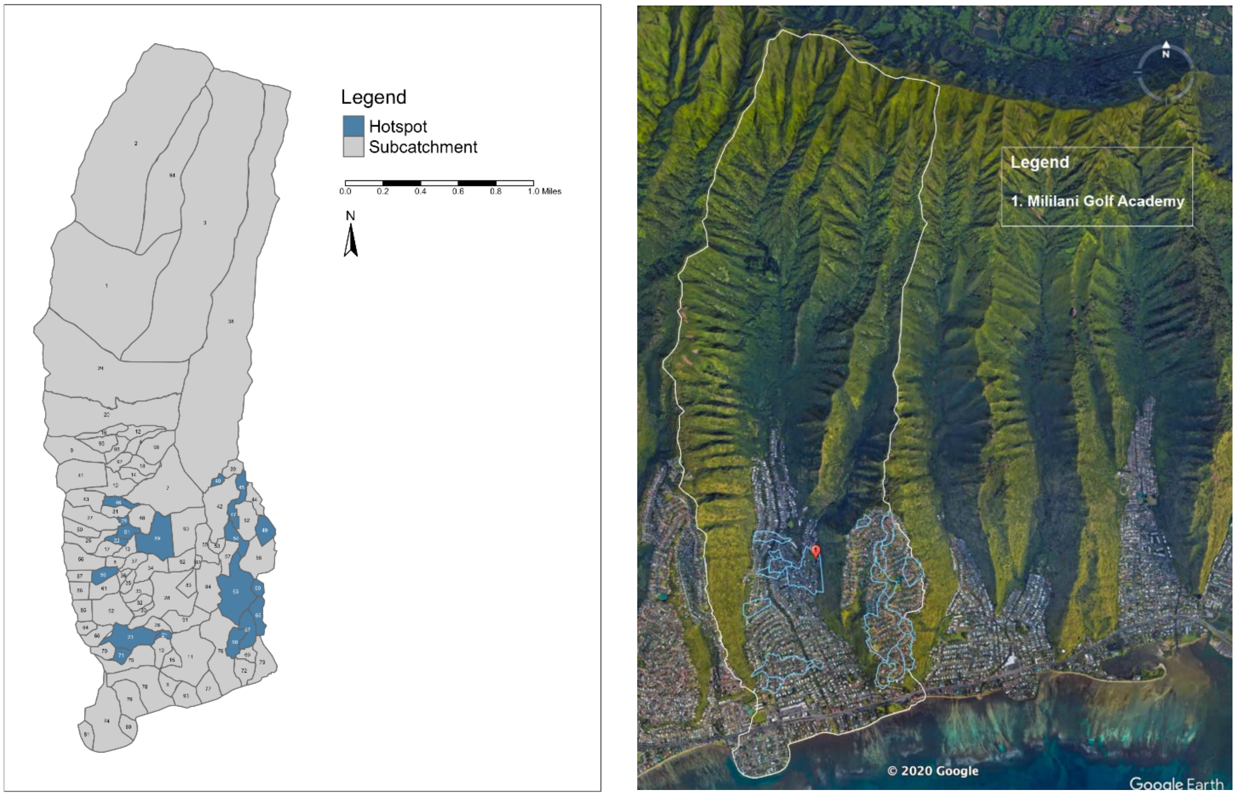


Figure 19. Potential Stormwater Runoff Hotspots Within the Wailupe Watershed. Left: Blue polygons indicate top 20 hotspot areas between both storm simulations. Right: Hotspot areas within Wailupe watershed overlaid onto current Google satellite image. One subcatchment contains a non-residential areas of interest and is marked with a location pin and are listed in the legend.

Table 2. Summary Output Table of Runoff Coefficient Results and Significant Parameters

Subcatchment	Runoff Coefficient December 2010 Storm	Runoff Coefficient March 2009 Storm	Curve Number December 2010 Storm (Dry Conditions)	Curve Number March 2009 Storm (Wet Conditions)	Slope	Percent Impervious	Area (Sqft)
45	0.793	0.719	43	58	10.84	75.81	205273.48
47	0.775	0.705	41	55	9.02	73.68	163180.85
60	0.751	0.702	51	73	10.20	66.28	130703.86
67	0.743	0.680	52	74	13.09	65.32	376961.02
71	0.728	0.660	51	73	1.23	63.34	161251.17
40	0.720	0.654	43	59	7.77	65.26	78272.63
54	0.718	0.634	42	58	11.99	65.91	301206.44
51	0.716	0.633	42	57	3.21	65.71	194382.01
5	0.710	0.682	52	75	4.97	59.23	42008.07
46	0.708	0.657	51	72	9.18	59.98	209977.29
29	0.706	0.634	42	58	4.30	63.75	62214.52
68	0.703	0.670	56	80	16.78	56.40	306366.86
23	0.702	0.611	52	73	2.09	60.16	712111.05
21	0.699	0.618	39	52	2.13	64.39	78832.74
63	0.692	0.602	49	69	11.35	59.60	1260905.98
59	0.686	0.617	48	67	9.36	58.62	241399.55
49	0.682	0.599	41	56	11.63	61.33	317060.05
65	0.679	0.622	52	75	12.29	54.99	309782.87
22	0.676	0.614	47	66	5.22	57.36	106889.43
89	0.669	0.595	52	74	12.27	54.38	929708.78

Peak Flow Hotspots

Hotspots were also determined for peak flow values. Peak flow is a measure of the maximum discharge value measured during the storm event and has implications for sediment transport. Peak flow ranges from 0 to 32.54 cfs for the December 19, 2010 storm and 0 to 91.58 cfs for the March 14, 2009 storm. Figure 20 shows the spatial distribution of peak flows for both storm events. The top 20 overlapping peak flow hotspots were once again determined (Figure 21, Table 3). Many of these common hotspots occur in the upper watershed but several do occur in the urban areas. For these urban hotspots, there are more associations with notable landmarks, including most of the large parks in the Wailupe watershed.

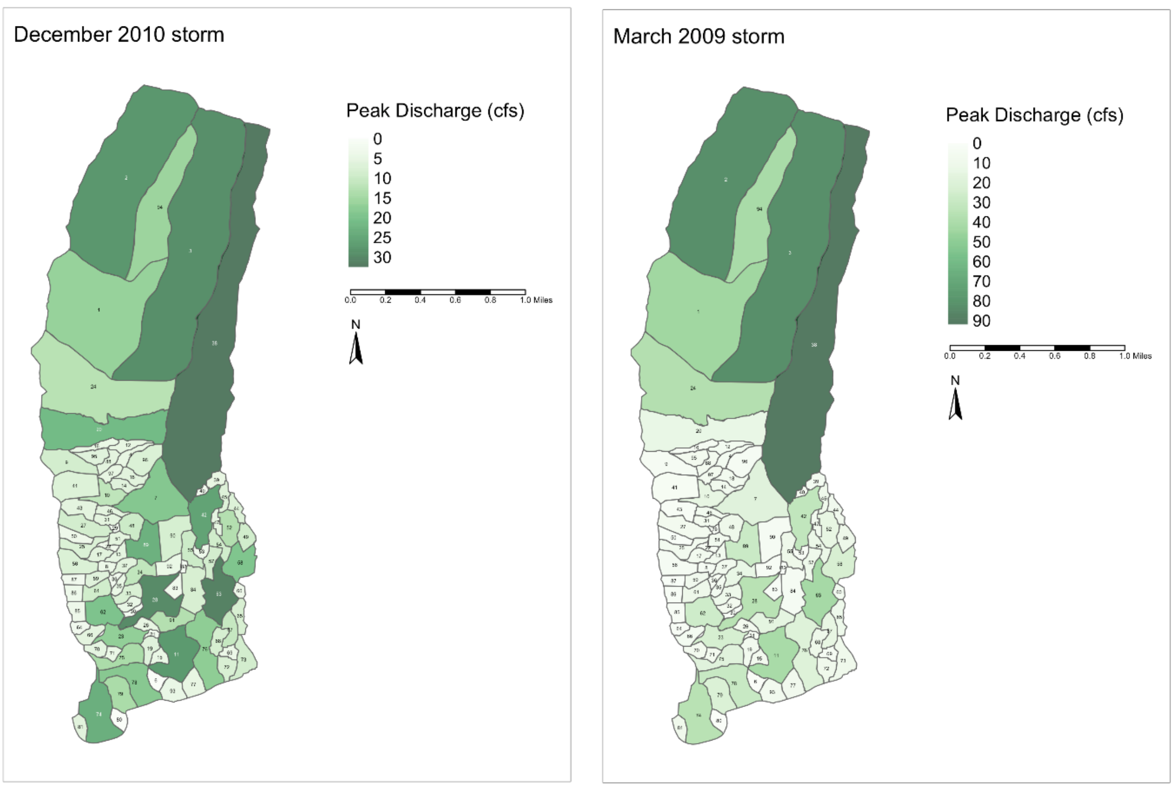


Figure 20. Modeled Peak Flow Results for Wailupe Watershed. Left: December 19, 2010 storm used for model calibration. Right: March 14, 2009 storm used for model validation.

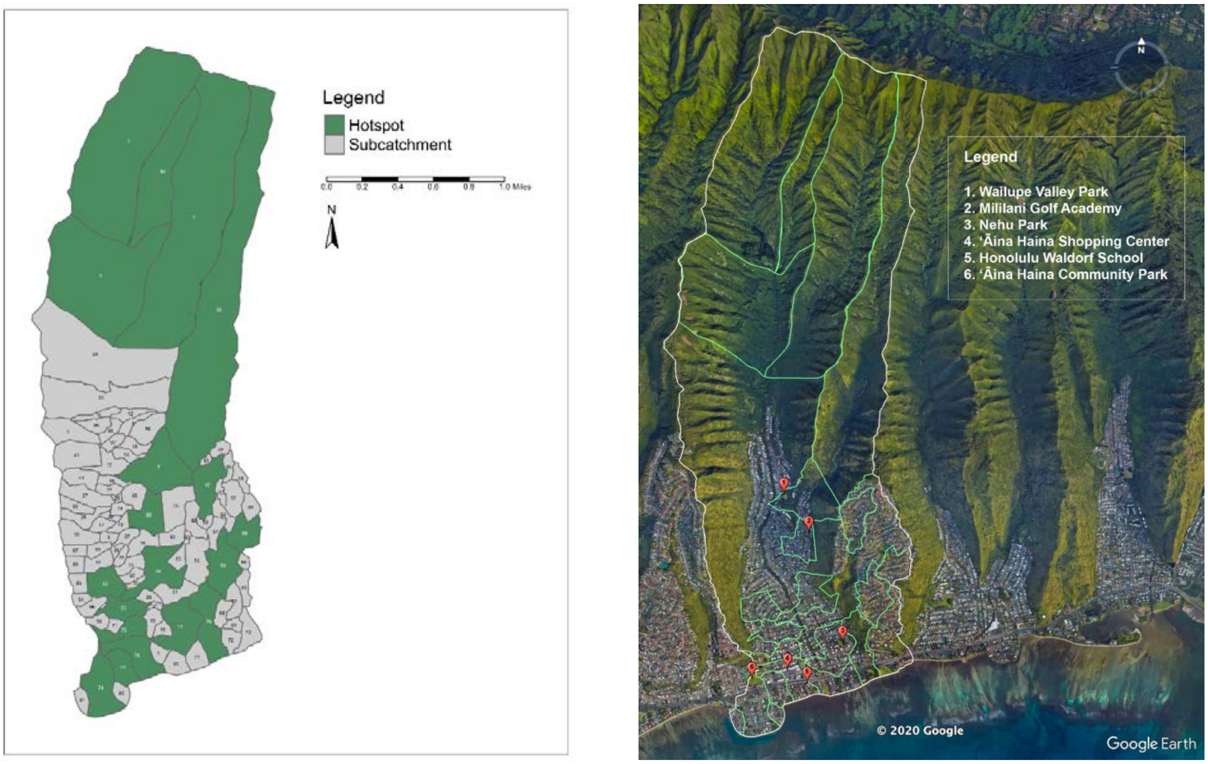


Figure 21. Potential Peak Flow Hotspots Within the Wailupe Watershed. Left: Green polygons indicate top 20 hotspot areas between both storm simulations. Right: Hotspot areas within Wailupe watershed overlaid onto current Google satellite image. Subcatchments containing non-residential areas of interests have a location pin and are listed in the legend.

Table 3. Summary Output Table of Peak Flow Results and Significant Parameters

Subcatchment	Peak Runoff (cfs) December 2010 Storm	Peak Runoff (cfs) March 2009 Storm	Curve Number December 2010 Storm (Dry Conditions)	Curve Number March 2009 Storm (Wet Conditions)	Slope	Percent Impervious	Area (Sqft)
38	32.54	91.58	58	84	29.49	0.09	12415473.2
63	31.09	41.25	49	69	11.35	59.60	1260906.0
28	29.91	35.64	51	73	9.70	45.65	1400355.0
3	28.98	81.97	53	76	33.95	0.00	13733857.7
2	27.80	82.39	49	69	36.41	0.00	11211635.2
11	27.47	40.87	49	69	0.95	60.18	1461121.3
42	25.49	31.54	45	62	12.77	52.08	1097149.0
74	23.39	34.84	42	57	0.51	49.95	1593473.1
89	23.00	28.35	52	74	12.27	54.38	929708.8
62	19.63	25.82	43	59	4.97	57.62	816823.7
58	19.26	22.24	43	59	13.47	50.49	794612.3
7	18.64	17.61	54	78	24.37	14.10	2174275.2
78	18.40	28.56	39	53	0.66	45.87	1272102.3
76	17.42	19.05	54	77	12.67	21.95	1533842.8
23	17.19	23.26	52	73	2.09	60.16	712111.1
1	16.47	43.86	45	63	28.12	0.00	8242850.5
94	16.17	40.33	51	72	36.32	0.00	3624922.8
75	14.26	17.83	50	71	3.10	49.97	646779.6
79	14.03	20.56	39	53	0.78	55.67	703208.6
91	13.17	15.54	54	77	7.23	49.20	543493.1

Modeled Trends

Subcatchments were categorized by urbanization level based on the percentage of impervious area within each subcatchment. We calculated an average for each of our results by urbanization category to be able to compare results across different types of subcatchments (Table 4).

Regression analyses were performed to see if the SWMM outputs showed a significant relationship between the total runoff generated in each subcatchment and various model inputs for both the December 2010 storm event and the March 2009 storm event. Model results and regression show that soil curve numbers ($p<0.001$), percent imperviousness ($p<0.001$) and area of the subcatchment in square feet ($p<0.001$) most significantly predict the amount of runoff in a subcatchment. The slope of a subcatchment also significantly predicts total runoff with a $p<0.001$ for the December 2010 storm and a $p<0.002$ for the March 2009 storm.

For the December 2010 storm, incremental increases in curve number (0.03), in slope (0.02) and in percent imperviousness (0.05) would each lead to a one-inch increase in the total runoff simulated by SWMM for a relevant subcatchment (Table 4). Similarly for the March 2009 storm, incremental increases in curve number (0.01), in slope (0.02) and in percent imperviousness (0.02) would each lead to a one-inch increase in the total runoff simulated by SWMM (Table 5). While area in square feet was significant (p<0.001) for both storm events, both linear regression models assigned it a coefficient of 0. Other SWMM inputs were tested for significance, including Manning's n and width of a subcatchment, but none were significant in predicting SWMM's total simulated runoff. Although these variables were helpful in making minor adjustments to the model, the main determinants of both simulated and actual runoff are therefore soil curve numbers, slope, area and percent imperviousness.

The regression analyses serve to confirm the validation and calibration of the model since the linear regression models show the same variables with very similar coefficients as significant to the models. The analyses help us understand not only how SWMM works, but also what real-world variables would be the most significant in predicting runoff. As the linear models predict, percent imperviousness is the most important variable in estimating runoff.

Tables 4 and 5 display the mean runoff coefficient, total runoff (in), impervious and pervious runoff (in), total infiltration (in) and peak runoff (cfs) for both the December 2010 and the March 2009 storm. The results show that the higher the urbanization level of the subcatchment, the higher the mean runoff coefficient and impervious runoff and the lower amount of total infiltration (in). There is a direct link between the percent imperviousness of a subcatchment and runoff.

Table 4. Linear Regression Results for December 19, 2020 Precipitation Event.

	Dependent variable: Total Runoff (Inches) for December 2010 Storm
Curve Number	0.03***
	(0.01)
Slope	0.02**
	(0.01)
Percent Impervious	0.05***
	(0.005)
Area (sqft)	-0.0000***
	(0.0000)
Width	0.0003
	(0.001)
Manning's n for Pervious Surfaces	-0.25
	(0.77)
Y-Intercept	-0.80
	(0.57)
Observations	97
Adjusted R^2	0.81
Residual Std. Error	0.44 (df = 90)
F Statistic	67.23*** (df = 6; 90)
Note:	*p<0.1;* ***p<0.05;*** p<0.001

Table 5. Linear Regression Results for March 14, 2009 Precipitation Event.

	Dependent variable:
	Total Runoff (Inches) for March 2009 Storm
Curve Number	0.01***
	(0.003)
Slope	0.02***
	(0.005)
Percent Impervious	0.02***
	(0.002)
Area (sqft)	0.0000***
	(0.00)
Width	-0.0002
	(0.0003)
Manning's n for Pervious Surfaces	-0.39
	(0.39)
Y-Intercept	-0.44
	(0.27)
Observations	97
Adjusted R^2	0.72
Residual Std. Error	0.22 (df = 90)
F Statistic	42.23*** (df = 6; 90)
Note:	*p<0.1; **p<0.05;*** p<0.001

Finally, figures 22 and 23 show a link between the percent of impervious land cover in a subcatchment and the amount of total simulated runoff. The more urbanized a subcatchment, the more runoff was generated.

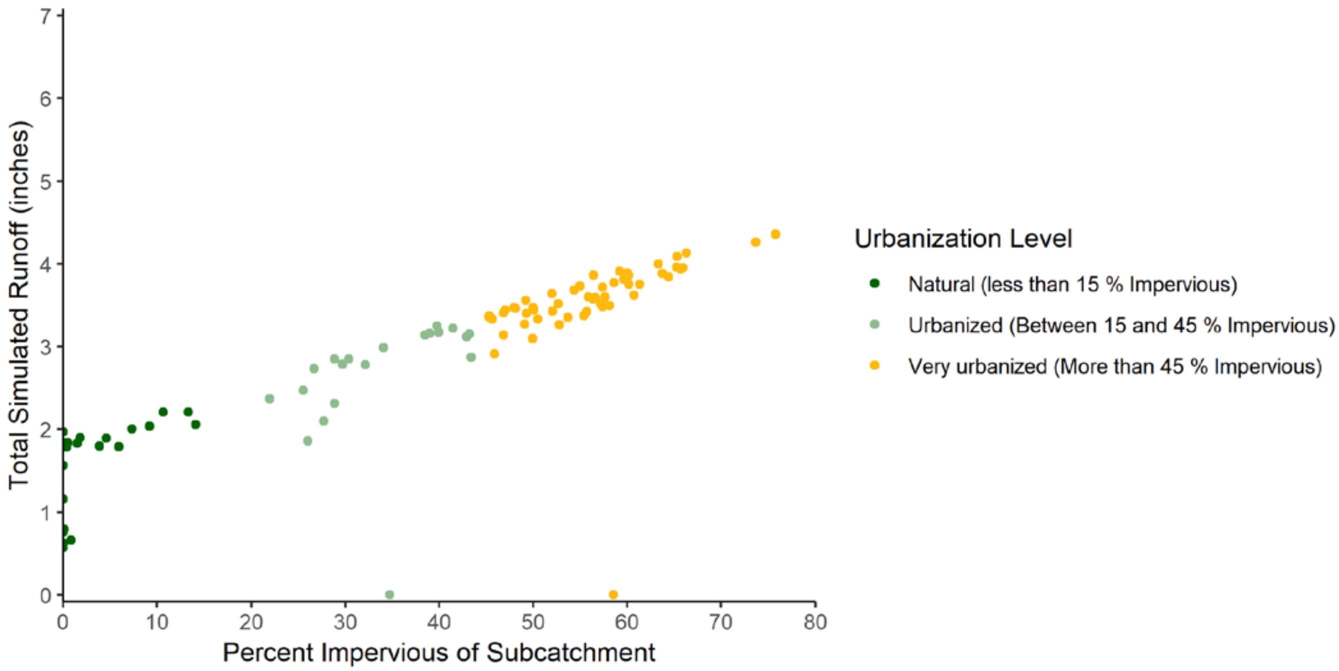


Figure 22. Relationship Between Total Simulated Runoff (inches) and Percent Imperviousness of Subcatchment (%) for the December 19, 2010 Precipitation Event. Observed data provided by NOAA precipitation gauge COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US).

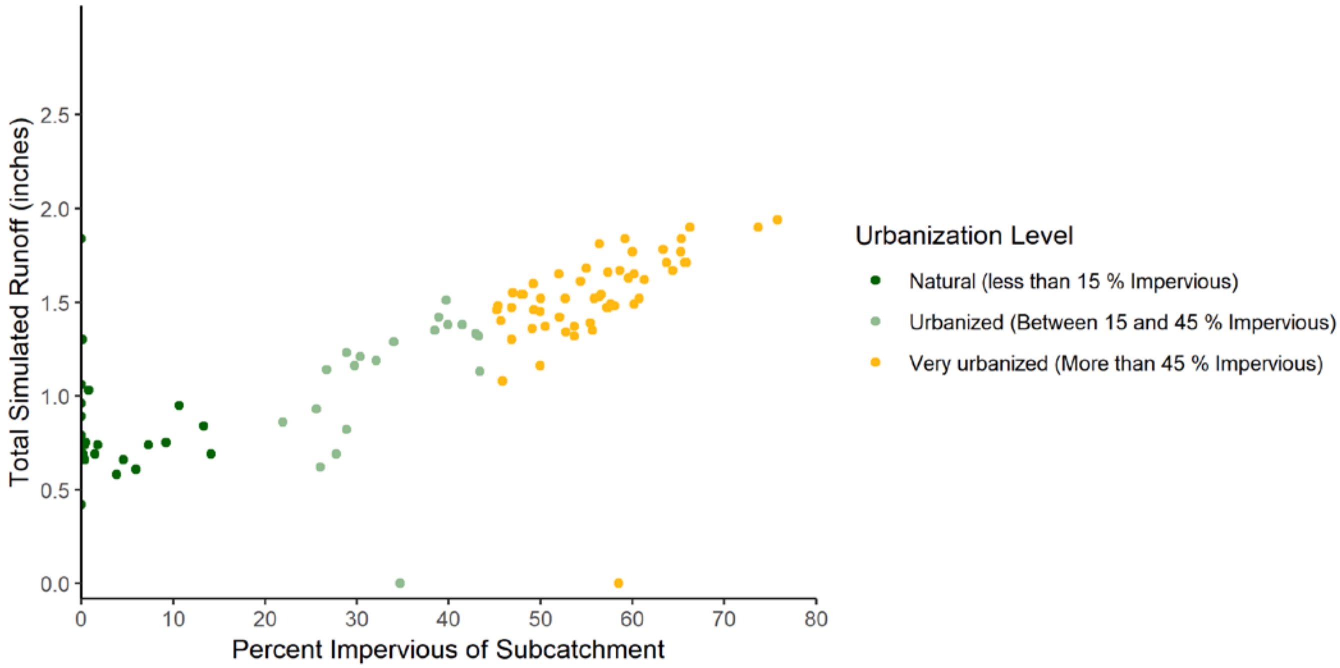


Figure 23. Relationship Between Total Simulated Runoff (inches) and Percent Imperviousness of Subcatchment (%) for the March 14, 2009 Precipitation Event. Observed data provided by NOAA precipitation gauge COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US).

Discussion

Model Fit and Application
The standard NSE value indicating that a model can accurately predict flow is 0.5 (Moriasi *et al.*, 2007). Our model meets that standard with a NSE of 0.65, indicating that our model can accurately predict flows in the Maunalua region. As with any hydrologic model, there can be improvements for the calibration to observed data. The discrepancies between simulated and observed flow are likely due to the different rainfall patterns in the upper and lower watershed. Without precipitation data throughout the watershed, especially in the upper watershed that receives greater amounts of rainfall, simulated runoff is lower than the observed runoff values and displays more pronounced peaks. Both of these characteristics are present in our model hydrographs. Furthermore, the model does not currently account for baseflow available in the stream, a possible reason for the differences between the simulated and observed flows for both storm events. Despite these discrepancies, our model is still useful to identify spatial distributions of runoff and the associated hotspot locations.

Main Findings
The results show that the upper, natural areas of Wailupe watershed contribute the least amount of total runoff in inches, followed by the urbanized and very urbanized areas of the watershed (Figures 22 and 23). The urbanized areas tend to be concentrated in the lower half of the watershed; a pattern repeated throughout Maunalua Bay as the upper watersheds are too steep to build. Our model suggests that urbanization of the region has increased runoff into the bay, potentially carrying sediments and other pollutants. Subcatchments in the urban watershed generally have higher impervious surface cover, leading to the higher runoff coefficients observed in comparison to those in the upper watershed (Figure 18).

When subcatchments within the watershed or normalized for area (via runoff coefficients), they varied in their total runoff contributions. These variations allowed us to rank subcatchments based on their relative contributions to total runoff (Figure 18). We found that subcatchments which had higher runoff coefficients in the March 2009 storm are also the same high contributors in the December 2010 storm. Overlaying the two storms provide us with reoccurring hotspots, which are likely to continue producing high volumes of runoff across different storm events (Figure 19, Table 2). Of the top 20 reoccurring hotspots, all are in the urban watershed in predominantly residential areas with impervious surface cover greater than 50%. Over half (11) of the hotspots located on Hawaiʻiloa ridge may be due imperviousness cover from roof tops, driveways, and wider streets coupled with relatively higher slope values for the lower, urban region (Table 2).

Although the urban subcatchments generally contribute higher total volumes of runoff, we found that the peak volumes of runoff actually occur in the upper region of the watershed (Figure 20). Peak flow can be attributed to high % slope (~25% or more) for peak flow hotspots in the upper reaches, and/or high % impervious cover (~45% or more) for peak flow hotspots in the lower reaches (Table 3). This is important because sediment is mobilized with higher volumes of water (Williams *et al.*, 2009; Wolanski *et al.*, 2009), suggesting that although urban areas do have high total runoff, sediment may actually be originating from the upper watershed, and transported in the lower watershed over impervious surfaces. This finding is consistent with observations of erosion scars on the mountain range in subcatchments 1 and 24 where bedrock is exposed (Sustainable Resources Group Intn'l, Inc., 2010), which is also visible in satellite imagery (Figure 21) by Wiliwilinui Ridge Trail. Previous assessments claim vegetative cover loss to be attributed to feral (pigs frequently referenced) and domestic animals the introduction of invasive species, and general decline of rainfall throughout the islands (Miller et al., 2009; Sustainable Resources Group Intn'l, Inc., 2010). From our model results and these claims, decreasing overall sediment at the source will require restoration efforts and animal management in the upper watershed. Subcatchment 7 is at the end of a steep ridge and confluence of two streams. This area has been recommended for the placement of an extended sediment detention basin in a previous planning document (Sustainable Resources Group Intn'l, Inc., 2010). Subcatchment 78 has ʻĀina Haina Shopping Center which is known to have high imperviousness due to the large parking lot. This landmark also has other pollution concerns due to the gas station and many parked vehicles ("Summary of Stormwater Retrofit Options", 2009).

However, efforts can still be made in the lower watershed to capture sediments before they enter the Bay. The bottoms of slopes are key areas where runoff containing potentially high volumes of sediment meet the urban area and are directed into the stormwater system. Strategically placed green infrastructure may be able to slow runoff down and capture sediment before it flows into pipes and eventually the Bay. Without addressing the source of sediment, however, these systems will likely require regular maintenance to remove sediment build-up. Furthermore, there may be additional physical and political constraints to the implementation of the green infrastructure designs considered in this analysis. The Koʻolau mountains are incredibly steep and, in many areas, very little space exists between houses and slopes. Most of this land is also privately owned. Projects proposed in this study will therefore be subject to these additional constraints, and implementation will likely require working closely with the local community.

During our project we have searched for data inputs required by SWMM for the Maunalua region. The data that is available to use and the corresponding limitations for using SWMM vary from watershed to watershed. We put together a table of what data is available for each watershed (Appendix A) and summarized the tools we used for this project (Appendix F). We have also noted crucial data that is not available for each watershed to be used for future studies to collect that data or to easily determine what kind of analysis can be done for each watershed.

Study Limitations

Precipitation Data

We are limited to two rain gages with 15-minute precipitation data within our study region, however rainfall varies at different elevations in the watershed. To be able to simulate the appropriate flow volume, we used estimated median monthly rainfall from the Hawaiʻi Rainfall Atlas, which are generated from the closest available rain gages. The spatial distance of rainfall gauges used to estimate rainfall in our representative watershed is larger, and the data provided is a monthly median, which is spread over a larger time frame than our observed 2-year 24-hour storm. The estimates may not be accurate given spatial heterogeneity of rainfall within the watershed, however in the absence of observed precipitation data, these estimates are useful. We use these estimates to simulate runoff in the model to provide discharge, and to calibrate Manning's N and Infiltration parameters in the model. Runoff values of each subcatchment will change with each storm, however we assume that hotspots will remain the same for most storms due to the relative definition of hotspot.

Stormwater Structure Data

Invert elevations of stormwater structures were not publicly available for most of the watershed and are in planning documents currently only accessible at the Honolulu City and County office computers. Although there were few that had invert elevations in the data, there is too much branching in the system to try to interpolate other invert values. For this reason, we used elevation of the land surface, then calculated length using the difference in elevation and distance between structures. The length is used in SWMM to calculate flow, and the conduits route these flows through the network. Due to the use of surface elevations as opposed to invert elevations, and some of the conduit branching was deleted due to flow path errors, our model may not be useful for considering improvements to gray infrastructure. This limitation is further exacerbated with some missing conduit dimensions that were estimated based on literature values or using an average of existing values.

Ecological Response

For this study, it is not possible to determine the response of ecological communities from simulated scenarios. As there are multiple stressors associated with declines in coral cover and proliferation of invasive algal communities on Maunalua Bay reef flats, and there is uncertainty surrounding the extent of coral recovery from reducing polluted stormwater runoff. Recovery of coral species in the Bay requires a holistic approach, and no single approach will achieve recovery. Although it has been determined that increases in light attenuation and reduction of suspended sediments supports coral health, little is still known about specific coral recovery in this region, and the sedimentation threshold that promotes it.

Other Sources of Pollution

There are other potential sources of pollutants in the Bay that should be considered for future studies within this region. Our project addressed peak flow volumes mobilizing sediment and total flow volumes, however nutrients, heavy metals, and other toxins are likely entering the Bay from urban land uses (State of Hawaii DOH CWB, 2015; Sustainable Resources Group Intn'l, Inc., 2010). A prevalent source of pollution to the bay may be onsite sewage disposal systems (septic tanks). A recent study on groundwater-delivered nutrients in the Bay indicates that areas with large concentrations of onsite sewage disposal systems have higher potential of sewage pollution (Richardson *et al.*, 2015). If the surrounding soil is saturated, the subsurface flow will carry sewage into the bay (Richardson *et al.*, 2015).

Additional Hotspots

There are other definitions for hotspots in the Maunalua Bay region cited in relevant literature. The (cite year) Wailupe and Kuliʻouʻou Watershed Assessment cites "chemicals stored in rusting and leaky containers, plastics, cigarette butts, oil, brake fluids, rush hour traffic, bad odor from drains, trash, fueling station, sediment, large areas of asphalt, manicured lawns" (Prescott, n.d.) as being pollution hotspots. Similarly, the Horsley Witten Group worked with Hawai'i's Office of Planning to develop a state LID guide, identifying outdoor liquid container storage, fueling stations, marinas, and storage sites as land use activities considered as hotspots (Horsley Witten

Group, 2006). We capture percent imperviousness in our current study, however other land use was outside of the scope of work for this project.

Conclusions

Study Relevance

This project contributes to the understanding of the hydrologic dynamics in the Maunalua Bay Region that are linked to the health of Maunalua Bay. Our evaluation of the Wailupe watershed has successfully identified effective management areas for both total runoff and peak flow (sediment) hotspots. Identification of these hotspots assists Mālama Maunalua in prioritizing areas within the Wailupe watershed that can be targeted for infrastructure that reduces stormwater pollution into the Bay. Furthermore, we have identified areas of data limitations to help Mālama Maunalua understand where future studies and research can be directed to reduce these gaps in quantitative knowledge. These deliverables will be provided to Mālama Maunalua to allow them to continue with this analysis for more watersheds in the Maunalua Bay region, effectively providing a comprehensive analysis of stormwater dynamics in the area. Through strategic restoration of the watershed back to a more natural hydrologic regime, the managers and community members within the region can help to restore and preserve the ecological integrity of Maunalua Bay for future generations.

Other watersheds in Hawaiʻi—such as Heʻeia on Oʻahu—are also spearheading community-based ridge-to-reef restoration efforts that emulate *ahupuaʻa* management systems (Campbell and Campbell, 2017). These efforts include removal of invasive species in the uplands and replanting of native flora, restoration of wetlands and the establishment of traditional Hawaiian polyculture, and restoration of the 800 year old Heʻeia fishpond (Campbell and Campbell, 2017). Our project adds to the growing knowledge of these efforts by aiding Mālama Maunalua in identification of areas to target restoration efforts within the watersheds of the Maunalua Bay region. Globally, there is increasing degradation of important and fragile coral reefs due to urbanization of adjacent and upland areas (Bartley *et al*., 2014). In addition to the major local significance of this project, our work will be applicable to other coastal communities around the world which face similar issues. It is our intent that this analysis and its future development will serve as a blueprint for other island communities which face similar threats to the marine environments they depend upon.

Recommendations

The model we have developed allows for a preliminary understanding of stormwater dynamics in the Wailupe watershed and has the potential to be adjusted and applied to other watersheds in the region to identify stormwater hotspots. Our recommendation is to use the model as part of a strategy to prioritize hotspots within the region for effective management when there are resource limitations. Our recommended management practice in each runoff hotspot is to increase infiltration of stormwater into soils by implementing green infrastructure in those hotspots. Implementation of green infrastructure could happen in two parts. First is to pair the model with the GreenPlan-IT tool to help watershed managers make decisions about what type of green infrastructure can work well in the hotspot subcatchment. Green infrastructure types are defined by their dimension and infiltration values in SWMM, however designs can vary vastly depending on the type of soil, storm, drainage area, and vegetation or other materials used.

GreenPlan-IT can provide a map of all the areas green infrastructure can be placed based on soil data and available space for the entire region. The spatial data for green infrastructure can be input into SWMM for green infrastructure performance (runoff values) that can be used for planning and shared with stakeholders.
The second is to do some ground truthing based on the tool's suggestions to determine if the areas recommended are viable. Some questions a watershed manager may consider for further analysis are whether there is enough space, if the soil conditions are ideal, and whether there may be regulatory barriers.

For green infrastructure to be implemented public spaces, we recommend integrating the community into the decision-making process and share with them the potential benefits that green infrastructure may have for reducing runoff in their community. Some questions for managers to consider is whether they are in favor of the idea of green infrastructure, where they think it would provide the most benefit, and what aesthetics they may prefer in the design. There is likely to be very limited public space in these hotspots, provided that all were predominantly residential areas. In order to strengthen community relations and increase understanding of stormwater pollution, Mālama Maunalua recently launched the C.P.R. stormwater management campaign in partnership with local businesses to target homeowners (C.P.R. Maunalua). Additionally, the City and County of Honolulu is currently in the planning stages of implementing a Storm Water Utility Fee which would charge property owners a fee based on the volume of runoff from their properties. This utility may further incentivize property owners to implement green infrastructure on their properties and would be an opportunity for our client to provide recommendations for green infrastructure to the community. Many homeowners across the island are concerned with both flooding and cost (State of Hawaii DPP, 2019). The GreenPlan-IT Toolkit offers a unique opportunity to communicate the benefits of green infrastructure to flood reduction and find a cost-effective option. For example, some important considerations for green infrastructure that can be provided by GreenPlan-IT Toolkit and our model are soil drainage, depth to water table, slope, and cost effectiveness. For highly drained soil types and low surrounding slope areas, rain gardens and bioretention cells may be aesthetically pleasing options. For slopes areas, an infiltration trench may be the quickest way to infiltrate water. For large multi-car driveways, permeable pavement may be a viable option for some property owners.

Our results indicate that peak volumes of runoff occur in the upper region of the watershed, suggesting that sediment likely originates from the upper watershed because sediment is mobilized with higher volumes of water (Williams *et al.*, 2009, Wolanski *et al.*, 2009). This is because sediment may settle out of low flow volumes, however they can accumulate and be mobilized during peak stream flow events (USGS, *Sediment and Suspended Sediment*). Green infrastructure is not recommended in these upper regions because they are already forested, and the slopes in those reaches are likely to be too steep for green infrastructure to be cost effective. Decreasing overall sediment at the source will require restoring vegetation or implementing other erosion control measures of mass wasting areas in the upper watershed observed on the western ridges in the watershed in subcatchments 1 and 24. An extended sediment detention basin was proposed for subcatchment 7 in a previous assessment (Sustainable Resources Group Intn'l, Inc., 2010) and our supports that recommendation. To address sediment in the lower watershed, managers can prioritize green infrastructure that provides sediment controls, such as bioretention cells and stormwater ponds (State of Hawaii DOT, 2007; Horsley Witten Group, 2006). Provided that space is very limited in the flat regions of the watershed, bioretention cells may be more feasible. Bioretention types green infrastructure may be the ideal to capture and amass sediment in vegetated cells, which make settled sediment less likely to mobilize in larger storm events (Horsley Witten Group, 2006). Another green infrastructure option for these lower reaches is permeable pavement. Permeable pavement can be ideal for commercial centers with large parking lots, such as Aina Haina shopping center in subcatchment 78. Permeable pavement allows for infiltration, but also helps control fine silts and sediments (State of Hawaii DOT, 2007; Horsley Witten Group, 2006). Some important considerations are cost and maintenance of these practices, particularly for large public and commercial areas.

Overall, our project is a preliminary step in developing a comprehensive plan for reducing stormwater pollution in the Maunalua Bay region. The tools and recommendations we provide Mālama Maunalua can be used to inform management decisions moving forward and help them work towards improving the health of Maunalua Bay. We've been honored to collaborate with them in developing this project and are excited to see the next phases unfold.

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Appendices

Appendix A

Data Availability and Limitations by Watershed: Maunalua Bay Region, 2019

KEY		
Data Availability	Letters	
Not available	**N**	
Available	**A**	
Incomplete	**I**	
Work arounds	Colors	
Processing required to obtain data	(blue)	**see methods*
Use an estimate (literature or other method)	(green)	**see methods*
None	(red)	
Unknown	(grey)	

See table on the next pages.

Data	Data Source	Data Type	Link	Data Components	Use in SWMM	Wai'alai Nui	Wai'alai Iki	Wailupe	Niu	Kuli'ou'ou
Conduits	City and County of Honolulu	Shapefile & table	http://honolulu-cchnl.opendata.arcgis.com/datasets/storm-water-conduit	Length	Length (flow calcualtion)	A	A	A	A	A
				Type	Cross section shape	A	A	A	A	A
				Diameter	Cross section dimensions	I	I	I	I	I
				Width	Cross section dimensions	I	I	I	I	I
				Height	Cross section dimensions	I	I	I	I	I
				Spatial location	Coordinates	A	A	A	A	A
Flowlines (streams)	National Hydrography Dataset	Shapefile & table	http://geoportal.hawaii.gov/datasets/nhd-flowlines	Spatial orientation	Subcatchments	A	A	A	A	A
				Length	Length (flow calcualtion)	A	A	A	A	A
	NA	*NA*	*NA*	Width	Cross section dimensions	N	N	N	N	N
				Height	Cross section dimensions	N	N	N	N	N
				Slope	Cross section dimensions	N	N	N	N	N
Structures	City and County of Honolulu	Shapefile & table	http://honolulu-cchnl.opendata.arcgis.com/datasets/storm-water-structure	Type	Node type	A	A	A	A	A
				Invert elevation	Invert elevation	I	I	I	I	I
				Spatial location	Coordinates	A	A	A	A	A
Discharge	U.S. Geological Survey National Water Informaiton System	Table	https://nwis.waterdata.usgs.gov/hi/nwis/	Date and time	Time step (calibration)	N	N	A	N	A
				Measurement	Quantity (calibration)	N	N	A	N	A
Precipitation (15-minute)	National Oceanic and Atmospheric Administration, National Centers for Environmental Information	Table	https://www.ncdc.noaa.gov/cdo-web/datasets#PRECIP_14	Date and time (Minutes)	Time step	N	N	A	N	N
				Measurement	Quantity	N	N	A	N	N
Precipitation (Hourly)	National Oceanic and Atmospheric Administration, National Centers for Environmental Information	Table	https://www.ncdc.noaa.gov/cdo-web/datasets/PRECIP_HLY/stations/COOP:511298/detail	Date (Hourly)	Time step	N	N	N	N	N
				Measurement	Quantity	N	N	N	N	N
Precipitation (Daily)	National Oceanic and Atmospheric Administration, National Centers for Environmental Information	Table	https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/locations/FIPS:15003/detail#stationlist	Date (Daily)	Time step	A	A	A	A	A
				Measurement	Quantity	A	A	A	A	A
DEM	The University of Hawai'i, Manoa	Shapefile	https://www.soest.hawaii.edu/coasts/data/oahu/dem.html	*NA*	Subcatchments	A	A	A	A	A
				NA	Slope (%)	A	A	A	A	A
Soil	Natural Resources Conservation Service's SSURGO	Shapefile	https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=HI	Soil hydrologic group	Curve number	A	A	A	A	A
				Average draining conditions	Curve number	A	A	A	A	A
Building footprints	City and County of Honolulu	Shapefile	http://geoportal.hawaii.gov/datasets/cchnl::building-footprints-cch	Spatial area	Imperviousness (%)	A	A	A	A	A
Land use land cover	National Land Cover Dataset 2011	Shapefile	https://www.mrlc.gov/data?f%5B0%5D=category%3Aland%20cover	Type	Curve number	A	A	A	A	A
Roads	Hawai'i Office of Planning	Shapefile	http://planning.hawaii.gov/gis/download-gis-data/	Spatial area	Imperviousness (%)	A	A	A	A	A

Data	Data Source	Data Type	Link	Data Components	Use in SWMM	Ka'alākei	Haha'ione	Kamilo Nui	Kamilo Iki	Portlock
Conduits	City and County of Honolulu	Shapefile & table	http://honolulu-cchnl.opendata.arcgis.com/datasets/storm-water-conduit	Length	Length (flow calcualtion)	A	A	A	A	A
				Type	Cross section shape	A	A	A	A	A
				Diameter	Cross section dimensions	I	I	I	I	I
				Width	Cross section dimensions	I	I	I	I	I
				Height	Cross section dimensions	I	I	I	I	I
				Spatial location	Coordinates	A	A	A	A	A
Flowlines (streams)	National Hydrography Dataset	Shapefile & table	http://geoportal.hawaii.gov/datasets/nhd-flowlines	Spatial orientation	Subcatchments	A	A	A	A	A
				Length	Length (flow calcualtion)	A	A	A	A	A
	NA	*NA*	*NA*	Width	Cross section dimensions	N	N	N	N	N
				Height	Cross section dimensions	N	N	N	N	N
				Slope	Cross section dimensions	N	N	N	N	N
Structures	City and County of Honolulu	Shapefile & table	http://honolulu-cchnl.opendata.arcgis.com/datasets/storm-water-structure	Type	Node type	A	A	A	A	A
				Invert elevation	Invert elevation	I	I	I	I	I
				Spatial location	Coordinates	A	A	A	A	A
Discharge	U.S. Geological Survey National Water Informaiton System	Table	https://nwis.waterdata.usgs.gov/hi/nwis/	Date and time	Time step (calibration)	N	N	N	N	N
				Measurement	Quantity (calibration)	N	N	N	N	N
Precipitation (15-minute)	National Oceanic and Atmospheric Administration, National Centers for Environmental Information	Table	https://www.ncdc.noaa.gov/cdo-web/datasets#PRECIP_14	Date and time (Minutes)	Time step	N	N	N	N	N
				Measurement	Quantity	N	N	N	N	N
Precipitation (Hourly)	National Oceanic and Atmospheric Administration, National Centers for Environmental Information	Table	https://www.ncdc.noaa.gov/cdo-web/datasets/PRECIP_HLY/stations/COOP:511298/detail	Date (Hourly)	Time step	A	N	N	N	N
				Measurement	Quantity	A	N	N	N	N
Precipitation (Daily)	National Oceanic and Atmospheric Administration, National Centers for Environmental Information	Table	https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/locations/FIPS:15003/detail#stationlist	Date (Daily)	Time step	N	A	N	A	N
				Measurement	Quantity	N	A	N	A	N
DEM	The University of Hawai'i, Manoa	Shapefile	https://www.soest.hawaii.edu/coasts/data/oahu/dem.html	*NA*	Subcatchments	A	A	A	A	A
				NA	Slope (%)	A	A	A	A	A
Soil	Natural Resources Conservation Service's SSURGO	Shapefile	https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=HI	Soil hydrologic group	Curve number	A	A	A	A	A
				Average draining conditions	Curve number	A	A	A	A	A
Building footprints	City and County of Honolulu	Shapefile	http://geoportal.hawaii.gov/datasets/cchnl::building-footprints-cch	Spatial area	Imperviousness (%)	A	A	A	A	A
Land use land cover	National Land Cover Dataset 2011	Shapefile	https://www.mrlc.gov/data?f%5B0%5D=category%3Aland%20cover	Type	Curve number	A	A	A	A	A
Roads	Hawai'i Office of Planning	Shapefile	http://planning.hawaii.gov/gis/download-gis-data/	Spatial area	Imperviousness (%)	A	A	A	A	A

Appendix B

Model Setup and Defaults

Open SWMM 5.1 and select File, then New to create a new project. For ease of use, add the Excel program as a tool in the model by selecting Tools, then Configure. See SWMM 5.1 user manual for more detailed steps. Next, we will select project defaults for the model.

1. Select Project, then Defaults to open the Project Defaults dialog.
2. In the ID Labels tab, input the following:
    a. Rain Gages = R
    b. Subcatchments = S
    c. Junctions = J
    d. Outfalls = O
    e. Dividers = D
    f. Storage units = SU
    g. Conduits = C
    h. Pumps = P
    i. Regulators = R
    j. ID Increment = 1
3. Subcatchments tab
    a. Most values will come from GIS layers or soil analysis (Area, Width, Slope, Imperv,), but other defaults, if not provided, are:
    b. Area = 100
    c. Width = 100
    d. Slope = 25
    e. Imperv = 25
    f. N_Imperv = 0.01
    g. N_Perv = 0.15
    h. S_Imperv = 0
    i. S_Perv = 0
    j. PctZero = 0
    k. RouteTo = "OUTLET"
    l. CurveNum = 80
    m. DryTime = 7
    n. **Infiltration model = Curve Number**
4. Nodes/Links tab
    a. Most values will come from GIS layers or R code.
    b. Conduit Geometry
        i. Barrels = [leave blank]
        ii. Max. Depth = 0
    c. Conduit Roughness = 0.01
        i. Cross section
        ii. Open Rectangular
        iii. Width = 30 ft
        iv. Depth = 10 ft
    d. Flow Units = CFS

e. Link Offsets = DEPTH
f. **Routing Model = Dynamic Wave**
g. **Force Main Equation = Darcy-Weisbach**

Decisions:

1. Infiltration Model: We chose curve number because curve number is widely used for hydrologic models because they are empirical and widely available.
2. Routing Model: We chose the dynamic wave model because its equations produce the most theoretically accurate results because it can account for pressurized flow in closed conduits, flooding, ponding, and backflow, as opposed to the simpler routing models available.
3. Main Equation: Darcy-Wesibach equation was used because it can relate head loss to velocity due to friction in the long conduits that characterize our region.
4. Depression storage: Values can be provided from EPA SWMM 5.1 Manual p. 182, table A.5, however we found that our model hydrograph peaks follow the observed data more closely when both values are set to 0.
5. N (Manning's n for roughness): Values are provided from the EPA SWMM 5.1 Manual p. 182, table A.6 for overland flow, p. 183, table A.7 for conduits
6. Max Depth is 0 because we do not have that information for stormwater structures.
7. Barrels: the number of barrels (i.e., number of parallel pipes of equal size, slope, and roughness) associated with a conduit (default is 1), see EPA SWMM 5.1 Manual p. 312. We did not observe many barrels in this system, so defaulted to leaving that column "blank"
8. Route To: for subcathcments with any urban infrastructure, select "OUTLET". For natural subcatchments with a gradient toward urban subcatchments, select "PERVIOUS"

Notes for Model Inputs:

- When preparing files for SWMM, they should be in the same format found in the .inp file or in the manual. Files were prepared in RStudio, for which there is a script to wrangle data into the SWMM format. Please see the Kahuwai github repo for annotated R codes. See methodology in each subsequent category.
- When inputting new data to the SWMM input file (.inp), use the excel backend tool (see SWMM Manual on how to add tools): right click SWMM file, select "Open with", click "Excel". In the excel file you can copy and paste data from each of the files provided from R codes under the appropriate subheading. Save the file, close, and re-open SWMM. The data should have been saved into the backend file and are now usable in the model front end.
- Subheadings usually only appear in the input file when it is drawn in the model interface first. Because the system is too large to replicate manually, we have opted to mass import these inputs by copying and pasting values into the input file. Examples of headings for each category are provided in the code files, and must be manually included in the input file if not already provided in the input file.

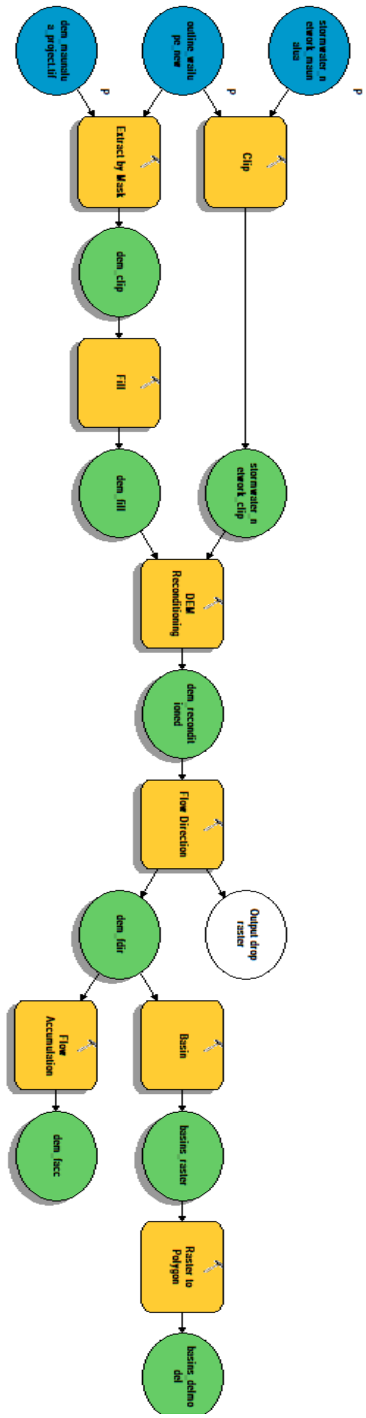
  Example:

  ```
  [JUNCTIONS]
  ;;Name  Elevation MaxDepth  InitDepth SurDepth  Aponded
  ;;---------- ---------- ---------- ---------- ---------- ----------
  ```

  Values go under the dashed lines in their respective columns.

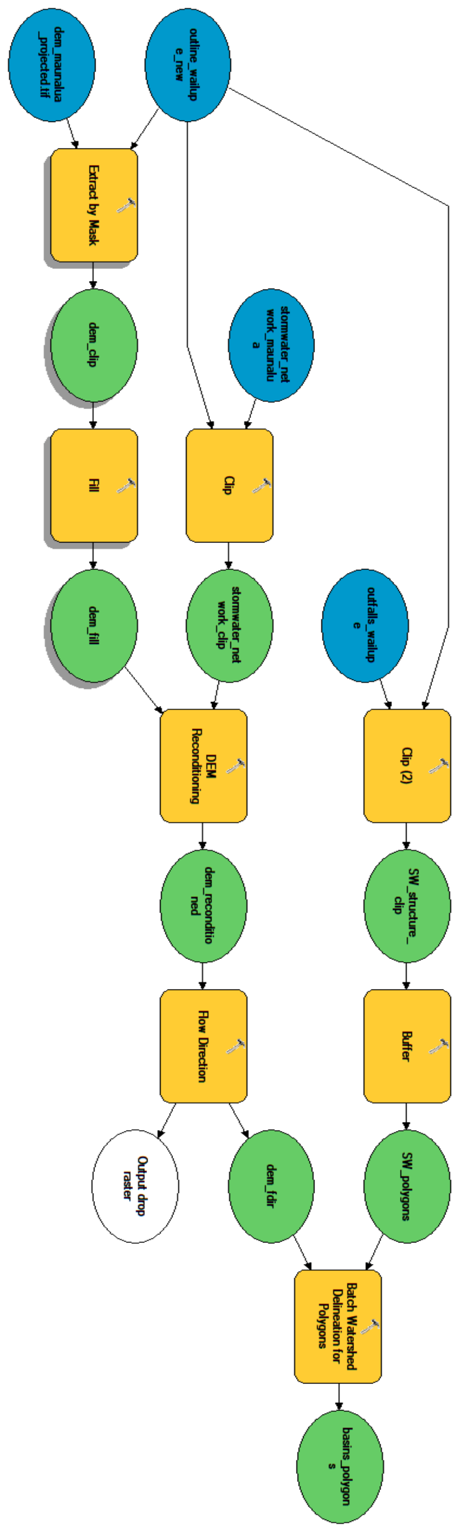
Appendix C

Urban Subcatchment Delineation ArcGIS Model 1



Appendix D

Urban Subcatchment Delineation ArcGIS Model 2



Appendix E

Subcatchment Characterization

[SUBCATCHMENTS]						
;;Name	Rain Gage	Outlet	Area	%Imperv	Width	%Slope
;;--------------	----------------	----------------	--------	--------	--------	--------
1	R3	2	189.2294713	0	400	28.12488788
2	R3	J3	257.3832658	0.000927115	400	36.40935203
3	R3	J1	315.2854249	0	400	33.94600956
4	R1	54869	5.606208797	38.51763637	181.0683568	20.19128626
5	R1	3574	0.964370922	59.22528719	400	4.973907902
6	R1	47515	5.354158477	58.53240322	325.7368173	0
7	R1	34620	49.9144007	14.10178763	400	24.37085007
8	R1	29080	3.56657301	46.87794523	340.6274911	3.156830956
9	R1	33758	20.28793237	1.783702012	400	34.31882952
10	R1	50229	12.10419084	46.82731603	400	13.03499906
11	R1	52990	33.54266921	60.17684089	400	0.94758568
12	R1	50337	6.370282664	28.88469268	213.2570013	18.41688055
13	R1	7716	4.824320976	60.72206092	245.8444061	2.801558317
14	R1	2562	5.614806045	51.97367076	313.9281088	10.06220211
15	R1	30889	4.392445182	53.68409461	343.0791734	0.780762234
16	R1	44800	5.875520233	29.72936196	201.9873096	25.49224019
17	R1	27267	5.626942699	48.09130146	252.7428987	10.78205321
18	R1	46595	6.756477089	41.48075899	238.0977829	17.3274096
19	R1	2276	6.964794011	43.40998739	500	2.445729247
20	R1	58565	74.84723585	5.926748961	400	28.73820831
21	R1	48342	1.809747547	64.38962281	196.3455652	2.133592209
22	R1	56627	2.453839345	57.3645861	303.318483	5.224537757
23	R1	25354	16.347791	60.15848873	376.7384679	2.091764046
24	R2	J8	136.7392529	0.81502431	400	4
25	R1	38313	9.971414734	26.67894757	266.9179648	27.32156393
26	R1	31847	4.740759218	52.66356043	413.1809556	2.385881052
27	R1	56624	16.13236034	13.33065868	404.2609881	27.94698162
28	R1	25430	32.14766911	45.64873898	500	9.695153025
29	R1	18089	1.428246197	63.75089696	150.3492408	4.303892997
30	R1	23545	2.439729423	28.87544298	234.8614455	1.17347833
31	R1	18047	5.273899034	47.00969557	379.9726325	10.27077404
32	R1	42095	4.626191728	55.41356127	316.7514505	1.91627193
33	R1	2639	7.491734208	52.76045359	500	2.383154493
34	R1	41061	10.08579054	55.84532683	294.1469088	6.571679077
35	R1	33691	3.764393752	58.1059099	340.4843972	2.502320422
36	R1	32784	2.369101434	57.37834523	235.1292855	3.413503412
37	R1	46516	5.442464896	57.21574745	273.7577318	2.866642563
38	R3	J12	285.019534	0.093206635	400	29.49279649
39	R1	26629	4.821504721	42.93308382	400	11.31944206
40	R1	51447	1.796889202	65.26444349	230.281359	7.774445572

41	R1	34619	23.50986751	0	400	31.78168357
42	R1	29339	25.18703005	52.07524372	400	12.77419164
43	R1	2564	11.30645045	0.158683592	400	33.91832406
44	R1	33079	5.662908261	56.58470774	283.1134235	9.792575178
45	R1	54877	4.712422198	75.81187507	181.738361	10.83737171
46	R1	2564	4.820406543	59.97948939	361.4689022	9.180995339
47	R1	32856	3.74611016	73.67874059	250.5848449	9.0178653
48	R1	38312	10.20981084	39.93227871	400	7.954645437
49	R1	34714	7.278684259	61.33457951	274.9393466	11.6266179
50	R1	42902	7.300710873	1.474599605	260.0748573	32.39232894
51	R1	2570	4.462388826	65.70617625	287.4622975	3.205696179
52	R1	47790	11.96705174	49.06820134	394.0179198	14.2092259
53	R1	36749	3.298068649	32.12886722	275.6939701	21.1789757
54	R1	15452	6.914736059	65.90850376	192.1327056	11.98504143
55	R1	22842	10.46891606	43.23871699	368.268433	14.01245628
56	R1	8685	14.57604202	7.289334	400	29.99659999
57	R1	36587	7.186397515	56.38068612	287.6148812	15.03656872
58	R1	19022	18.24175557	50.48965135	400	13.47371249
59	R1	36513	5.541761199	58.61615029	267.7160368	9.355130215
60	R1	7792	3.000542454	66.27512006	229.0237664	10.20005574
61	R1	46533	8.812706186	49.27959815	346.2453048	8.729538441
62	R1	20748	18.75165821	57.62114314	400	4.969306881
63	R1	41136	28.94636649	59.59508223	400	11.35084752
64	R1	55704	4.131323083	10.63857967	310.6520905	28.08302572
65	R1	48455	7.111623298	54.98557019	240.6828265	12.2859432
66	R1	11448	7.121412551	30.37886608	252.202672	20.46153661
67	R1	14326	8.653818712	65.31544476	224.7427524	13.09451411
68	R1	18099	7.033202619	56.40239857	270.0457074	16.77800082
69	R1	48465	3.929655688	39.74706986	202.3597452	23.71009394
70	R1	43756	5.419065059	38.95121684	283.9928982	18.90064401
71	R1	17007	3.701810928	63.33945328	287.435246	1.229756545
72	R1	99	8.101160393	45.27106014	400	3.150903879
73	R1	100	13.59150568	25.5618759	400	10.67842504
74	R1	17009	36.58104361	49.9518791	400	0.513034194
75	R1	43757	14.84798888	49.96926038	351.9314151	3.103798958
76	R1	31848	35.2121217	21.94615359	400	12.66893273
77	R1	2283	11.92885531	27.73969292	400	0.063163121
78	R1	35543	29.20339895	45.86953124	400	0.662519556
79	R1	48348	16.14341963	55.67441413	400	0.780962719
80	R1	50187	7.536745984	34.72397236	400	0
81	R1	11459	6.630587686	53.67397184	400	0.202127771
82	R1	55040	1.503913327	50.03240953	149.3288852	12.98454078
83	R1	23469	5.719406509	0	217.7397256	33.80248846
84	R1	29985	19.80289409	4.567331708	400	27.63411142
85	R1	53065	6.598306727	0.488281567	400	30.45274774
86	R1	51140	5.966280139	0	400	32.79587617
87	R1	48405	5.063567492	0.354659927	301.7778016	32.53339197
88	R1	28217	5.643741425	45.34938012	390.845496	12.4884884
89	R1	52128	21.3431386	54.37988009	400	12.26721668
90	R1	35938	21.10621911	3.833246125	400	32.04143777
91	R1	46468	12.47686211	49.19776606	400	7.225773467

92	R1	54804	8.379104746	0.359272275	354.2603677	32.32297981
93	R1	J20	11.95255457	26.0080801	400	0.094002039
94	R3	J2	83.21662663	0	400	36.32299579
95	R1	7803	7.394075804	34.04731109	246.300007	25.74114412
96	R1	9678	14.43286193	9.212696318	400	31.66308143
97	R1	24463	5.014875437	47.90957767	366.7086881	12.80407377
[SUBAREAS]						
;;Subcatchment	N-Imperv	N-Perv	S-Imperv	S-Perv	PctZero	RouteTo
;;--------------	----------	----------	----------	----------	----------	----------
1	0.01	0.4	0.2	0.3	0	OUTLET
2	0.01	0.4	0.2	0.3	0	OUTLET
3	0.01	0.4	0.2	0.3	0	OUTLET
4	0.01	0.4	0.2	0.3	0	OUTLET
5	0.01	0.15	0.2	0.3	0	OUTLET
6	0.01	0.15	0.2	0.3	0	OUTLET
7	0.01	0.4	0.2	0.3	0	OUTLET
8	0.01	0.15	0.2	0.3	0	OUTLET
9	0.01	0.4	0.2	0.3	0	OUTLET
10	0.01	0.4	0.2	0.3	0	OUTLET
11	0.01	0.15	0.2	0.3	0	OUTLET
12	0.01	0.4	0.2	0.3	0	OUTLET
13	0.01	0.15	0.2	0.3	0	OUTLET
14	0.01	0.15	0.2	0.3	0	OUTLET
15	0.01	0.15	0.2	0.3	0	OUTLET
16	0.01	0.4	0.2	0.3	0	OUTLET
17	0.01	0.15	0.2	0.3	0	OUTLET
18	0.01	0.4	0.2	0.3	0	OUTLET
19	0.01	0.15	0.2	0.3	0	OUTLET
20	0.01	0.4	0.2	0.3	0	OUTLET
21	0.01	0.15	0.2	0.3	0	OUTLET
22	0.01	0.15	0.2	0.3	0	OUTLET
23	0.01	0.15	0.2	0.3	0	OUTLET
24	0.01	0.4	0.2	0.3	0	OUTLET
25	0.01	0.4	0.2	0.3	0	OUTLET
26	0.01	0.15	0.2	0.3	0	OUTLET
27	0.01	0.4	0.2	0.3	0	OUTLET
28	0.01	0.15	0.2	0.3	0	OUTLET
29	0.01	0.15	0.2	0.3	0	OUTLET
30	0.01	0.15	0.2	0.3	0	OUTLET
31	0.01	0.15	0.2	0.3	0	OUTLET
32	0.01	0.15	0.2	0.3	0	OUTLET
33	0.01	0.15	0.2	0.3	0	OUTLET
34	0.01	0.15	0.2	0.3	0	OUTLET
35	0.01	0.15	0.2	0.3	0	OUTLET
36	0.01	0.15	0.2	0.3	0	OUTLET
37	0.01	0.15	0.2	0.3	0	OUTLET
38	0.01	0.4	0.2	0.3	0	OUTLET
39	0.01	0.15	0.2	0.3	0	OUTLET
40	0.01	0.15	0.2	0.3	0	OUTLET

41	0.01	0.4	0.2	0.3	0	OUTLET
42	0.01	0.15	0.2	0.3	0	OUTLET
43	0.01	0.4	0.2	0.3	0	OUTLET
44	0.01	0.15	0.2	0.3	0	OUTLET
45	0.01	0.15	0.2	0.3	0	OUTLET
46	0.01	0.15	0.2	0.3	0	OUTLET
47	0.01	0.15	0.2	0.3	0	OUTLET
48	0.01	0.15	0.2	0.3	0	OUTLET
49	0.01	0.15	0.2	0.3	0	OUTLET
50	0.01	0.4	0.2	0.3	0	OUTLET
51	0.01	0.15	0.2	0.3	0	OUTLET
52	0.01	0.15	0.2	0.3	0	OUTLET
53	0.01	0.15	0.2	0.3	0	OUTLET
54	0.01	0.15	0.2	0.3	0	OUTLET
55	0.01	0.15	0.2	0.3	0	OUTLET
56	0.01	0.4	0.2	0.3	0	OUTLET
57	0.01	0.15	0.2	0.3	0	OUTLET
58	0.01	0.15	0.2	0.3	0	OUTLET
59	0.01	0.15	0.2	0.3	0	OUTLET
60	0.01	0.15	0.2	0.3	0	OUTLET
61	0.01	0.15	0.2	0.3	0	OUTLET
62	0.01	0.15	0.2	0.3	0	OUTLET
63	0.01	0.15	0.2	0.3	0	OUTLET
64	0.01	0.4	0.2	0.3	0	OUTLET
65	0.01	0.15	0.2	0.3	0	OUTLET
66	0.01	0.4	0.2	0.3	0	OUTLET
67	0.01	0.15	0.2	0.3	0	OUTLET
68	0.01	0.15	0.2	0.3	0	OUTLET
69	0.01	0.15	0.2	0.3	0	OUTLET
70	0.01	0.15	0.2	0.3	0	OUTLET
71	0.01	0.15	0.2	0.3	0	OUTLET
72	0.01	0.15	0.2	0.3	0	IMPERVIOUS
73	0.01	0.15	0.2	0.3	0	IMPERVIOUS
74	0.01	0.15	0.2	0.3	0	OUTLET
75	0.01	0.15	0.2	0.3	0	OUTLET
76	0.01	0.4	0.2	0.3	0	OUTLET
77	0.01	0.15	0.2	0.3	0	OUTLET
78	0.01	0.15	0.2	0.3	0	OUTLET
79	0.01	0.15	0.2	0.3	0	OUTLET
80	0.01	0.15	0.2	0.3	0	OUTLET
81	0.01	0.15	0.2	0.3	0	OUTLET
82	0.01	0.15	0.2	0.3	0	OUTLET
83	0.01	0.4	0.2	0.3	0	OUTLET
84	0.01	0.4	0.2	0.3	0	OUTLET
85	0.01	0.4	0.2	0.3	0	OUTLET
86	0.01	0.4	0.2	0.3	0	OUTLET
87	0.01	0.4	0.2	0.3	0	OUTLET
88	0.01	0.4	0.2	0.3	0	OUTLET
89	0.01	0.15	0.2	0.3	0	OUTLET
90	0.01	0.4	0.2	0.3	0	OUTLET
91	0.01	0.15	0.2	0.3	0	OUTLET

92	0.01	0.4	0.2	0.3	0	OUTLET
93	0.01	0.15	0.2	0.3	0	OUTLET
94	0.01	0.4	0.2	0.3	0	OUTLET
95	0.01	0.4	0.2	0.3	0	OUTLET
96	0.01	0.4	0.2	0.3	0	OUTLET
97	0.01	0.4	0.2	0.3	0	OUTLET

Appendix F

Model Results Tables

Summary Output Table of Results from SWMM Simulation for March 14, 2009 Precipitation Event December 19, 2010 Precipitation Event.

subcatchment	total_precip_in	total_runon_in	total_evap_in	total_infil_in	imperv_runoff_in	perv_runoff_in	total_runoff_in	total_runoff_10_6_gal	peak_runoff_cfs	runoff_coeff
1	5.5	0	0	3.78	0	0.57	0.57	2.93	16.47	0.104
2	5.5	0.42	0	3.6	0	0.76	0.76	5.29	27.8	0.128
3	5.5	0	0	3.38	0	0.63	0.63	5.38	28.98	0.114
4	5.5	0	0	2.08	2.06	1.08	3.14	0.48	4.99	0.572
5	5.5	0	0	1.4	3.17	0.74	3.91	0.1	1.29	0.71
6	5.5	0	0	1.73	0	0	0	0	0	0
7	5.5	0	0	2.86	0.75	1.3	2.06	2.79	18.64	0.374
8	5.5	0	0	2.13	2.51	0.63	3.14	0.3	3.93	0.571
9	5.5	0	0	3.17	0.09	1.81	1.9	1.05	8.56	0.346
10	5.5	0	0	1.83	2.51	0.9	3.41	1.12	11.62	0.62
11	5.5	0	0	1.43	3.19	0.56	3.75	3.41	27.47	0.681
12	5.5	0	0	2.35	1.55	1.3	2.85	0.49	4.89	0.518
13	5.5	0	0	1.66	3.24	0.38	3.62	0.47	5.38	0.658
14	5.5	0	0	1.64	2.78	0.85	3.64	0.55	6.29	0.661
15	5.5	0	0	1.91	2.86	0.49	3.35	0.4	4.49	0.609
16	5.5	0	0	2.42	1.6	1.2	2.79	0.45	4.48	0.508
17	5.5	0	0	1.81	2.58	0.89	3.46	0.53	5.91	0.629
18	5.5	0	0	2.01	2.22	1	3.22	0.59	6.13	0.586
19	5.5	0	0	2.38	2.32	0.55	2.87	0.54	6.28	0.522
20	5.5	0	0	2.91	0.32	1.47	1.79	3.63	21.31	0.325
21	5.5	0	0	1.45	3.44	0.4	3.84	0.19	2.28	0.699
22	5.5	0	0	1.58	3.08	0.64	3.72	0.25	3.01	0.676
23	5.5	0	0	1.38	3.2	0.67	3.86	1.71	17.19	0.702
24	5.5	0	0	3.17	0.04	0.61	0.66	2.45	12.46	0.12
25	5.5	0	0	2.46	1.43	1.3	2.73	0.74	7.24	0.496
26	5.5	0	0	1.75	2.82	0.7	3.52	0.45	5	0.64
27	5.5	0	0	2.93	0.72	1.49	2.21	0.97	8.5	0.402
28	5.5	0	0	1.9	2.43	0.9	3.33	2.91	29.91	0.606
29	5.5	0	0	1.42	3.42	0.47	3.88	0.15	1.93	0.706
30	5.5	0	0	2.92	1.55	0.76	2.31	0.15	1.78	0.42

31	5.5	0	0	1.84	2.52	0.92	3.44	0.49	5.59	0.625
32	5.5	0	0	1.9	2.96	0.42	3.37	0.42	4.83	0.614
33	5.5	0	0	2.01	2.82	0.44	3.26	0.66	7.61	0.593
34	5.5	0	0	1.67	2.98	0.62	3.6	0.99	11.08	0.654
35	5.5	0	0	1.78	3.11	0.4	3.5	0.36	4.24	0.637
36	5.5	0	0	1.81	3.07	0.4	3.48	0.22	2.67	0.632
37	5.5	0	0	1.75	3.05	0.47	3.52	0.52	6.03	0.64
38	5.5	0	0	3.11	0	0.79	0.79	6.13	32.54	0.144
39	5.5	0	0	2.15	2.3	0.82	3.12	0.41	5.15	0.568
40	5.5	0	0	1.35	3.5	0.46	3.96	0.19	2.55	0.72
41	5.5	0	0	3.47	0	1.56	1.56	1	7.09	0.284
42	5.5	0	0	1.82	2.78	0.66	3.43	2.35	25.49	0.624
43	5.5	0	0	3.32	0.01	1.81	1.81	0.56	5.56	0.33
44	5.5	0	0	1.7	3.03	0.56	3.59	0.55	6.98	0.653
45	5.5	0	0	0.95	4.05	0.31	4.36	0.56	6.69	0.793
46	5.5	0	0	1.4	3.21	0.68	3.89	0.51	5.82	0.708
47	5.5	0	0	1.05	3.94	0.32	4.26	0.43	5.3	0.775
48	5.5	0	0	2.08	2.14	1.03	3.17	0.88	9.46	0.576
49	5.5	0	0	1.53	3.28	0.47	3.75	0.74	9.11	0.682
50	5.5	0	0	3.3	0.08	1.76	1.83	0.36	3.61	0.334
51	5.5	0	0	1.36	3.51	0.43	3.94	0.48	5.77	0.716
52	5.5	0	0	2	2.63	0.64	3.27	1.06	13.17	0.594
53	5.5	0	0	2.48	1.72	1.06	2.78	0.25	3.28	0.505
54	5.5	0	0	1.34	3.52	0.43	3.95	0.74	8.83	0.718
55	5.5	0	0	2.11	2.32	0.83	3.15	0.89	9.7	0.572
56	5.5	0	0	3.13	0.39	1.61	2	0.79	7.16	0.364
57	5.5	0	0	1.72	3.02	0.55	3.57	0.7	8.78	0.648
58	5.5	0	0	1.93	2.7	0.63	3.33	1.65	19.26	0.605
59	5.5	0	0	1.51	3.14	0.64	3.77	0.57	6.33	0.686
60	5.5	0	0	1.18	3.55	0.58	4.13	0.34	3.85	0.751
61	5.5	0	0	1.86	2.64	0.77	3.4	0.81	8.85	0.619
62	5.5	0	0	1.65	3.07	0.54	3.6	1.83	19.63	0.655
63	5.5	0	0	1.45	3.17	0.64	3.81	2.99	31.09	0.692
64	5.5	0	0	2.99	0.57	1.64	2.21	0.25	2.67	0.401
65	5.5	0	0	1.54	2.94	0.79	3.73	0.72	8	0.679
66	5.5	0	0	2.36	1.63	1.22	2.85	0.55	5.63	0.518
67	5.5	0	0	1.2	3.49	0.6	4.09	0.96	10.62	0.743
68	5.5	0	0	1.42	3.02	0.85	3.86	0.74	8.44	0.703

69	5.5	0	0	2.02	2.13	1.12	3.25	0.35	4.01	0.591
70	5.5	0	0	2.11	2.09	1.07	3.16	0.46	5.33	0.574
71	5.5	0	0	1.28	3.38	0.62	4	0.4	4.42	0.728
72	5.5	0	0	1.89	3.36	0.95	3.36	0.74	7.77	0.611
73	5.5	0	0	2.75	2.47	1.1	2.47	0.91	8.48	0.448
74	5.5	0	0	1.98	2.64	0.45	3.1	3.08	23.39	0.563
75	5.5	0	0	1.77	2.66	0.81	3.47	1.4	14.26	0.63
76	5.5	0	0	2.61	1.17	1.2	2.37	2.27	17.42	0.431
77	5.5	0	0	2.8	1.47	0.63	2.1	0.68	5	0.382
78	5.5	0	0	2.19	2.43	0.48	2.91	2.31	18.4	0.529
79	5.5	0	0	1.79	2.96	0.46	3.42	1.5	14.03	0.622
80	5.5	0	0	2.66	0	0	0	0	0	0
81	5.5	0	0	1.87	2.85	0.5	3.35	0.6	5.9	0.609
82	5.5	0	0	1.85	2.69	0.75	3.44	0.14	1.76	0.625
83	5.5	0	0	3.17	0	1.97	1.97	0.31	3.09	0.358
84	5.5	0	0	3.19	0.24	1.64	1.89	1.01	8.1	0.343
85	5.5	0	0	3.33	0.03	1.81	1.84	0.33	3.75	0.335
86	5.5	0	0	3.34	0	1.83	1.83	0.3	3.48	0.333
87	5.5	0	0	3.33	0.02	1.82	1.84	0.25	2.88	0.334
88	5.5	0	0	1.89	2.43	0.94	3.37	0.52	5.65	0.613
89	5.5	0	0	1.58	2.9	0.78	3.68	2.13	23	0.669
90	5.5	0	0	3.27	0.2	1.59	1.8	1.03	8.19	0.327
91	5.5	0	0	1.7	2.63	0.93	3.56	1.21	13.17	0.647
92	5.5	0	0	3.36	0.02	1.76	1.78	0.41	4.25	0.324
93	5.5	0	0	3.11	1.38	0.48	1.86	0.6	4.77	0.338
94	5.5	0	0	3.52	0	1.16	1.16	2.62	16.17	0.21
95	5.5	0	0	2.23	1.83	1.17	2.99	0.6	6.28	0.544
96	5.5	0	0	3.1	0.49	1.55	2.04	0.8	7.32	0.371
97	5.5	0	0	1.8	2.57	0.9	3.47	0.47	5.12	0.631

Summary Output Table of Results from SWMM Simulation for December 19, 2010 Precipitation Event.

subcatchment	total_precip_in	total_runon_in	total_evap_in	total_infil_in	imperv_runoff_in	perv_runoff_in	total_runoff_in	total_runoff_10_6_gal	peak_runoff_cfs	runoff_coeff
1	6.24	0	0	3.04	0	0.79	0.79	4.08	43.86	0.127
2	6.24	0.57	0	2.6	0	1.06	1.06	7.4	82.39	0.156
3	6.24	0	0	2.07	0	0.96	0.96	8.26	81.97	0.155
4	2.7	0	0	0.89	0.96	0.39	1.35	0.21	5.38	0.502
5	2.7	0	0	0.61	1.49	0.35	1.84	0.05	1.62	0.682

6	2.7	0	0	0.89	0	0	0	0	0	0
7	2.7	0	0	1.18	0.35	0.34	0.69	0.94	17.61	0.256
8	2.7	0	0	1.08	1.17	0.13	1.3	0.13	4.05	0.48
9	2.7	0	0	1.23	0.05	0.69	0.74	0.41	4.42	0.273
10	2.7	0	0	0.8	1.16	0.31	1.47	0.48	13.91	0.544
11	2.7	0	0	0.67	1.37	0.12	1.49	1.36	40.87	0.553
12	2.7	0	0	0.96	0.72	0.5	1.23	0.21	4.74	0.454
13	2.7	0	0	0.86	1.48	0.04	1.52	0.2	7.07	0.562
14	2.7	0	0	0.72	1.29	0.36	1.65	0.25	7.44	0.612
15	2.7	0	0	0.98	1.31	0.06	1.37	0.16	5.68	0.506
16	2.7	0	0	1.06	0.74	0.42	1.16	0.19	4.36	0.43
17	2.7	0	0	0.81	1.19	0.35	1.54	0.24	6.75	0.57
18	2.7	0	0	0.88	1.03	0.35	1.38	0.25	6.92	0.512
19	2.7	0	0	1.23	1.07	0.05	1.13	0.21	7.31	0.418
20	2.7	0	0	1	0.15	0.46	0.61	1.24	13.37	0.226
21	2.7	0	0	0.74	1.59	0.08	1.67	0.08	2.82	0.618
22	2.7	0	0	0.76	1.43	0.22	1.66	0.11	3.41	0.614
23	2.7	0	0	0.62	1.43	0.22	1.65	0.73	23.26	0.611
24	6.24	0	0	1.61	0.05	0.98	1.03	3.83	37.36	0.165
25	2.7	0	0	1.04	0.67	0.47	1.14	0.31	6.77	0.423
26	2.7	0	0	0.84	1.3	0.22	1.52	0.2	6.04	0.564
27	2.7	0	0	1.25	0.34	0.51	0.84	0.37	5.65	0.312
28	2.7	0	0	0.85	1.11	0.29	1.4	1.22	35.64	0.519
29	2.7	0	0	0.71	1.59	0.13	1.71	0.07	2.2	0.634
30	2.7	0	0	1.49	0.72	0.1	0.82	0.05	1.7	0.303
31	2.7	0	0	0.82	1.18	0.38	1.55	0.22	6.32	0.575
32	2.7	0	0	0.98	1.36	0.03	1.39	0.18	6.19	0.516
33	2.7	0	0	1.04	1.3	0.04	1.34	0.27	9.55	0.494
34	2.7	0	0	0.82	1.36	0.16	1.52	0.42	13.58	0.564
35	2.7	0	0	0.92	1.44	0.04	1.48	0.15	5.29	0.547
36	2.7	0	0	0.94	1.43	0.05	1.47	0.09	3.29	0.545
37	2.7	0	0	0.9	1.4	0.07	1.47	0.22	7.52	0.543
38	6.24	0	0	1.42	0.01	1.29	1.3	10.05	91.58	0.208
39	2.7	0	0	1.05	1.08	0.26	1.33	0.17	5.01	0.493
40	2.7	0	0	0.68	1.63	0.13	1.77	0.09	2.84	0.654
41	2.7	0	0	1.55	0	0.42	0.42	0.27	3.36	0.156
42	2.7	0	0	0.89	1.26	0.15	1.42	0.97	31.54	0.524
43	2.7	0	0	1.38	0	0.69	0.69	0.21	2.73	0.257

44	2.7	0	0	0.85	1.4	0.14	1.54	0.24	7.75	0.571
45	2.7	0	0	0.47	1.86	0.08	1.94	0.25	8.63	0.719
46	2.7	0	0	0.63	1.49	0.28	1.77	0.23	7.21	0.657
47	2.7	0	0	0.53	1.83	0.08	1.9	0.19	6.68	0.705
48	2.7	0	0	0.93	0.99	0.39	1.38	0.38	10.18	0.51
49	2.7	0	0	0.78	1.51	0.1	1.62	0.32	10.79	0.599
50	2.7	0	0	1.39	0.04	0.65	0.69	0.14	1.69	0.255
51	2.7	0	0	0.68	1.61	0.1	1.71	0.21	7.08	0.633
52	2.7	0	0	1.01	1.21	0.14	1.36	0.44	14.2	0.502
53	2.7	0	0	1.17	0.81	0.38	1.19	0.11	2.58	0.44
54	2.7	0	0	0.67	1.61	0.1	1.71	0.32	11	0.634
55	2.7	0	0	1.02	1.07	0.25	1.32	0.38	10.95	0.489
56	2.7	0	0	1.33	0.18	0.56	0.74	0.29	3.89	0.275
57	2.7	0	0	0.87	1.4	0.13	1.53	0.3	9.8	0.565
58	2.7	0	0	0.97	1.24	0.13	1.37	0.68	22.24	0.507
59	2.7	0	0	0.72	1.45	0.22	1.67	0.25	7.86	0.617
60	2.7	0	0	0.53	1.65	0.25	1.9	0.15	4.97	0.702
61	2.7	0	0	0.89	1.22	0.24	1.46	0.35	10.51	0.54
62	2.7	0	0	0.83	1.39	0.1	1.49	0.76	25.82	0.552
63	2.7	0	0	0.68	1.43	0.19	1.63	1.28	41.25	0.602
64	2.7	0	0	1.25	0.27	0.69	0.95	0.11	2.18	0.353
65	2.7	0	0	0.68	1.36	0.32	1.68	0.32	9.77	0.622
66	2.7	0	0	1.01	0.76	0.44	1.21	0.23	5.46	0.446
67	2.7	0	0	0.53	1.6	0.24	1.84	0.43	13.9	0.68
68	2.7	0	0	0.56	1.4	0.41	1.81	0.35	10.65	0.67
69	2.7	0	0	0.85	1	0.51	1.51	0.16	4.38	0.558
70	2.7	0	0	0.93	0.98	0.44	1.42	0.21	5.5	0.525
71	2.7	0	0	0.57	1.55	0.24	1.78	0.18	5.73	0.66
72	2.7	0	0	0.83	1.46	0.36	1.46	0.32	8.87	0.539
73	2.7	0	0	1.32	0.93	0.3	0.93	0.34	8.41	0.344
74	2.7	0	0	0.99	1.13	0.03	1.16	1.15	34.84	0.43
75	2.7	0	0	0.81	1.2	0.25	1.45	0.59	17.83	0.538
76	2.7	0	0	1.09	0.54	0.32	0.86	0.82	19.05	0.317
77	2.7	0	0	1.4	0.65	0.05	0.69	0.22	7.33	0.257
78	2.7	0	0	1.12	1.06	0.03	1.08	0.86	28.56	0.402
79	2.7	0	0	0.91	1.31	0.04	1.35	0.59	20.56	0.5
80	2.7	0	0	1.36	0	0	0	0	0	0
81	2.7	0	0	0.95	1.27	0.05	1.32	0.24	8.31	0.49

82	2.7	0	0	0.89	1.26	0.26	1.52	0.06	1.82	0.561
83	2.7	0	0	1.17	0	0.89	0.89	0.14	2.12	0.329
84	2.7	0	0	1.33	0.11	0.54	0.66	0.35	3.94	0.244
85	2.7	0	0	1.39	0.01	0.73	0.75	0.13	2.17	0.276
86	2.7	0	0	1.4	0	0.75	0.75	0.12	2.13	0.279
87	2.7	0	0	1.39	0.01	0.74	0.74	0.1	1.68	0.276
88	2.7	0	0	0.84	1.14	0.35	1.48	0.23	6.34	0.55
89	2.7	0	0	0.7	1.32	0.28	1.61	0.93	28.35	0.595
90	2.7	0	0	1.42	0.1	0.49	0.58	0.33	3.9	0.216
91	2.7	0	0	0.71	1.21	0.39	1.6	0.54	15.54	0.591
92	2.7	0	0	1.44	0.01	0.65	0.66	0.15	1.97	0.246
93	2.7	0	0	1.61	0.61	0.01	0.62	0.2	7.11	0.23
94	6.24	0	0	2.41	0	1.84	1.84	4.16	40.33	0.295
95	2.7	0	0	0.95	0.85	0.44	1.29	0.26	6.35	0.477
96	2.7	0	0	1.34	0.23	0.52	0.75	0.29	4.11	0.278
97	2.7	0	0	0.8	1.2	0.34	1.54	0.21	5.96	0.571

Appendix G

Runoff Ratio Summary Tables

Summary Runoff and Imperviousness Results for the December 19, 2010 Precipitation Event.

Minimum Runoff Coefficient	Maximum Runoff Coefficient	Median Runoff Coefficient	Minimum Impervious Runoff (in)	Maximum Impervious Runoff (in)	Median Impervious Runoff (In)	Minimum Pervious Runoff (in)	Maximum Pervious Runoff (in)	Median Pervious Runoff (in)
0	0.793	0.594	0	4.05	2.51	0	1.97	0.76

Summary Runoff and Imperviousness Results for the March 14, 2009 Precipitation Event.

Minimum Runoff Coefficient	Maximum Runoff Coefficient	Median Runoff Coefficient	Minimum Impervious Runoff (in)	Maximum Impervious Runoff (in)	Median Impervious Runoff (In)	Minimum Pervious Runoff (in)	Maximum Pervious Runoff (in)	Median Pervious Runoff (in)
0	0.719	0.507	0	1.86	1.16	0	1.84	0.28

Appendix H

Summary of Tools and Github link for R codes

Spatial analysis was done with ArcGIS and ArcGIS Pro. The spatial analyst license (purchased) as well as the Arc Hydro toolset (free) are required. R and R Studio (both open source data analysis software) were used to clean data and run statistical and numerical analyses. All data were exported to a .csv format for input into SWMM. Google Earth was used to compare intermediate outputs such as surface imperviousness to satellite imagery.

R codes are included in this document in Appendix J. The Github link for R codes:
https://github.com/nataliedornan/Kahuwai

Appendix I

Project Protocols

i. Precipitation Data Protocol

Author: Natalie Dornan

EPA SWMM requires precipitation data from the region of interest to simulate runoff and flow from storm events. The software allows for multiple rain gages and precipitation events to be applied to the model to better predict hydrography. While the model has the capacity to run long simulations over multiple months, for our model we chose 2 year, 24-hour storm events that lasted between 11 and 24 hours. We obtained data from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information Climate Data Portal. We chose data that was sampled at 15-minute intervals to capture the varying levels of rainfall throughout the small storm events. Currently, the Maunalua Bay region has 2 long term datasets with 15-minute interval data, one in the Wailupe watershed and the other in Hawai'i Kai. For the purposes of developing SWMM for the Maunalua Bay region, we decided to run preliminary simulations in the Wailupe watershed using data from gage COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US). However, it is important to note that there is a large gradient in rainfall from the upper watershed at ~1,000ft to the lowest part of the watershed at the shoreline. As such, further data regarding the geospatial differences in rainfall for the watershed are recommended. Currently, the Rainfall Atlas of Hawai'i is an excellent source to find rainfall values in data limited regions. To account for discrepancies in runoff volume one could adjust raw data to account for the differences in other parts of the watershed, however it would be best to install multiple rain gauges at multiple elevations for accuracy. An additional important factor when choosing storm events to run in SWMM is that the precipitation data needs to be paired with stream gage data to facilitate in model calibration. This protocol will cover the process involved in selecting, downloading, preparing, and inputting precipitation data into SWMM for this project.

Data Source

The National Oceanic and Atmospheric Administration, National Centers for Environmental Information. Climate Data online: Dataset Discovery
Metadata: Precipitation Metadata

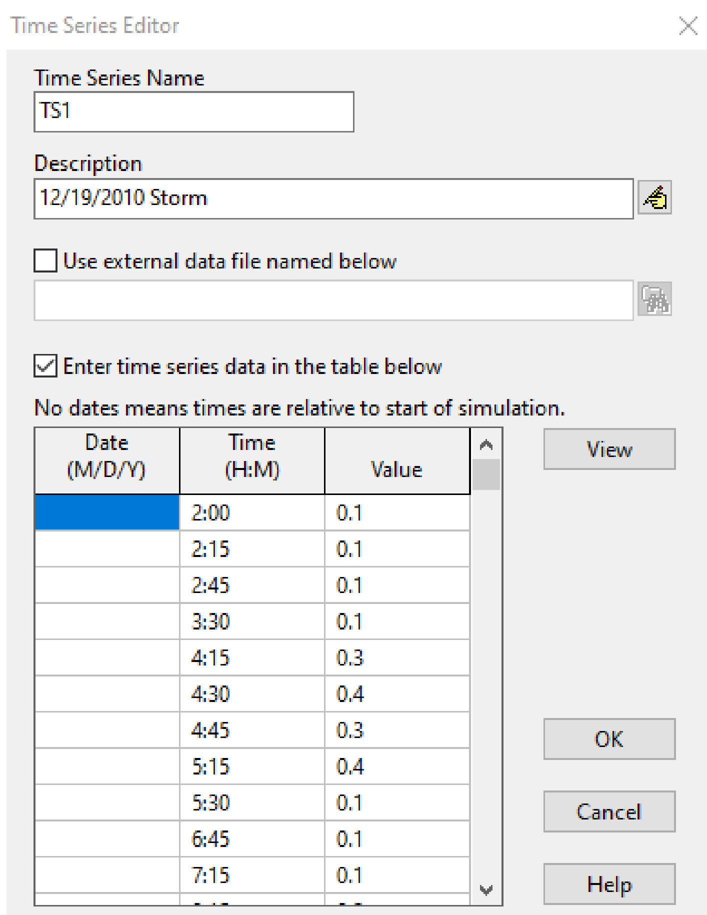
For this project, we submitted a request for 15-minute precipitation data for stations COOP:519500 (WAILUPE VALLEY SCHOOL 723.6 HI US) and COOP:511308 (HAWAII KAI G.C.724.19 HI US).
Data Types = QGAG and QPCP
Units = Standard
Custom Flags = Station Name, Include Geographic Location, Include Data Flags
File type = .csv

Protocol

1. Submit an online data request through the Dataset Discovery Portal with appropriate parameters selected (see above). Once email with data has been received, download to computer, and place it in a file to load into RStudio.
2. Data was uploaded and prepared entirely in R Studio for reproducibility. See Appendix for the RMarkdown annotations and code for further detail.
3. Once uploaded, precipitation data was explored and processed using R packages tidyverse, lubridate, and tseries.
4. Data processing involved the following steps:
    a. Removal of all NaN values and flagged data to ensure data integrity.
    b. Transformation of 15-minute intervals into daily intervals to better visualize precipitation patterns and compare with USGS stream discharge data.
    c. Plotting of data time series to verify patterns and total volume with local news articles.
    d. To further determine the periods with the most data points, data were explored by finding the number of days per year with the most data points.

e. Once the year with the most data had been determined, the data were replotted for that year to observe patterns and locate a representative storm to then pull 15-minute data from to feed into SWMM.

5. Once a storm with 15-minute data had been selected, the data frame was exported as a .csv file to then be input into the SWMM rain gauge. The rain gauge contains appropriate geospatial information (XY coordinates) so that it may be placed appropriately in the model's watershed. NOTE: It is okay if the storm you select does not have every 15-minute interval over the entire storm period.

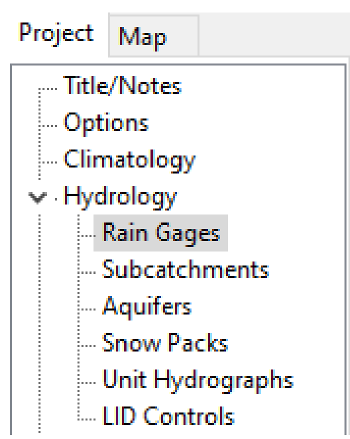


6. To input the data into SWMM, two primary steps need to be taken: creating a rain gage in the same location of the gage that collected data, and creation of a time series for your precipitation data.

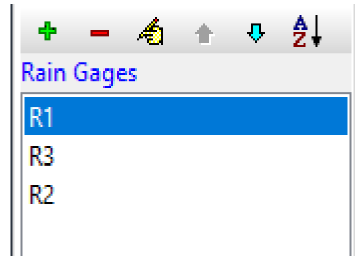
Time Series

1. Select the "Time Series" tab in the Project menu.
2. To create a new rainfall time series, click the green plus sign at the bottom of the Project menu.
3. Input time series name and a short description. You have the option to use an external file or enter the time series manually. For storms that fall over a single day, you do not need to input a date.
4. Once you have finished inputting your time points and values, click "OK".

Rain Gages



1. Select the "Hydrology" tab in the Project menu.
2. Click "Rain Gages".
3. To create a new Rain Gage, click the green plus sign at the bottom of the Project menu.
4. Select the area in the model that you would like to place the gage and click to drop the gage there.
5. Select the new gage and click the edit symbol to add information to the gage.
6. Here, you can add information such as gage name, XY coordinates, rain format, time interval, data source, and time series.
   a. Rain Format = VOLUME
   b. Time Interval = 0:15



c. Data Source = TIMESERIES
d. TIME SERIES - Series Name = time series you choose to associate with the rain gage
e. Data File - Rain Units = IN (inches)
f. Exit to save information

ii. Subcatchment Delineation

Author: Tara Jagadeesh

SWMM requires that the watershed of interest be divided into smaller "subcatchments" between which water and pollutants flow. Subcatchment delineation traditionally involves separating parts of a watershed based on the direction that water flows down a topographic gradient. Although this method is widely used across natural watersheds, delineating urban catchments poses a challenge. In urbanized watersheds, the natural topography is altered such that water no longer simply flows according to topography but is also directed by infrastructure such as roads and pipes. The watersheds of Maunalua Bay are distinctly divided between these two characteristics, with vegetated land in the upper regions and urban land in the lower regions. Because our goal is to determine where in the built landscape green infrastructure should be placed to return the greatest reduction in pollutant loading, we decided that a higher resolution of subcatchments was required for the urban areas. Therefore, we combined several different delineation methods.

Upper watershed

The upper region of the watershed has a very steep topographic gradient with well-defined peaks and valleys. There is no urban development here, so water flows entirely based on topography and vegetation. For these areas, we used subcatchments that had been previously delineated by the USGS National Hydrology Dataset using standard flow direction methods with ArcGIS Spatial Analyst Tools. In the case that watershed boundaries do not already exist, this can be done manually by:

1. Fill sinks in the cropped DEM (Spatial Analyst - Fill).
2. Generate a flow direction raster (Spatial Analyst - Flow Direction).
3. Create basins form the flow direction raster (Spatial Analyst - Basins).
4. Create the watershed boundaries from the basins raster (Raster To Polygon).

Lower watershed

The lower region of the watershed looks quite different from the upper region. Except for the steady downward slope, the region is almost entirely flat. Water is instead directed by roofs, driveways, roads, and underground pipes. Traditional methods of delineation are therefore unsuitable. To address these differences, we looked to other urban watersheds and combined two different methods.

1. Delineation by DEM reconditioning

DEM data is available for the island of O'ahu at a resolution of 10m. While this is adequate for traditional methods of delineation, it is unable to capture at a finer scale the urban infrastructure that directs flow. Using these methods thus requires reconditioning the DEM to consider the built environment. This entire process was built into a single ArcGIS model, but below is an overview of the steps we used for the first iteration of urban subcatchment delineation

<u>1) Establish the stormwater network:</u>

Before the DEM can be reconditioned, the stormwater infrastructure must be connected as an entire network. This requires combining the conduit, stormwater structures, and streams data. Because the conduit data does not perfectly align with streams data, the network was manually edited to join conduit outfalls to the stream. Furthermore, some parts of the stormwater network were missing (such as “floating” conduits which did not connect to the greater system). We manually reconnected those pipes that we could easily verify the existence of (either through having visited the sites in person, or by using Google Earth). All editing was done using the ArcGIS topography and editor tools.

<u>2) Fill sinks (Spatial Analyst – Fill Sinks)</u>:
Standard methods of watershed delineation follow a process which involves filling sinks in the DEM. This can be done using ArcGIS tool “fill sinks.” This step reduces the potential for water to pool and get trapped in imperfections within the DEM. Traditionally, this step is performed first before any additional analyses are done on the DEM. However, we decided to fill the sinks before reconditioning the DEM due to the problem of this tool treating parts of the stormwater network in the reconditioned DEM as sinks. Filling sinks prior to reconditioning prevented the tool from creating gaps in our network.

<u>3) Burn the stormwater network into the existing DEM (ArcHydro – DEM Reconditioning)</u>:
Because the original DEM does not consider infrastructure, our next step was to recondition the DEM with our stormwater network. This essentially means decreasing the elevation of areas where infrastructure exists so that water now flows into these depressions. We reconditioned the DEM with our network using the ArcHydro tool “DEM reconditioning.” Due to the complexity of the urban environment, we considered only pipes and streams in this analysis. Roads and roofs likely also impact the flow of water; however, because this water inevitably ends up in the nearby stormwater infrastructure, we accepted this simplification.

<u>4) Run the standard delineation tools</u>:
Once the DEM was reconditioned to consider the urban environment, we were able to re-run the tools used in the standard watershed delineation. As previously mentioned, we filled sinks before reconditioning the DEM. Therefore, the next steps were:

1. Generate a flow direction raster (Spatial Analyst - Flow Direction).
2. Create basins form the flow direction raster (Spatial Analyst - Basins).
3. Create the watershed boundaries from the basins raster (Raster To Polygon).

The output for this was a series of smaller subcatchments that were primarily concentrated around the stormwater network, which is what we expected.

<u>5) Merge subcatchments</u>:
The final step of this process was to evaluate the subcatchments that the model created and merge those that were determined to be at too high of a resolution. This was largely done visually by re-grouping catchments that were part of the same stormwater network branch but for which the model determined were separate. This final step gave us a preliminary delineation of urban subcatchments.

Overview of this process:

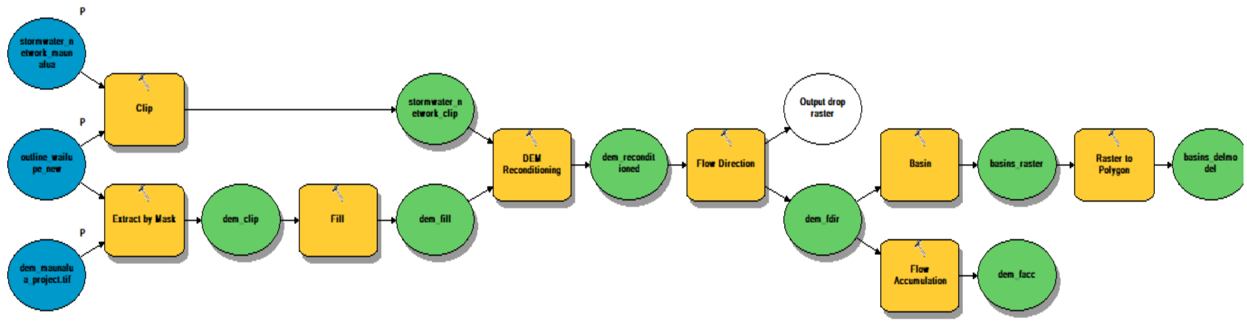


Figure 1: Delineation by DEM reconditioning ArcGIS model

The standard delineation method using a reconditioned DEM outlined above was sufficient to delineate most of the urban regions of the watershed. However, in some areas these tools were insufficient to delineate subcatchments into the smaller size that our analysis in SWMM requires. For these regions, we decided to use a different method to delineate further.

2. Delineation by polygons

This method was modeled after the approach of the Pennsylvania Department of Environmental Protection ("Consideration in Using GIS"). In this approach, inlets for water into the sewer system are treated as separate polygons for which water can flow into. Subcatchments are then defined as the area that drains into a specific polygon. We used this approach to increase the resolution of subcatchments in particular areas of the watershed for which the previous method was insufficient. A second ArcGIS model was built to automate this process.

1. Define inlets in the regions of interest as polygons.
2. Run the "batch watershed delineation by polygons" ArcHydro tool using the reconditioned DEM. This tool relied again on the reconditioned DEM which considers the stormwater network.

Overview of this process:

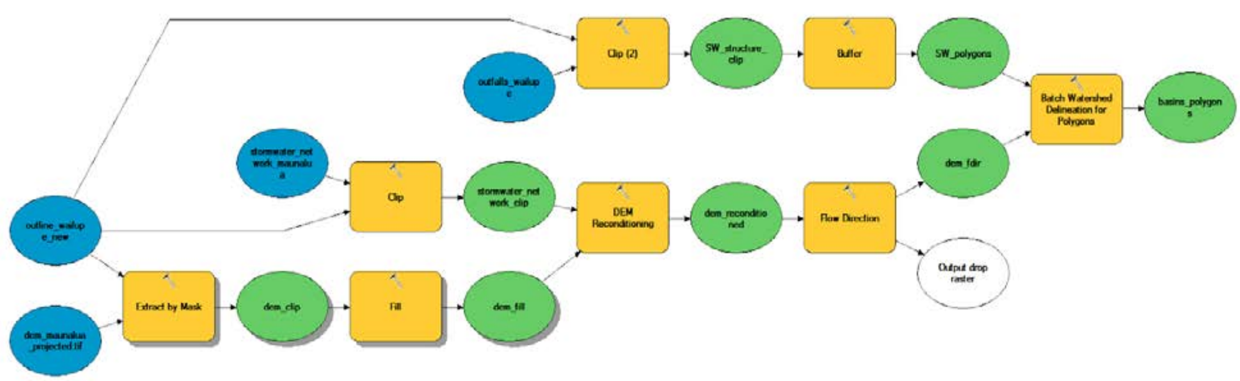


Figure 2: Delineation by polygons ArcGIS model

After subcatchments were delineated, we performed this analysis on the entire watershed to cross check its accuracy with the first method. Watersheds were delineated within similar boundaries for each method, albeit at a higher resolution for this second method. This finding allowed us to continue using these smaller subcatchments with greater confidence.

Final subcatchment processing

Once all three methods for delineation were complete, we combined the subcatchments into a single layer suitable for further analysis. To merge, we used the union and the merge tools -they will give you similar outputs- and did it one layer at a time. Note that this will likely create duplicates of subcatchments as you merge the layers. We manually went in and deleted duplicate subcatchments, or readjusted boundaries. The result does have gaps in between subcatchments, but these gaps are too small to have an influence on the result from SWMM.

We performed this entire analysis for the Wailupe watershed. Although the original Wailupe watershed boundary extended further West, we altered this outline to better account for the built stormwater network. Our new outline included only those subcatchments which were not cut off by the original boundary and that drained specifically into Wailupe outfalls.

Additional processing of the finalized subcatchments layer was necessary to input the data into SWMM. First, the vertices of the GIS shapefile were converted to points. XY coordinates were then added to the points by using the "calculate geometry" function in ArcGIS. The final table was exported as .csv to transfer the data into the appropriate SWMM input file.

iii. Subcatchment Hydrology Characteristics

Author: Eleonore Durand

SWMM requires several characteristics for each subcatchment to simulate runoff. Some of these characteristics that we calculated for each subcatchment are percent impervious cover, soil curve number, and slope. Each of these influences either the volume or velocity of runoff. This protocol explains how we calculated percent impervious cover, soil curve number and slope and should be used only after you have delineated subcatchments.

Percent Impervious Cover

1. Navigate to an open data layers for buildings & rooftops, roads, and bike paths.
2. Create a union for the layers.
3. Check between google earth and your resulting layer to see if you missed any large impervious area. If so, you can add polygons with the create a polygon tool in the editor tool.
4. Ensure your layer is a polygon layer.
5. Using the table intersection tool in ArcGIS with the impervious layer and the subcatchment layer, compute the percent impervious cover of each subcatchment.

Soil Curve Number

1. Intersect the soil layer with the land use layer to obtain both land cover and soil hydrologic group in one layer in ArcGIS.
2. Export attribute table to excel.
3. Visualize hydrologic conditions of various land cover using Google Earth and decide good versus fair conditions.
4. Pair each land cover with corresponding land cover in NRCS' curve number table (see above)
5. Check the drainage conditions for the dual soil groups: if adequately drained they get the first letter, if not they remain "D"
6. Use R and write a series of "case_when" code to attribute the correct curve numbers by soil hydrologic groups and land cover type (see table and code)
7. Export new table to ArcGIS.
8. Using the Table Intersection tool in ArcGIS, pair the soil curve numbers with the subcatchment layer that you have created previously (see subcatchment how to). This will compute a percentage of a curve number for each subcatchment.
9. Export that table to R and do a weighted mean by subcatchment to choose 1 curve number for each subcatchment. You can then export that table back to ArcGIS for further analysis or use it directly as the model input table.

10. Note that we have computed soil curve numbers for an average number of antecedent dry days. If the storm that you are inputting in the model has a higher number of antecedent dry days, then you would increase all curve numbers by 15. If the storm has a low number of antecedent dry days, then you would lower all curve numbers in the subcatchments by 15.

Table 1. Soil Curve Numbers by Land Cover and Hydrologic Groups found in the Maunalua Bay Region, O‘ahu.

Land Cover	Hydrologic Group A	Hydrologic Group B	Hydrologic Group C	Hydrologic Group D
Grassland: poor condition	68	79	86	89
Unconsolidated shore	0	0	0	0
Bare Land/Bare soil	77	86	91	94
Open Space Developed- good	39	61	74	80
Evergreen forest- fair	36	60	73	79
Scrub Shrub	36	42	55	62
Open Water	0	0	0	0
Impervious surface- like shrubland	36	42	55	62
Palustrine Scrub Shrub wetland (woody wetland)	86	86	86	86
Palustrine Forested wetland (woody wetland)	86	86	86	86
Palustrine Aquatic Bed	NA	NA	NA	NA
Estuarine Emergent wetland	80	80	80	80
Palustrine emergent wetland	80	80	80	80
Pasture/Hay	40	61	73	79
Unclassified - here: open water	0	0	0	0
Cultivated Land	62	74	82	86

Slope

1. Using a DEM layer, you can use the slope tool in ArcGIS to calculate the slope (note, this can be time consuming for your computer).
2. Convert the DEM layer to a polygon layer.
3. Using the Table Intersection tool, pair the subcatchment and slope layers to compute a percentage of different slopes for each subcatchment.
4. Export that table to R and do a weighted mean by subcatchment to calculate one average slope for each subcatchment. You can then export that table back to ArcGIS for further analysis or directly put in the slopes in your input table for SWMM.

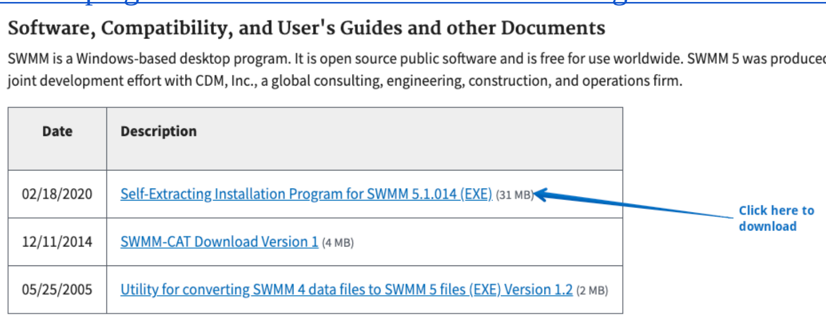
iv. SWMM Setup and Input File Preparation

Author: Erica Johnson

To analyze the hydrology of the Maunalua Bay Region, we used the U.S. Environmental Protection Agency (EPA) Storm Water Management Model 5.1 (US EPA, 2019 [SWMM 5.1.013]). SWMM is an open source tool that is available for download with associated manuals from the EPA's online platform. SWMM requires stormwater network data to properly simulate and route runoff. The three elements of the stormwater network (conduits, structures, and streams) exist as separate data files and are obtained from the City and County of Honolulu public database. For the model to run, these elements must be connected to each other in the model platform as they would in reality. Although the stormwater network was established in subcatchment methods, additional processing was necessary for SWMM-specific inputs.

SWMM Setup

In this protocol you will find instructions on how to set up the model, and the default settings and model equations we decided to use.

1. Download Storm Water management Model from the EPA website below: https://www.epa.gov/water-research/storm-water-management-model-swmm
    a. 

    Software, Compatibility, and User's Guides and other Documents

    SWMM is a Windows-based desktop program. It is open source public software and is free for use worldwide. SWMM 5 was produced in a joint development effort with CDM, Inc., a global consulting, engineering, construction, and operations firm.

Date	Description
02/18/2020	Self-Extracting Installation Program for SWMM 5.1.014 (EXE) (31 MB)
12/11/2014	SWMM-CAT Download Version 1 (4 MB)
05/25/2005	Utility for converting SWMM 4 data files to SWMM 5 files (EXE) Version 1.2 (2 MB)

    b. Please note that it is only PC compatible.
2. Open SWMM 5.1 and from the menu at the top of the SWMM program window, select File, then New to create a new project.
3. It is recommended for ease of use to add the Excel program as a tool in the model. From the menu at the top of the SWMM program window, select Tools, then Configure. Type in the tool name (Excel) and select the Excel program from your computer.
    a. See SWMM 5.1 user manual for more detailed steps.
    b. Next, we will select project defaults for the model.
4. In the menu at the top of the SWMM program window, select Project, then Defaults to open the Project Defaults dialog.
5. In the ID Labels tab, input the following:
    a. Rain Gages = R
    b. Subcatchments = S
    c. Junctions = J
    d. Outfalls = O
    e. Dividers = D
    f. Storage units = SU

g. Conduits = C
h. Pumps = P
i. Regulators = R
j. ID Increment = 1

6. In the Subcatchments tab. Input the following:
    a. Most values will come from GIS layers or soil analysis (Area, Width, Slope, Imperv,), but other defaults, if not provided, are:
    b. Area = 100
    c. Width = 100
    d. Slope = 25
    e. Imperv = 25
    f. N_Imperv = 0.01
    g. N_Perv = 0.15
    h. S_Imperv = 0.2
    i. S_Perv = 0.3
    j. PctZero = 0
    k. RouteTo = "OUTLET"
    l. CurveNum = 80
    m. DryTime = 7
    n. Infiltration model = Curve Number
7. In the Nodes/Links tab, input the following:
    a. Most values will come from GIS layers or R code.
    b. Conduit Geometry
        i. Barrels = [leave blank]
        ii. Max. Depth = 0
    c. Conduit Roughness = 0.01
        i. Cross section
        ii. Open Rectangular
        iii. Width = 30 ft
        iv. Depth = 10 ft
    d. Flow Units = CFS
    e. Link Offsets = DEPTH
    f. Routing Model = Dynamic Wave
    g. Force Main Equation = Darcy-Weisbach
8. Save and close your project.
9. With the Excel tool, you will be able to Right click you project file, select “Open with” from the menu, then select “Excel”. You should be able to see the input file in excel form.

   a. Alternately, your input file may have been saved separately from your project file. The excel file will have the same name as your project file and can be opened using excel.
   b. Any changes made to the input file will be reflected in your project file.

10. Notes on decisions made for model defaults:
    a. Infiltration Model: We chose curve number because curve number is widely used for hydrologic models because they are empirical and widely available.
    b. Routing Model: We chose the dynamic wave model because its equations produce the most theoretically accurate results because it can account for pressurized flow in closed conduits, flooding, ponding, and backflow, as opposed to the simpler routing models available.
    c. Main Equation: Darcy-Weisbach equation was used because it can relate head loss to velocity due to friction in the long conduits that characterize our region.
    d. Depression storage: Values can be provided from EPA SWMM 5.1 Manual p. 182, table A.5, however we found that our model hydrograph peaks follow the observed data more closely when both values are set to 0.
    e. N (Manning's n for roughness): Values are provided from the EPA SWMM 5.1 Manual p. 182, table A.6 for overland flow, p. 183, table A.7 for conduits
    f. Max Depth is 0 because we do not have that information for stormwater structures.
    g. Barrels: the number of barrels (i.e., number of parallel pipes of equal size, slope, and roughness) associated with a conduit (default is 1), see EPA SWMM 5.1 Manual p. 312. We did not observe many barrels in this system, so defaulted to leaving that column "blank".
    h. Route To: for subcatchments with any urban infrastructure, select "OUTLET". For natural subcatchments with a gradient toward urban subcatchments, select "PERVIOUS".

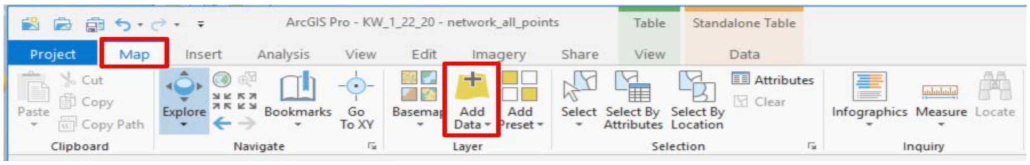
SWMM Input File Preparation (ArcGIS and R Processing)
In this protocol you will process data from map layers using the ArcGIS tool, and export these data into CSV files that can be further processed into the format necessary to run SWMM.

Tools:

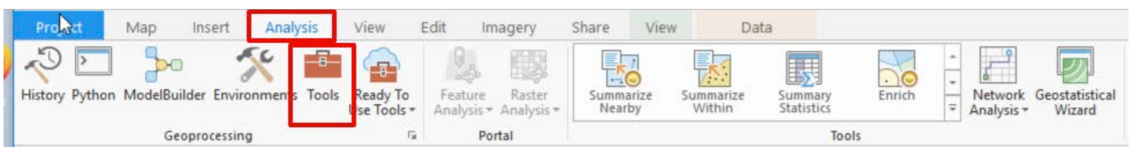
- ArcGIS Pro
- R with RStudio

Protocol (Arc GIS Processing):

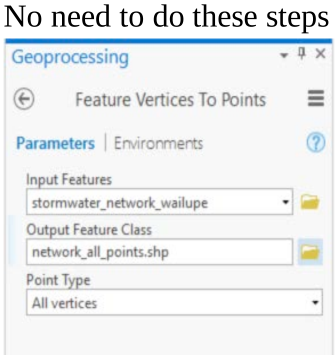
1. In ArcGIS Pro, add the data layers from the Subcatchments methods. In the menu at the top of the screen, click the “Map” tab, then click the “Add Data” button. This will open up a file browser window where you can select what layers to import to a new project.

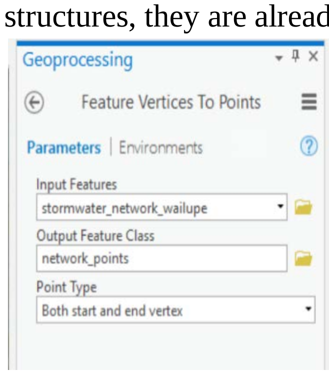


2. After importing all the data layers, we will use the tools in the program. To get to tools, click the “Analysis” tab in the upper menu, then click the “Tools” button. You should be able to use a search menu to find the tools you need.

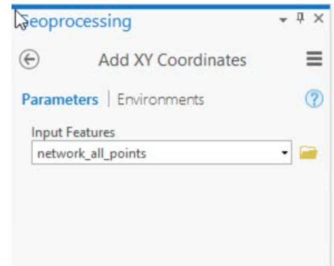


3. To convert the stormwater network (streams and conduits) and subcatchments to points by using the **Feature Vertices to Points** tool.
    a. In the tool menu, select your input feature (stormwater network or subcatchments) and provide the file location and name for the output feature.
    b. Under point type, select “Both start and end vertex” for the stormwater network for the first layer, then click “Run”. Then repeat the step and select “All vertices” for the next layer and click “Run”.
    c. Under point type for subcatchments, select “All vertices”, then click “Run” at the bottom of the tool.
    d. You will have new layers whose shape is outlined by points.
    e. No need to do these steps for structures, they are already points.

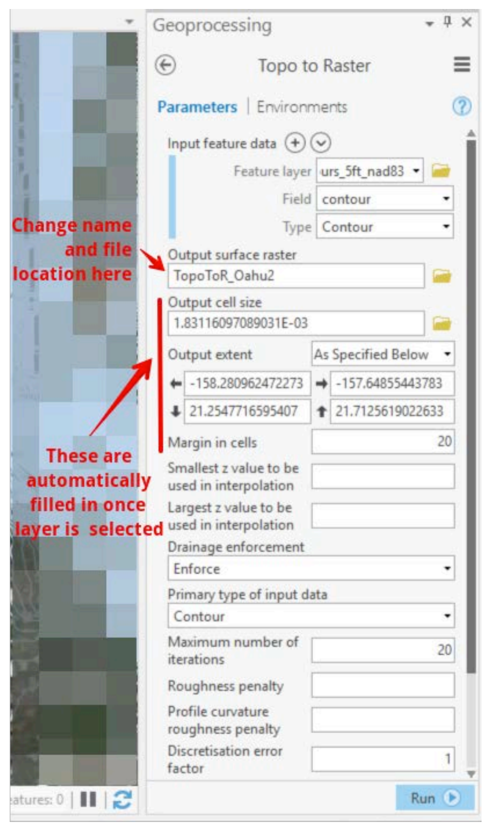




4. Get latitude and longitude (XY) coordinates for the stormwater network, structures, and subcatchment points. Make sure your map is set to degrees. Use the **Add XY Coordinates (Project Management)** tool.

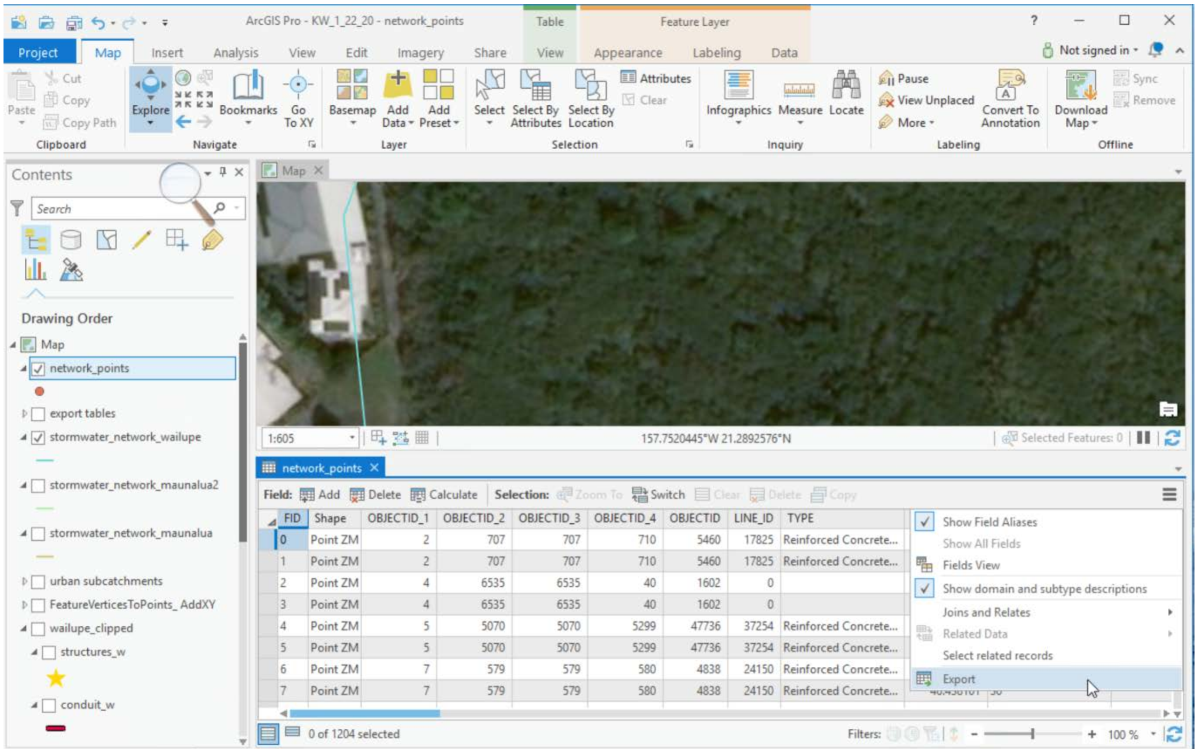


   a. Select your input feature (stormwater network endpoints, stormwater network vertices, or subcatchments), then click "Run" at the bottom. Repeat for each feature layer.
   b. This will not add new layers to your map, but just information in each layer's attribute table.
5. Add elevation and subcatchment to the attribute table of each feature. To do this, add the 5ftContour topographic layer (or other high resolution layer) and the subcatchments layer from the subcatchments protocol to your map.
6. Convert the 5ftContour topographic layer to a raster layer by using the **Topo to Raster tool**.
   a. Select the 5ftContour file as the input file, select an output file location and name, match contour to contour, then click "Run".
   b. You will have a new raster layer for the 5ftcontour map.
7. Convert the subcatchments layer to a raster layer using the **Polygon to Raster** tool.



8. Extract elevation and subcatchment values to your feature points for your stormwater network by using the **Extract Multi Values to Points** tool using the new raster layers.
   a. Select your stormwater network end point as input point features, then select your 5ftContour raster and your subcatchments raster as your input raster layers.
   b. You can name the columns "elevation" and "subcatchment" at this point.
   c. Check the interpolate values at point locations box, then click "Run".
   d. You will have a two new column in your attribute table.
9. We would like to identify stormwater structures that are outfalls for specific conduits. To do this, we will join Structures to Conduits by Spatial Join which will use the XY coordinates to match structures to conduit endpoints (stormwater network endpoints file).
   a. Right click the stormwater network endpoints layer, select **Joins and relates**, then select **Spatial join**.
   b. Select your Target feature (stormwater network endpoints file), and your Join feature (stormwater structures), then choose a file location and name.
   c. For the Join operation, select Join one to one.
   d. For the Match Option, select Intersect, then click "Run".
   e. You will have a new layer.
      i.

10. Export csv files of all layers you have processed.
    a. Right click each layer, then click “Attribute table”.
    b. Click the menu (three lines) on the upper right corner of the attribute table and select Export. Add a “.csv” to the end of the file name for the output file to be a csv.
    c. These files will be wrangled into the appropriate format for SWMM.



Protocol (R Processing):

1. Files exported from the attribute tables of the map layers via ArcGIS are ready to be processed using the annotated R codes found in the group project GitHub repo: https://github.com/nataliedornan/Kahuwai.
2. Compile the code output files into one file, with the appropriate headers. This file will be the input file for SWMM.
3. The code is pasted into this protocol for ease of reference.

SWMM Processing

In this protocol you will open the SWMM input file, then copy and paste the data you have organized through processing files in R. Once those data have been pasted into the input file and saves, you will open the SWMM file and manually correct some of the imperfections in the stormwater flow routing network.

1. When preparing files for SWMM, they should be in the same format found in the input (.inp) file (or see the SWMM the manual). Files were prepared in RStudio, for which

there is a script to wrangle data into the SWMM format. Please see the group project GitHub repo: **https://github.com/nataliedornan/Kahuwai** for annotated code methodology in each subsequent category.

2. Subheadings usually only appear in the input file when it is drawn in the model interface first. Examples of headings for each category are provided in the code files and must be manually included in the input file if not already provided in the input file. Values go under the dashed lines in their respective columns.
    a. Example:
    b. [JUNCTIONS]
    c. ;;Name Elevation MaxDepth InitDepth SurDepth Aponded
    d. ;;---------- ---------- ---------- ---------- ---------- ----------
3. To input data into the SWMM input file (.inp), use the excel backend tool.
    a. From the menu at the top of the SWMM program window, select Tools, then Configure. Type in the tool name (Excel) and select the Excel program from your computer. See SWMM 5.1 user manual for more detailed steps.
    b. Save and close the file on your computer.
    c. Find the SWMM file in your computer files. Right click SWMM file, select "Open with", then click "Excel".
    d. In the excel file you can copy and paste data from each of the files provided from R codes under the appropriately formatted subheading annotated in the R code.
    e. Entries that are meant to be left blank are populated with an "NA" which is equivalent to a "blank" in R. When pasting code into the input file, be sure to remove the "NA" text and leave the column blank.
    f. Save the file, close, and re-open SWMM. The data should have been saved into the backend file and are now usable in the model front end.
4. Once data is in SWMM, there are a few things that must be completed manually. Open the SWMM file.
5. The channelized stream in the lower urban subcatchments needs to be connected to stormwater infrastructure by junctions/nodes.
    a. Although it may already look connected, the conduit path may overlap junctions without actually being connected
    b. It is advisable to draw the conduit manually in SWMM, junction to junction and can be done fairly quickly following the conduit path provided in the R code. Be sure to delete the initial conduit after tracing its pathway.
6. Connect each subcatchment to its appropriate rain gage. The Hawaiian Rain Atlas from the Precipitation methods can help with assigning subcatchments to rain gages
7. Some subcatchments will need to be manually connected to a junction/node or other subcatchment to route the subcatchment flow to. Double click on the subcatchment. On the menu that appears, type in the junction/node name you would like for it to route flow to.

   a. In some instances, a subcatchment in the forested region will have no conduits. You can use a different flow routing method for this by double clicking the subcatchment and in the menu specify “PERVIOUS” as the routing method.
   b. Then select a subcatchment to route flow to instead of a junction/node.
8. Correct any “backwards” flow directions. You can enable flow direction arrows to display on conduits. We are using surface elevation and opposed to invert elevation (a data limitation), so there may be a few conduits which direct flow in the wrong direction.
   a. In this system flow is usually directed toward the stream and then toward the ocean.
   b. If you notice a flow arrow going the wrong direction, do not simply reverse the flow. Either remove the link and draw one that simulates the appropriate flow direction or remove the link and any link up stream if it is at the fringes of the system.

viii. Model Calibration

Author: Natalie Dornan and Eleonore Durand

As with any hydrologic model, once all data has been input appropriately it will need to be calibrated to optimize the hydrograph for accuracy. SWMM allows for the upload of multiple types of calibration data for comparison against simulated results. For this project, we utilized stream discharge data from the USGS station 16247550 (Wailupe Gulch at E. Hind Dr. Bridge) for model calibration. The data for this stream gage was downloaded from the USGS National Water Information System. Discharge data was filtered and processed to match the appropriate storm duration, saved as a text document with the associated conduit link name where the real gage is located, and uploaded into SWMM by clicking “Project” > “Calibration Data” > “Link Flow Rate”. Once the calibration file is uploaded and a simulation is ran, you can navigate to the associated conduit or link with the calibration file and compare the simulated results with the actual results.

Once you have the initial hydrograph, you can proceed to adjust other parameters in the model for a better fit. The most sensitive parameters that our project identified for SWMM related to subcatchment characteristics and included: Subcatchment Width, Infiltration, and Manning’s N for impervious and pervious surfaces. Ultimately, it is largely up to the model’s operator which calibration methods are to be used.

For the calibration of our model, we manually calculated the subcatchment widths as per SWMM guidelines by dividing the subcatchment area by the length of the longest flow path. However, it has been found that there is a strong positive relationship between subcatchment width and total runoff. As such, it has been suggested by other users that the subcatchment width values be capped at 400 ft, which was done for the purposes of our calibration.

Furthermore, curve numbers can change depending on antecedent weather conditions. As such, we accounted for this by adjusting the curve number appropriately after investigation of the conditions leading up to the storm event.

For the last calibration parameter, Manning’s N for pervious surfaces was adjusted based on subcatchment characteristics. If the subcatchment was more natural and vegetated, a higher Manning’s N (0.4) was applied to that subcatchment. Conversely, if a subcatchment was largely impervious with some landscaped vegetation, the Manning’s N was lower (0.15).

Appendix J

R Codes

i. Stormwater Infrastructure Network

This page was left blank intentionally.

Precipitation Data

This is code to explore and tidy precipitation data downloaded from the NOAA National Center for Environmental Information website for rain gauges in Wailupe watershed, Maunalua Bay Region

Natalie Dornan

March 12, 2020

NOTE: Figures will be hidden from knitted markdown.

Code setup

```
##Load Packages
library(tidyverse)
library(lubridate)
library(stringr)
library(tseries)

## Read in files
## These are the original datasets downloaded from NOAA NCEIS.
## Wailupe and Hawaii Kai are 15 min data sets, 77 and 08 indicate
## from which years the data encompasses.
rain_dat_77 = read.csv("NOAA_WailupeHawaiiKai_77.csv")
rain_dat_08 = read.csv("NOAA_WailupeHawaiiKai_08.csv")


##Use lubridate to clean up the dates and times
rain_dat_77$DATE <- ymd(rain_dat_77$DATE)
rain_dat_08$DATE <- ymd(rain_dat_08$DATE)
```

Data Tidying

Tidy up the data to make it a little easier to work with. This code creates a new dataframe from the orifical dataset. Here we are only looking at the Wailupe gauge. Columns were renamed and data was filtered to remove flags.

```
wailupe_tidy_77 <- rain_dat_77 %>%
  rename(station = STATION, station_name = STATION_NAME, elevation = ELEVATION,
         lat = LATITUDE, lon = LONGITUDE, date = DATE, time = TIME, qgag = QGAG,
         qgag_flag = Measurement.Flag, qgag_qual = Quality.Flag, qgag_units = Units,
         qpcp = QPCP, qpcp_flag = Measurement.Flag.1, qpcp_qual = Quality.Flag.1,
         qpcp_units = Units.1) %>% #renames columns
  filter(station_name == "WAILUPE VALLEY SCHOOL 723.6 HI US") %>% #filter to Wailupe gauge only
  filter(qpcp != "-9999",
         qpcp != "999",
         qpcp != "999.99",
```

```
         qpcp_flag != "g",
         qpcp_flag != "{",
         qpcp_flag != "}",
         qpcp_flag != "[",
         qpcp_flag != "]",
         qgag != "-9999.00",
         qgag != "-9999",
         qgag_flag != "g",
         qgag_flag != "V",
         qgag_flag != "P",
         qgag_flag != "{",
         qgag_flag != "}",
         qgag_flag != "[",
         qgag_flag != "]") ## removes all flagged data
```

Look at Wailupe Dataset in a daily format to explore total rainfall over a 24 hour periode

```
wailupe_daily_77 <- wailupe_tidy_77 %>%
  group_by(date) %>%
  summarize(
    daily_pcp = sum(qpcp),
    daily_vol = sum(qgag)) ## gives total summed precip data per day. HT is given in inches.
```

Look at the timeseries of daily Wailupe Data

```
##TS TIME

wailupe_daily_77$date <- ymd(wailupe_daily_77$date)

wailupe_ts <- wailupe_daily_77 %>%
  ts(daily_gag, start=c(1996, 1), end=c(2014, 12), frequency=12)

plot(wailupe_ts)
```

```
######################## standard ggplot

wailupe_plot_pcp <- ggplot(wailupe_daily_77, aes(date, daily_pcp)) +
  geom_line()

wailupe_plot_pcp
```

```
######################## refined ggplot

wailupe_ts_plot <- wailupe_daily_77 %>%
  ggplot(aes(x=date, y=daily_pcp)) +
  geom_col(fill = "dodgerblue4", position = "dodge") +
  labs(x= "Year", y= "Precipitation (inches)") +
  #scale_y_continuous()+
  #scale_x_date(limits= as.Date(c("1996-01-04","2013-12-24")),
  #breaks= seq("1996-01-04","2013-12-24", by= 5),expand= c(0,0))+
  theme_classic()

wailupe_ts_plot
```

Now search for 2 year, 24 hour storm events

```r
##Search for 2 year, 24 hour storm events (4.78 inches plus/minus 4.12-5.57 inches
##90% confidence interval)

wailupe_investigate_1 <- wailupe_daily_77 %>%
  filter(daily_pcp > "4.12",
         daily_pcp < "5.57")

## Storms that fall in this range are on:
# 2004-01-02
# 2005-01-29
# 2010-12-19

## Look at scatter of qpcp vs qgag
scatterplot <- ggplot(wailupe_daily_77, aes(x= daily_pcp, y = daily_vol)) +
                        geom_point()

scatterplot
```

Choosing a representative storm

Awesome. The data is tidied and explored, now we need to pull out a good calibration sub-dataset to feed into our model. To do this, Natalie will filter by year, and see the percentage of data present per year (#days in data/365). Then, she will choose a representative dataset from the resulting subset.

```r
######################
wailupe_05_investigate <- wailupe_tidy_77 %>%
  filter(date >"2005-1-1",
         date <"2005-12-31") %>%
  summarize(
    days_05 = length(date),
    annual_percent = (days_05/365)*100)

######################
wailupe_06_investigate <- wailupe_tidy_77 %>%
  filter(date >"2006-1-1",
         date <"2006-12-31") %>%
  summarize(
    days_06 = length(date),
    annual_percent = (days_06/365)*100)

######################
wailupe_07_investigate <- wailupe_tidy_77 %>%
  filter(date >"2007-1-1",
         date <"2007-12-31") %>%
  summarize(
    days_07 = length(date),
    annual_percent = (days_07/365)*100)

######################

wailupe_08_investigate <- wailupe_tidy_77 %>%
  filter(date >"2008-1-1",
         date <"2008-12-31") %>%
  summarize(
```

```r
    days_08 = length(date),
    annual_percent = (days_08/365)*100
                )

#################

wailupe_09_investigate <- wailupe_tidy_77 %>%
  filter(date >"2009-1-1",
         date <"2009-12-31") %>%
  summarize(
    days_09 = length(date),
    annual_percent = (days_09/365)*100
  )

#################
wailupe_10_investigate <- wailupe_tidy_77 %>%
  filter(date >"2010-1-1",
         date <"2010-12-31") %>%
  summarize(
    days_10 = length(date),
    annual_percent = (days_10/365)*100
  )

#################
wailupe_11_investigate <- wailupe_tidy_77 %>%
  filter(date >"2011-1-1",
         date <"2011-12-31") %>%
  summarize(
    days_11 = length(date),
    annual_percent = (days_11/365)*100
  )
#################
wailupe_12_investigate <- wailupe_tidy_77 %>%
  filter(date >"2012-1-1",
         date <"2012-12-31") %>%
  summarize(
    days_12 = length(date),
    annual_percent = (days_12/365)*100
  )

#################
wailupe_13_investigate <- wailupe_tidy_77 %>%
  filter(date >"2013-1-1",
         date <"2013-12-31") %>%
  summarize(
    days_13 = length(date),
    annual_percent = (days_13/365)*100
  )
```

The more recent data (Since 2008) has better reporting. Now, filter years with targeted storm events. DISCHARGE DATA IS FROM 10/25/08-2019, so in order to properly calibrate the SWMM model a storm needs to be within these dates.

```r
## filter dataset from 2008-2014
wailupe_daily_08_14 <- wailupe_daily_77 %>%
  filter(date > "2008-01-01",
         date < "2014-12-31")

## look at histogram plot to investigate storm frequency over given time period
hist <- ggplot(wailupe_daily_08_14, aes(x= daily_pcp)) +
  geom_histogram()

hist
```

```
## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.
```

```r
############### 2008

wailupe_08 <- wailupe_daily_77 %>%
  filter(date >"2008-10-25",
         date <"2008-12-31")

wailupe_plot_08 <- ggplot(wailupe_08, aes(date, daily_pcp)) +
  geom_col() +
  xlab("Date") +
  ylab("Precipitation (inches)")

wailupe_plot_08
```

```r
############### 2009

wailupe_09 <- wailupe_daily_77 %>%
  filter(date >"2009-01-01",
         date <"2009-12-31")

wailupe_plot_09 <- ggplot(wailupe_09, aes(date, daily_pcp)) +
  geom_col() +
  xlab("Date") +
  ylab("Precipitation (inches)")

wailupe_plot_09
```

```r
############### 2010

wailupe_10 <- wailupe_daily_77 %>%
  filter(date >"2010-01-01",
         date <"2010-12-31")

wailupe_plot_10 <- ggplot(wailupe_10, aes(date, daily_pcp)) +
  geom_col() +
  xlab("Date") +
  ylab("Precipitation (inches)")

wailupe_plot_10
```

```r
############### 2013

wailupe_13 <- wailupe_daily_77 %>%
```

```r
  filter(date >"2013-01-01",
         date <"2013-12-31")

wailupe_plot_13 <- ggplot(wailupe_13, aes(date, daily_pcp)) +
  geom_col() +
  xlab("Date") +
  ylab("Precipitation (inches)")

wailupe_plot_13
```

```r
##Plot selected storm events, export as .csv for SWMM input and .jpeg for visualization)

#####

wailupe_storm_10 <- wailupe_tidy_77 %>%
  filter(date > "2010-12-18",
         date < "2010-12-20")

wailupe_storm_10$datetime10 <- as.POSIXct(paste0("2010-12-19 ", wailupe_storm_10$time),
                                          tz = "GMT")

storm_plot_10 <- wailupe_storm_10 %>%
  ggplot(aes(x=datetime10, y=qpcp)) +
  geom_col(fill = "dodgerblue4") +
  labs(x= "Time (hour)", y= "Precipitation (inches)") +
  scale_y_continuous(limits= c(0,0.5), breaks= seq(0,0.5, by= .1),expand= c(0,0))+
  scale_x_datetime(date_labels = "%H:%M", date_breaks = "2 hour")+
  theme_classic()

storm_plot_10
```

```r
ggsave("storm_plot_10.pdf", width = 6, height =4)
ggsave("storm_plot_10.png", width = 6, height =4)

write.csv(wailupe_storm_10, file = "wailupe_storm_20101219_r.csv")
```

Isolate another smaller storm event with associated discharge data for model validation

```r
#2009 storm @ 2.8 inches
wailupe_storm_09 <- wailupe_tidy_77 %>%
  filter(date >"2009-03-13",
         date <"2009-03-15")

wailupe_storm_09$datetime09 <- as.POSIXct(paste0("2009-03-14",wailupe_storm_09$time),
                                          tz = "GMT")

storm_plot_09 <- wailupe_storm_09 %>%
  ggplot(aes(x=datetime09, y=qpcp)) +
  geom_col(fill = "dodgerblue4") +
  labs(x= "Time (hour)", y= "Precipitation (inches)") +
  scale_y_continuous(limits= c(0,0.5), breaks= seq(0,0.5, by= .1),expand= c(0,0))+
  scale_x_datetime(date_labels = "%H:%M", date_breaks = "1 hour")+
  theme_classic()

storm_plot_09
```

```r
ggsave("storm_plot_09.pdf", width = 6, height =4)
ggsave("storm_plot_09.png", width = 6, height =4)

write.csv(wailupe_storm_09, file = "wailupe_storm_20090314_r.csv")
```

Soil Curve Numbers

This is code to generate soil curve numbers for each subcatchment in Wailupe.

Eleonore Durand

May 13, 2020

Code Setup

```
#load necessary packages

library(tidyverse)
```

Load soil hydrologic groups data

```
soil_union <- read_csv("soil_land_union_maunalua.csv") %>%
  select(OBJECTID_1, hydgrpdcd, Class_Name, Shape_Length, Shape_Area) %>%
  filter(hydgrpdcd != "NA")

unique(soil_union$Class_Name) # get all the class names
```

See methodology for further explanation as to how we found the curve number for each land class, but here is the table for ease of coding:

Land Cover Hydrologic group A Hydrologic group B Hydrologic group C Hydrologic group D
Grassland: poor condition 68 79 86 89
Unconsolidated shore 0 0 0 0
Bare Land/Bare soil 77 86 91 94
Open Space Developed- good 39 61 74 80
Evergreen forest- fair 36 60 73 79
Scrub Shrub 36 42 55 62
Open Water 0 0 0 0
Impervious surface- like shrubland 36 42 55 62
Palustrine Scrub Shrub wetland
(woody wetland) 86 86 86 86
Palustrine Forested wetland
(woody wetland) 86 86 86 86
Palustrine Aquatic Bed NA NA NA NA
Estuarine Emergent wetland 80 80 80 80
Palustrine emergent wetland 80 80 80 80
Pasture/Hay 40 61 73 79
Unclassified - here: open water 0 0 0 0
Cultivated Land 62 74 82 86

Assign curve numbers to each group

Soil Curve Number Adjustments

This is code to adjust the soil curve numbers for each subcatchment in Wailupe using weighted means.

Eleonore Durand

May 13, 2020

Code Setup

```
library(tidyverse) #loading in the packages
```

Weighted means for curve numbers

```
#Load data for curve numbers from final curve numbers code
ind_cn_all<- read_csv("subcatch_2_12_cn.csv") %>%
  filter (curve_numbers_csv_CN != "NA")

all_cn_weighted<- ind_cn_all %>%
  group_by(OBJECTID_1) %>% #grouping by subcatchment and then doing a weighted mean
  summarize(mean_cn= weighted.mean(curve_numbers_csv_CN, PERCENTAGE))

slopes_ind<- read_csv("subcatch_2_12_slope.csv")

slope_weighted<- slopes_ind %>%
  group_by(OBJECTID_1) %>% #grouping by subcatchment and then doing a weighted mean
  summarize(mean_slope=weighted.mean(Slope, PERCENTAGE))

write.csv(all_cn_weighted, file = "subcatch_2_12_cn_weighted.csv")

write.csv(slope_weighted, file = "subcatch_2_12_slope_weighted.csv")
```

```r
curve_numbers_maunalua <- soil_union %>%
  mutate(CN=
           case_when(Class_Name =="Grassland" & hydgrpdcd== "A" ~ 68,
                     Class_Name =="Grassland" & hydgrpdcd== "B" ~ 79,
                     Class_Name =="Grassland" & hydgrpdcd== "C" ~ 86,
                     Class_Name =="Grassland" & hydgrpdcd== "D" ~ 89,
                     Class_Name =="Unconsolidated Shore"~ 0,
                     Class_Name =="Bare Land" & hydgrpdcd== "A" ~ 77,
                     Class_Name =="Bare Land" & hydgrpdcd== "B" ~ 86,
                     Class_Name =="Bare Land" & hydgrpdcd== "C" ~ 91,
                     Class_Name =="Bare Land" & hydgrpdcd== "D" ~ 94,
                     Class_Name =="Open Space Developed" & hydgrpdcd== "A" ~ 39,
                     Class_Name =="Open Space Developed" & hydgrpdcd== "B" ~ 61,
                     Class_Name =="Open Space Developed" & hydgrpdcd== "C" ~ 74,
                     Class_Name =="Open Space Developed" & hydgrpdcd== "D" ~ 80,
                     Class_Name =="Evergreen" & hydgrpdcd== "A" ~ 36,
                     Class_Name =="Evergreen" & hydgrpdcd== "B" ~ 60,
                     Class_Name =="Evergreen" & hydgrpdcd== "C" ~ 73,
                     Class_Name =="Evergreen" & hydgrpdcd== "D" ~ 79,
                     Class_Name =="Scrub Shrub" & hydgrpdcd== "A" ~ 39,
                     Class_Name =="Scrub Shrub" & hydgrpdcd== "B" ~ 42,
                     Class_Name =="Scrub Shrub" & hydgrpdcd== "C" ~ 55,
                     Class_Name =="Scrub Shrub" & hydgrpdcd== "D" ~ 62,
                     Class_Name =="Open Water" ~ 0,
                     Class_Name =="Impervious Surface" & hydgrpdcd== "A" ~ 39,
                     Class_Name =="Impervious Surface" & hydgrpdcd== "B" ~ 42,
                     Class_Name =="Impervious Surface" & hydgrpdcd== "C" ~ 55,
                     Class_Name =="Impervious Surface" & hydgrpdcd== "D" ~ 62,
                     Class_Name =="Estuarine Emergent Wetland" ~ 80,
                     Class_Name =="Estuarine Scrub Shrub Wetland" ~ 86,
                     Class_Name =="Estuarine Forested Wetland" ~ 86,
                     Class_Name =="Cultivated Land" & hydgrpdcd== "A" ~ 62,
                     Class_Name =="Cultivated Land" & hydgrpdcd== "B" ~ 74,
                     Class_Name =="Cultivated Land" & hydgrpdcd== "C" ~ 82,
                     Class_Name =="Cultivated Land" & hydgrpdcd== "D" ~ 86

           ))
```

Then export this file to a csv and merge back the CN column to your attribute file for your union land uses/soil type. Double check that you are joining by the right column, here OBJECTID_1.

Wailupe Subcatchments

This is code to process the subcatchments layer for use in SWMM.

Erica Johnson

May 12, 2020

Code Setup

```
#Load packages
library(tidyverse)
library(dplyr)
library(data.table)
library(janitor)

points <- read_csv("subc_points.csv") %>%
  clean_names() %>%
  rename(name = subcatchment_name,
         x = point_x,
         y = point_y
         ) %>%
  select(name, x, y)

attributes <- read_csv("subc_attributes.csv") %>%
  clean_names() %>%
  rename(name = objectid_1)
```

Process subcatchments for SWMM

Collect Name, Area, Width, X and Y coordinates of each polygon and arrange them into the SWMM format. Rain gage and Outlets were assigned manually in SWMM

See example SWMM format below:

[SUBCATCHMENTS]
;;Name Rain Gage Outlet Area %Imperv Width %Slope CurbLen SnowPack

```
#If you have run the stormwater_network_wailupe_final.rmd, this file will be available.
#If not, use the alternate code chunk below

subc_outlet <- read_csv("subc_outlet.csv") %>% rename(name = subc, outlet = node)

merge_a <- merge(points, attributes, by = "name") %>% distinct (name, .keep_all = TRUE)
merge <-merge (merge_a, subc_outlet, by="name", all = TRUE)

subc <- merge %>%
  mutate(
    area_acre = area_sqft*0.0000229568
    ) %>%
```

```
  rename(
    area = area_acre,
    imperv = percent_imp
  ) %>%
  distinct()

#add columns for "subcatchments" file.


subc$rain_gage <- "R1"
#placeholder until you can manually assign the correct rain gage to the correct subcatchment
subc$curblen <- 0

#arrange
subc_file <- subc %>%
  select(
    name,
    rain_gage,
    outlet,
    area,
    imperv,
    width,
    slope,
    curblen
    ) %>%
  distinct(name, .keep_all = TRUE)

write.csv(subc_file ,"inp_subcatchments.csv", row.names = FALSE)
```

Alternate code chunk

```
merge <- merge(points, attributes, by = "name" )

subc <- merge %>%
  mutate(
    area_acre = area_sqft*0.0000229568
    ) %>%
  rename(
    area = area_acre,
    imperv = percent_imp
  ) %>%
  distinct()

#add columns for "subcatchments" file.
subc$rain_gage <- "R1"
subc$outlet <- "J1"
subc$curblen <- 0

#arrange
subc_file <- subc %>%
  select(
    name,
    rain_gage,
    outlet,
```

```r
    area,
    imperv,
    width,
    slope,
    curblen
    ) %>%
  distinct(name, .keep_all = TRUE)

write.csv(subc_file ,"inp_subcatchments.csv", row.names = FALSE)
```

[SUBAREAS]
;;Subcatchment N-Imperv N-Perv S-Imperv S-Perv PctZero RouteTo PctRouted
;;————— ———- ———- ———-
1 0.01 0.1 0.05 0.05 25 OUTLET

```r
suba <- subc_file %>%
  select(name) %>%
  rename (subcatchment = name) %>%
  distinct()

suba$n_imperv <- 0.01 #manning's n for impervious surfaces - values from SWMM Manual

suba$n_perv <- 0.4 #manning's n for pervious (natural) surfaces. 0.4 for forested subcatchments.
#Later, identify urban subcatchments and input 0.15. - values from SWMM Manual

suba$s_imperv <- 0.2 #impervious surface depth of depression storage (in) - values in SWMM Manual

suba$s_perv <- 0.3 #pervious (natural) surface depth of depression storage - values in SWMM manual

suba$pctzero <- 0
suba$RouteTo <- "OUTLET"

#n is for Manning's n, and s is for Depth of Depression Storage.

write.csv(suba ,"inp_subareas.csv", row.names = FALSE)
```

[INFILTRATION]
;;Subcatchment CurveNum DryTime
;;————— ———- ———- ———-

```r
infil <- subc %>%
  select(name,
         curve_number
         ) %>%
  rename (
    subcatchment = name
    ) %>%
  distinct()

infil$Blank <- 0.5 #this is conductivity, however this may have been depreciated in the model
infil$DryTime <- 7 #units in days

write.csv(infil ,"inp_infiltration.csv", row.names = FALSE)
```

[Polygons]

;;Subcatchment X-Coord Y-Coord
;;————— —————— ——————

```
polygons <- points %>%
  select(
    name,
    x,
    y) %>%
  rename(subcatchment = name
         ) %>%
  distinct()

write.csv(polygons ,"inp_polygons.csv", row.names = FALSE)
```

Wailupe Stormwater Network

This is code to process the stormwater network for use in SWMM.

Erica Johnson

May 7, 2020

Code Setup

Read libraries and data file here

```
#Libraries
library(tidyverse)
library(dplyr)
library(data.table)
library(geosphere)
library(janitor)



#Data with clean names
data <- read_csv("sw_network_endpoints_wailupe.csv") %>% clean_names()
vertices_dt <- read_csv("sw_network_allpoints_wailupe.csv") %>% clean_names()
```

Data Tidying

Select columns with the data we need to use. Rename them for easy reference.

```
network <- data %>%
  select(
  objectid,
  point_x,
  point_y,
  elevation,
  subcatch_r,
  roughness,
  type,
  diameter,
  width,
  height,
  type_1
  ) %>%
  rename(
    name = objectid,
    x = point_x,
    y = point_y,
    subc = subcatch_r,
    elevation = elevation,
    shape = type,
```

```
    structure = type_1
    ) %>%
  mutate (shape = str_replace_all(shape, "Reinforced Concrete Pipe", "CIRCULAR")) %>%
  mutate (shape = str_replace_all(shape, "Box Culvert", "RECT_CLOSED")) %>%
  mutate (shape = str_replace_all(shape, "Channel", "TRAPEZOIDAL")) %>%
  mutate (shape = str_replace_all(shape, "Ditch", "RECT_OPEN")) %>%
  mutate (shape = str_replace_all(shape, "Other", "RECT_OPEN")) %>%
  distinct()
```

"Length" provided by USGS is distance between xy points. This "length"" is not the actual length of the conduit because it does not take into consideration height (xyz), so we will use the difference between lower distance between xy points calcualte the actual length further down in the code.

We will also re-calculate distance between xy points because different sources return different values for some of the conduits and some conduits need to have this distance calculated anyway because it is blank.

Step 1 - Create unique names for nodes with the same x and y coordinates, and unique names for conduits

```
#Index xy coordinates with unique IDs if different, same IDs if repeated
unique <- network %>%
  mutate(
    node = group_indices(
      network, x, y
      )
    )

#Assign nodes the letter j for "junction" (SWMM terminology) and conduits the letter c for
#"conduit" (SWMM terminology)

unique$c <- "C"
unique$j <- "J"

#conduits
unique$name= paste(unique$c,unique$name)

#remove space
unique$name <- gsub(
  '\\s+', '', unique$name
  )
#node
unique$node= paste(unique$j,unique$node)

#remove space
unique$node <- gsub(
  '\\s+', '', unique$node
  )
```

2. Arrange and reshape data

Note: each conduit has start and end coordinates and nodes, - so there are duplicate rows for each conduit. We want to reshape this data to have both xy and nodes in the same row.

```
#arrange by conduit name and descending elevation
arrange <- unique[
  with(
  unique, order(
    name,
    -elevation,
    na.last=FALSE)
  ),
  ]

#reshape data
reshape_dt <- dcast(
  setDT(arrange),
  name + roughness ~ rowid(name, prefix="node"),
  value.var=c("node", "x", "y", "elevation"))
```

3. Length

We must now calculate the length of the conduits using the following steps: a. Find distance "length" between xy coordinates of each conduit using geosphere. b. Use difference in elevation to calculate height c. Use pythag. theorem to calculate length

```
#part a -  distance (adjust code based on number of pairs.
#This dataset has 18 based on the longest conduit)

dist <- reshape_dt %>%
  rowwise(
  ) %>%
  mutate (
    dist_m = distm(c(x_node1, y_node1),
                   c(x_node2, y_node2),
                   fun = distHaversine
                   )
    ) %>%
  mutate(
    dist_ft = dist_m*3.28084
    )

#part b and c - height then length
lengths <- dist %>%
  mutate (
    length = sqrt(
      (dist_ft)^2 + (elevation_node1-elevation_node2)^2)
        )%>%
  rename (
    from_node = node_node1,
    to_node = node_node2
  )
```

4. file output for conduits

[CONDUITS]
;;Name From Node To Node Length Roughness InOffset OutOffset InitFlow MaxFlow
;;———- ———- ———- ———- ———- ———- ———- ———- ———-

** The channelized stream needs to connect with the stormwater infrastructure via junctions/nodes in the urban region. It is feasible to connect them manually by drawing in the stream conduit in SWMM.

Use roughness value 0.01, for concrete pipes found in Appendix A-8 pg. 184 of EPA manual

```
conduits <- lengths %>%
  mutate(
    roughness = ifelse(is.na(roughness), 0.01, roughness)
    ) %>%
  select(
    name,
    from_node,
    to_node,
    length,
    roughness
    )

conduits$inoffset <- 0
conduits$outoffset <- 0
conduits$initflow <- 0
conduits$maxflow <- 0


write.csv(conduits,"inp_conduits.csv", row.names = FALSE)
```

5. file output for **conduit cross sections**

[XSECTIONS]
;;Link Shape Geom1 Geom2 Geom3 Geom4 Barrels Culvert
;;———— ———— ————- ———-

```
xsection_dt <- merge(
  lengths,
  unique,
  by = "name"
  ) %>%
  select (
    name,
    length,
    shape,
    diameter,
    width,
    height
    )
```

a - concrete pipe dimensions

```
pipes<- xsection_dt %>%
  filter(
    shape == "CIRCULAR"
    ) %>%
  rename(
    geom1 = diameter,
    link = name
    ) %>%
  mutate(
```

```
    geom1 = ifelse(is.na(geom1), "23", geom1)
    ) %>%
  mutate(
    geom1 = ifelse((geom1=="Other"), "23", (geom1))
    )%>%
  select(
    link,
    shape,
    length,
    geom1
  )
pipes$geom2 <- 0
pipes$geom3 <- 0
pipes$geom4 <- 0
pipes$barrels <-
pipes$culvert <- 0
```

b - box culverts, ditches, and "other" conduit dimensions

```
ditch_box <- xsection_dt %>%
  filter(
    shape == "RECT_CLOSED" | shape == "RECT_OPEN"
    ) %>%
  rename (
    geom1 = width,
    geom2 = height,
    link = name
    ) %>%
  mutate(
    geom1 = ifelse(is.na(geom1), 5, geom1)
    ) %>%
  mutate(geom2 = ifelse(is.na(geom2), 5, geom2)
         ) %>%
  select(
    link,
    shape,
    length,
    geom1,
    geom2

  )
ditch_box$geom3 <- 0
ditch_box$geom4 <- 0
ditch_box$barrels <-
ditch_box$culvert <- 0
```

c - channel (channelized stream) dimenssions

```
channel <- xsection_dt %>%
  filter(
    is.na(shape)
    ) %>%
  mutate(
    shape = ifelse(is.na(shape), "TRAPEZOIDAL", shape)
    ) %>%
```

```
  rename(
    geom1 = width,
    geom2 = height,
    link = name
    ) %>%
  mutate(
    geom1 = ifelse(is.na(geom1), 30, geom1)
    ) %>%
  mutate(
    geom2 = ifelse(is.na(geom2), 10, geom2)
    ) %>%
  select(
     link,
    shape,
    length,
    geom1,
    geom2
    )
#Geom3 and Geom4 are side lopes, which literature indicate vary from 1/1 to 1/2.
#Ive seen side slopes perpendicular to the ground, especially where homes are built.
channel$geom3 <- 1
channel$geom4 <- 1
channel$barrels <-
channel$culvert <- 0
```

e- bind all tables

```
xsections_df <- rbind(
  pipes,
  ditch_box,
  channel
  ) %>%
  select(
    link,
    shape,
    geom1,
    geom2,
    geom3,
    geom4,
    barrels,
    culvert,
    length
    ) %>%
  distinct(
    link,
    shape,
    geom1,
    geom2,
    .keep_all = TRUE
    )

xsections <- rbind(
  pipes,
  ditch_box,
```

```
  channel
  ) %>%
  select(
    link,
    shape,
    geom1,
    geom2,
    geom3,
    geom4,
    barrels,
    culvert
    ) %>%
  distinct(
    link,
    shape,
    geom1,
    geom2,
    .keep_all = TRUE
    )

write.csv(xsections,"inp_xsections.csv", row.names = FALSE)
```

8. Junctions and coordinates/vertices

[JUNCTIONS]
;;Name Elevation MaxDepth InitDepth SurDepth Aponded
;;——————— ————- ————- ————-

```
junctions <- unique %>% filter(
    structure != "Inlet/Outlet" | is.na(structure)
    ) %>%
  select(
    node,
    elevation
    ) %>%
  rename(
    name = node
    ) %>%
  distinct(
    name,
    .keep_all = TRUE
  )
junctions$maxdepth <- 0
junctions$initdepth <- 0
junctions$surdepth <- 0
junctions$aponded <- 0

#filter for structure type in here so we can designate which junctions are outfalls
write.csv(junctions,"inp_junctions.csv", row.names = FALSE)
```

Here is a csv that will help determine what junction to route each subcatchment's outlet to.

```
route_to <- unique %>%
  select(
    node,
```

Graphs of SWMM Results

This is code to analyze the results from SWMM and create figures

Eleonore Durand

February 13, 2020

NOTE: Figures will be be hidden from knitted markdown.

Code setup - Load packages

```
library(tidyverse) #For data wrangling
library(stargazer) #For creating nice tables
library(kableExtra) #For creating nice tables
library(hydroGOF)
```

Analysis of dry storm results

```
subcatch<- read_csv("subcatchments_all.csv") %>%
  mutate(subcatchment= OBJECTID_1) %>%
  select(subcatchment, Curve_Number, Slope, percent_imp, Area_sqft)

swm_results_dry<-read_csv("wailupe10_dry_summary.csv")

#Characterize results by urbanization level
results_dry<- merge(subcatch, swm_results_dry, by = "subcatchment") %>%
  mutate(runoff_normalized=
           total_runoff_in/Area_sqft) %>%
  mutate(Urbanization_level=
           case_when(
             percent_imp <15 |percent_imp == 15 ~ "Natural (less than 15 % Impervious)",
             percent_imp >15 & percent_imp <45 ~ "Urbanized (Between 15 and 45 % Impervious)",
             percent_imp >44.9999 ~ "Very urbanized (More than 45 % Impervious)"
             )
           )

write.csv(results_dry, file = "results_dry.csv") ##Export as .csv for use with graph maps

#Perform a linear regression for the SWMM dry storm results
results_regression_dry<- lm(total_runoff_in ~Curve_Number + Slope + percent_imp +
                              Area_sqft, data = results_dry)

#Graph the relationship bw simulated runoff and impervious cover by urbanization level
runoff_imp_graph_dry<- results_dry %>%
  ggplot(aes(x=percent_imp, y=total_runoff_in))+
  geom_point(aes(color=Urbanization_level))+
  labs(x= "Percent Impervious of Subcatchment", y= "Total Simulated Runoff (inches)")+
```

```
  scale_y_continuous(limits= c(0,7), breaks= seq(0,7, by= 1),expand= c(0,0.08))+
  scale_x_continuous(limits= c(0,80), breaks= seq(0,80, by= 10),expand= c(0,0))+
  scale_color_manual(name= "Urbanization Level", values= c("darkgreen", "darkseagreen",
                                                            "darkgoldenrod1"))+
  theme_classic()
runoff_imp_graph_dry
```

```
#Save runoff vs. impervious graph
ggsave("runoff_imp_dry.pdf", width = 8, height =4)
ggsave("runoff_imp_dry.png", width = 8, height =4)

#Create a table for the regression results
regress_table_dry<- stargazer(results_regression_dry, type ="html", digits= 2,
                          dep.var.labels = "Total Runoff (Inches)",
                       covariate.labels = c("Curve Number", "Slope", "Percent Impervious",
                                            "Area (sqft)", "Y-Intercept"),
                       omit.stat = c("rsq"))
regress_table_dry
```

Analysis of wet storm results

```
swm_results_wet<-read_csv("Wailupe10_wet_summary.csv")

#Characterize results by urbanization level
results_wet<- merge(subcatch, swm_results_wet, by = "subcatchment") %>%
  mutate(runoff_normalized=
           total_runoff_in/Area_sqft) %>%
  mutate(Urbanization_level=
           case_when(
             percent_imp <15 |percent_imp == 15 ~ "Natural (less than 15 % Impervious)",
             percent_imp >15 & percent_imp <45 ~ "Urbanized (Between 15 and 45 % Impervious)",
             percent_imp >44.9999 ~ "Very urbanized (More than 45 % Impervious)"
             )
           )

write.csv(results_wet, file = "results_wet.csv") ##save for use with graph maps

#Perform a linear regression for the SWMM wet storm results
results_regression_wet<- lm(total_runoff_in ~Curve_Number + Slope + percent_imp + Area_sqft,
                            data = results_wet)

#Graph the relationship bw simulated runoff and impervious cover
runoff_imp_graph_wet<- results_wet %>%
  ggplot(aes(x=percent_imp, y=total_runoff_in))+
  geom_point(aes(color=Urbanization_level))+
  labs(x= "Percent Impervious of Subcatchment", y= "Total Simulated Runoff (inches)")+
  scale_y_continuous(limits= c(0,3), breaks= seq(0,2.5, by= 0.5),expand= c(0,0.08))+
  scale_x_continuous(limits= c(0,80), breaks= seq(0,80, by= 10),expand= c(0,0))+
  scale_color_manual(name= "Urbanization Level", values= c("darkgreen", "darkseagreen",
                                                            "darkgoldenrod1"))+
  theme_classic()

#Create a graph of the relationship vw simulated runof and impervious cover normalized by area
```

```r
runoff_norm_wet<- results_wet %>%
  ggplot(aes(x=percent_imp, y=runoff_normalized))+
  geom_point(aes(color=Urbanization_level))+
  labs(x= "Percent Impervious of Subcatchment",
       y= "Total Simulated Runoff Normalized by Area (inches/sqft)")+
  scale_y_continuous(expand= c(0,0))+
  scale_x_continuous(limits= c(0,80), breaks= seq(0,80, by= 10),expand= c(0,0))+
  scale_color_manual(name= "Urbanization Level", values= c("darkgreen", "darkseagreen",
                                                           "darkgoldenrod1"))+
  theme_classic()

runoff_norm_wet
```

```r
runoff_imp_graph_wet
```

```r
#Save runoff vs. impervious graph
ggsave("runoff_imp_wet.pdf", width = 8, height =4)
ggsave("runoff_imp_wet.png", width = 8, height =4)

#Create a table of the regression results
regress_table_wet<- stargazer(results_regression_wet, type ="html", digits= 2,
                          dep.var.labels = "Total Runoff (Inches)",
                       covariate.labels = c("Curve Number", "Slope", "Percent Impervious",
                                            "Area (sqft)", "Y-Intercept"),
                       omit.stat = c("rsq"))
regress_table_wet
```

Analysis of simulated vs observed runoff

```r
#Graph observed vs simulated runoff

observed<- read_csv("c35_observed.csv")
simulated <- read_csv("C35_simulated_adj_cn25.csv")

discharge<- merge(observed, simulated, by = "time_step")

summary(discharge)


dischargettest<- t.test(discharge$discharge_obs_cfs, discharge$simulated_flow_cfs)

regress<- lm(discharge_obs_cfs ~ simulated_flow_cfs, data = discharge)

regress

sim<- discharge$simulated_flow_cfs
obs<- discharge$discharge_obs_cfs


sutcliffe<- NSE(sim, obs, na.rm=TRUE, FUN=NULL, epsilon=c("Pushpalatha2012"))

sutcliffe
```

```r
write.csv(discharge,file = "discharge_obv_sim1.csv", row.names = FALSE)

graph<- ggplot(discharge, aes(x=discharge_obs_cfs, simulated_flow_cfs))+
  geom_point()

graph
```

```r
calibrate_graph<- discharge %>%
  ggplot()+
  geom_line(aes(x=time_step, y=discharge_obs_cfs), color="darkseagreen")+
  geom_line(aes(x=time_step, y=simulated_flow_cfs), color= "darkgoldenrod1")+
  theme_classic()+
  labs(x="Time (hours)", y="Discharge (cfs)")+
  scale_y_continuous(limits= c(0,275), breaks= seq(0,250, by= 25),expand= c(0,0))+
  scale_x_continuous(limits= c(0,22), breaks= seq(0,22, by= 2),expand= c(0,0))+
  annotate("text", label= "Observed", x=19.5, y=65, size=3.5)+
  annotate("text", label= "Simulated", x=19.5, y=25, size=3.5)


calibrate_graph
```

```r
#Save discharge graphs from the 2010 "dry" storm
ggsave("discharge10.pdf", width = 8, height =4)
ggsave("dischage10.png", width = 8, height =4)

results_table<- results_wet %>%
  group_by(Urbanization_level) %>%
  summarize(
    number_of_subcatch=length(subcatchment),
    runoff_coefficient=round(mean(runoff_coeff),2),
    total_runoff_inches=round(mean(total_runoff_in),2),
    impervious_runoff_inches=round(mean(imperv_runoff_in),2),
    pervious_runoff_inches=round(mean(perv_runoff_in), 2),
    total_infiltration_inches= round(mean(total_infil_in),2),
    peak_runoff_cubicfs=round(mean(peak_runoff_cfs),2)

  )

results_table

table_pretty<-results_table %>%
              kable(col.names=c("Urbanization Level","Number of Subcatchments",
                                "Runoff Coefficient", "Total Runoff (in)",
                                "Impervious Runoff (in)", "Pervious Runoff (in)",
                                "Total Infiltration (in)", "Peak Runoff (cfs)")) %>%
  kable_styling(bootstrap_options = "striped")

table_pretty

results_table_dry<- results_dry %>%
  group_by(Urbanization_level) %>%
  summarize(
    number_of_subcatch=length(subcatchment),
    runoff_coefficient=round(mean(runoff_coeff),2),
```

```r
    total_runoff_inches=round(mean(total_runoff_in),2),
    impervious_runoff_inches=round(mean(imperv_runoff_in),2),
    pervious_runoff_inches=round(mean(perv_runoff_in), 2),
    total_infiltration_inches= round(mean(total_infil_in),2),
    peak_runoff_cubicfs=round(mean(peak_runoff_cfs),2)

  )

min_range_runoff_table_dry<- results_dry %>%
  summarize(
  min_runoff_coeff = min(runoff_coeff),
  max_runoff_coeff = max(runoff_coeff),
  median_runoff_coeff = median(runoff_coeff),
  min_imp_runoff= min(imperv_runoff_in),
  max_imp_runoff= max(imperv_runoff_in),
  med_imp_runoff=median(imperv_runoff_in),
  min_per_runoff=min(perv_runoff_in),
  max_per_runoff=max(perv_runoff_in),
  med_per_runoff=median(perv_runoff_in)
  ) %>%
  kable(col.names=c("Minimum Runoff Coefficient", "Maximum Runoff Coefficient",
                   "Median Runoff Coefficient", "Minimum Impervious Runoff (in)",
                   "Maximum Impervious Runoff (in)", "Median Impervious Runoff (In)",
                   "Minimum Pervious Runoff (in)", "Maximum Pervious Runoff (in)",
                   "Median Pervious Runoff (in)")) %>%
  kable_styling(bootstrap_options = "striped")

min_range_runoff_table_dry

results_table_dry

table_pretty_dry<-results_table_dry %>%
              kable(col.names=c("Urbanization Level","Number of Subcatchments",
                                 "Runoff Coefficient", "Total Runoff (in)",
                                 "Impervious Runoff (in)", "Pervious Runoff (in)",
                                 "Total Infiltration (in)", "Peak Runoff (cfs)")) %>%
  kable_styling(bootstrap_options = "striped")

table_pretty_dry

min_range_runoff_table_wet<- results_wet %>%
  summarize(
  min_runoff_coeff = min(runoff_coeff),
  max_runoff_coeff = max(runoff_coeff),
  median_runoff_coeff = median(runoff_coeff),
  min_imp_runoff= min(imperv_runoff_in),
  max_imp_runoff= max(imperv_runoff_in),
  med_imp_runoff=median(imperv_runoff_in),
  min_per_runoff=min(perv_runoff_in),
  max_per_runoff=max(perv_runoff_in),
  med_per_runoff=median(perv_runoff_in)
  ) %>%
  kable(col.names=c("Minimum Runoff Coefficient", "Maximum Runoff Coefficient",
```

```
                    "Median Runoff Coefficient", "Minimum Impervious Runoff (in)",
                    "Maximum Impervious Runoff (in)", "Median Impervious Runoff (In)",
                    "Minimum Pervious Runoff (in)", "Maximum Pervious Runoff (in)",
                    "Median Pervious Runoff (in)")) %>%
  kable_styling(bootstrap_options = "striped")

min_range_runoff_table_wet
```

Analysis of observed vs simulated runoff for 2009 storm

```
observed09<- read_csv("c35_observed_09.csv")
simulated09 <- read_csv("C35_simulated09.csv")

discharge09<- merge(observed09, simulated09, by = "time_step")

summary(discharge09)

dischargettest09<- t.test(discharge09$discharge_obs_cfs, discharge09$simulated_flow_cfs)

regress09<- lm(discharge_obs_cfs ~ simulated_flow_cfs, data = discharge09)

regress09

sim09<- discharge09$simulated_flow_cfs
obs09<- discharge09$discharge_obs_cfs


sutcliffe09<- NSE(sim09, obs09, na.rm=TRUE, FUN=NULL, epsilon=c("Pushpalatha2012"))

sutcliffe09

write.csv(discharge09, file = "discharge_obv_sim09.csv", row.names = FALSE)

graph09<- ggplot(discharge09, aes(x=discharge_obs_cfs, simulated_flow_cfs))+
  geom_point()

graph
```

```
calibrate_graph09<- discharge09 %>%
  ggplot()+
  geom_line(aes(x=time_step, y=discharge_obs_cfs), color="darkseagreen")+
  geom_line(aes(x=time_step, y=simulated_flow_cfs), color= "darkgoldenrod1")+
  theme_classic()+
  labs(x="Time (hours)", y="Discharge (cfs)")+
  scale_y_continuous(limits= c(0,300), breaks= seq(0,300, by= 25),expand= c(0,0))+
  scale_x_continuous(limits= c(0,12), breaks= seq(0,12, by= 2),expand= c(0,0))+
  annotate("text", label= "Observed", x=8, y=150, size=3.5)+
  annotate("text", label= "Simulated", x=8, y=77, size=3.5)


calibrate_graph09
```

```
##save discharge graphs from the 2009 "wet" storm
ggsave("discharge09_final.pdf", width = 8, height =4)
ggsave("dischage09_final.png", width = 8, height =4)
```

Top 15 subcatchments

```
dry_runoff_coef_top_15 <- top_n(results_dry, 15, runoff_coeff)

dry_peak_top_15 <-top_n(results_dry, 15, peak_runoff_cfs)

wet_runoff_coef_top_15 <- top_n(results_wet, 15, runoff_coeff)

wet_peak_top_15 <- top_n(results_wet, 15, peak_runoff_cfs)

write.csv(dry_runoff_coef_top_15, file = "dry_runoff_top_15.csv", row.names = FALSE)

write.csv(wet_runoff_coef_top_15, file = "wet_runoff_top_15.csv", row.names = FALSE)

write.csv(dry_peak_top_15,file = "dry_peak_top_15.csv", row.names = FALSE)

write.csv(wet_peak_top_15, file = "wet_peak_top_15.csv", row.names = FALSE)
```

Visualizing the sediment data from 09

```
sediment09<- read_csv("sediment_09_r.csv") %>%
  mutate(discharge_obs_cfs =
           case_when(time_step <0 ~ 0))

discharge_4_graph<- read_csv("c35_observed_09.csv") %>%
  mutate(susp_sed =
           case_when(time_step <0 ~ 0))

sedimentandflow<- rbind(sediment09, discharge_4_graph)

sediment_flow_graph <- sedimentandflow %>%
  ggplot()+
  geom_line(aes(x=time_step, y= discharge_obs_cfs), color= "blue")+
  geom_point(aes(x=time_step, y=susp_sed), color= "red")+
  theme_classic()

sediment_flow_graph
```

```
obs_discharge_09<- discharge09 %>%
  ggplot(aes(x=time_step, y=discharge_obs_cfs)) +
  geom_line(color= "darkseagreen")+
  scale_x_continuous(expand = c(0,0), breaks= seq(0,11, by =1))+
  scale_y_continuous(expand = c(0,0), breaks= seq(0,300, by=50))+
  labs(x= "Time (hours)", y= "Observed Discharge (cfs)")+
  theme_classic()

obs_discharge_09
```

```r
ggsave("observed_discharge_09.pdf", width = 8, height =4)
ggsave("observed_discharge_09_1.png", width = 8, height =4)

sediment_graph<- sediment09 %>%
  ggplot()+
  geom_point(aes(x=time_step, y=susp_sed), size= 5, color= "darkgoldenrod1")+
  geom_segment(aes(x=time_step, xend=time_step, y=0, yend=susp_sed), size=1.5,
               color="darkgoldenrod1")+
  scale_y_continuous(expand = c(0,0), breaks= seq(0,2500, by=250), limits= c(0, 2500))+
  scale_x_continuous(expand = c(0,0), breaks= seq(0,14, by =1), limits=c(0,14))+
  labs(x= "Time (hours)", y= "Suspended Sediments (mg/L)")+
  theme_classic()

sediment_graph
```

```r
ggsave("observed_sediment_09.pdf", width = 8, height =4)
ggsave("observed_sediment_09_gold.png", width = 8, height =4)
```

Maps of SWMM Results

This is code to create maps from the output files generated in Results_Graphs (Note: You must run Results_Graphs before this)

Tara Jagadeesh

February 13, 2020

NOTE: -tmap_save() and st_write() are functions to export tmap outputs as images (such as .png) and to export shapefiles, respectively.
-Something about these functions sometimes returns an error which stops the code from running, BUT they still create outputs -They have been annotated out of this code, so if you wish to export the outputs then simply remove the "##" from those lines of code

-Maps will be hidden from knitted markdown.

Code setup - Load packages

```
library(tidyverse) #For data wrangling
library(sf) #For shapefiles
library(tmap) #For mapmaking
library(tmaptools) #For mapmaking
library(here) #For loading shapefiles
library(janitor) #For cleaning names
```

Maps for dry storm hotspots

```
results_dry<- read_csv("results_dry.csv") ##read in file from 4.Results_Maps

#Combine subcatchments outline with dry storm results
subcatch_dry <- read_sf(dsn = here("5.Results_Maps","shapefiles"),
                        layer = "subcatch_outline") %>%
  st_transform(crs = 4326) %>% #Set coordinate system
  clean_names() %>% #Clean the names of columns
  select(subcatchment = objectid_1) %>%
  merge(results_dry) %>% #Merge the subcatchment outlines to the SWMM results for
  #the dry storm (from Results_Graphs)
  filter(subcatchment != "5") #Remove subcatchment 5 which is a mistake (overlaps another
  #subcatchment)


#  Map total volume hotspots
hotspots_dry_total <- tm_basemap("OpenStreetMap.Mapnik") +
  tm_shape(subcatch_dry, unit = "Miles") +
  tm_polygons("runoff_coeff", alpha = 0.8, palette = "Blues", style = "cont", n=8,
              title = "Runoff Coefficient") +
  tm_layout(title = "December 2010 storm", inner.margins=c(.05, .05, 0.1, .53),
```

```r
           legend.position =  c(.6,.63), legend.title.size = 1.4, legend.text.size = 1) +
  tm_text("subcatchment", size = 0.3) +
  tm_scale_bar(position = c(.6,.58), breaks = c(0, 0.2, 0.4, 0.6, 0.8,1)) +
  tm_compass(position = c(.58,.51))
tmap_save(hotspots_dry_total, here("5.Results_Maps", "output_maps",
                                   "hotspots_dry_total.png"))

#  Map peak flow hotspots
hotspots_dry_peak <- tm_basemap("OpenStreetMap.Mapnik") +
  tm_shape(subcatch_dry, unit = "Miles") +
  tm_polygons("peak_runoff_cfs", alpha = 0.75, palette = "Greens", style = "cont", n=8,
             legend.hist = TRUE, title = "Peak Discharge (cfs)") +
  tm_layout(title = "December 2010 storm", inner.margins=c(.05, .05, 0.1, .53),
           legend.position =  c(.6,.35), legend.title.size = 1.4, legend.text.size = 1) +
  tm_text("subcatchment", size = 0.3) +
  tm_scale_bar(position = c(.6,.61), breaks = c(0, 0.2, 0.4, 0.6, 0.8,1)) +
  tm_compass(position = c(.58,.54))
##tmap_save(hotspots_dry_peak, here("5.Results_Maps", "output_maps","hotspots_dry_peak.png"))
```

Maps for wet storm hotspots

```r
results_wet<- read_csv("results_wet.csv") ##read in file from 4.Results_Maps

#Combine subcatchments outline with wet storm results
subcatch_wet <- read_sf(dsn = here("5.Results_Maps","shapefiles"), layer = "subcatch_outline") %>%
  st_transform(crs = 4326) %>%
  clean_names() %>%
  select(subcatchment = objectid_1) %>%
  merge(results_wet) %>%
   filter(subcatchment != "5")

#  Total volume hotspots
hotspots_wet_total <- tm_basemap("OpenStreetMap.Mapnik") +
  tm_shape(subcatch_wet, unit = "Miles") +
  tm_polygons("runoff_coeff", alpha = 0.8, palette = "Blues", style = "cont", n=8,
             legend.hist = TRUE, title = "Runoff Coefficient") +
  tm_layout(title = "March 2009 storm", inner.margins=c(.05, .05, 0.1, .53),
           legend.position =  c(.6,.32), legend.title.size = 1.4, legend.text.size = 1) +
  tm_text("subcatchment", size = 0.3) +
  tm_scale_bar(position = c(.6,.59), breaks = c(0, 0.2, 0.4, 0.6, 0.8,1)) +
  tm_compass(position = c(.58,.52))
##tmap_save(hotspots_wet_total, here("5.Results_Maps", "output_maps","hotspots_wet_total.png"))


#  Peak flow hotspots
hotspots_wet_peak <- tm_basemap("OpenStreetMap.Mapnik") +
  tm_shape(subcatch_wet, unit = "Miles") +
  tm_polygons("peak_runoff_cfs", alpha = 0.75, palette = "Greens", style = "cont", n=8,
             legend.hist = TRUE, title = "Peak Discharge (cfs)") +
  tm_layout(title = "March 2009 storm", inner.margins=c(.05, .05, 0.1, .53),
           legend.position =  c(.6,.27), legend.title.size = 1.4, legend.text.size = 1) +
  tm_text("subcatchment", size = 0.3) +
  tm_scale_bar(position = c(.6,.54), breaks = c(0, 0.2, 0.4, 0.6, 0.8,1)) +
```

```r
  tm_compass(position = c(.58,.47))
##tmap_save(hotspots_wet_peak, here("5.Results_Maps", "output_maps","hotspots_wet_peak.png"))
```

Maps for top 20 hotspots commonly found between the dry storm and the wet storm

```r
#Top 20 of total volume
top20_dry_total <- subcatch_dry %>%  #Find top 20 hotspots for the dry storm
  arrange(-runoff_coeff) %>%
  head(20)

top20_wet_total <- subcatch_wet %>% #Find top 20 hotspots for the wet storm
  arrange(-runoff_coeff) %>%
  head(20)

#Find the top 20 hotspots that occur in both storms
common_total_vector <- as.data.frame(intersect(top20_dry_total$subcatchment,
                                               top20_wet_total$subcatchment))
colnames(common_total_vector) <- c("subcatchment")

#Select the top 20 hotspots
common_total <- subcatch_dry %>%
  mutate(hotspot = case_when(
  subcatchment == "21" |
  subcatchment == "22" |
  subcatchment == "23" |
  subcatchment == "29" |
  subcatchment == "40" |
  subcatchment == "45" |
  subcatchment == "46" |
  subcatchment == "47" |
  subcatchment == "49" |
  subcatchment == "51" |
  subcatchment == "54" |
  subcatchment == "59" |
  subcatchment == "60" |
  subcatchment == "63" |
  subcatchment == "65" |
  subcatchment == "67" |
  subcatchment == "68" |
  subcatchment == "71" |
  subcatchment == "89" ~ "Hotspot"))

common_total$hotspot <- as.factor(common_total$hotspot)

#Create a map of the top 20 hotspots
top20_total_map <- tm_basemap("Hydda.Base") +
  tm_shape(common_total, unit = "Miles") +
  tm_polygons("hotspot", title = "Legend", textNA = "Subcatchment", palette="#045a8d",
              alpha = 0.8)+
  tm_layout(inner.margins=c(.05, .05, .05, .52), legend.position =  c(.56,.8),
            legend.title.size = 1.4, legend.text.size = 1) +
  tm_text("subcatchment", size = 0.3) +
```

```r
  tm_scale_bar(position = c(.56,.75), breaks = c(0, 0.2, 0.4, 0.6, 0.8,1)) +
  tm_compass(position = c(.54,.68))

tmap_save(top20_total_map, here("5.Results_Maps", "output_maps","top20_total_map.png"))


#Top 20 of peak volume
top20_dry_peak <- subcatch_dry %>%
  arrange(-peak_runoff_cfs) %>%
  head(20)

top20_wet_peak <- subcatch_wet %>%
  arrange(-peak_runoff_cfs) %>%
  head(20)

common_peak_vector <- as.data.frame(intersect(top20_dry_peak$subcatchment,
                                              top20_wet_peak$subcatchment))
colnames(common_peak_vector) <- c("subcatchment")

common_peak <- subcatch_dry %>%
  mutate(hotspot = case_when(
  subcatchment == "1" |
  subcatchment == "2" |
  subcatchment == "3" |
  subcatchment == "7" |
  subcatchment == "11" |
  subcatchment == "23" |
  subcatchment == "28" |
  subcatchment == "38" |
  subcatchment == "42" |
  subcatchment == "58" |
  subcatchment == "62" |
  subcatchment == "63" |
  subcatchment == "74" |
  subcatchment == "75" |
  subcatchment == "76" |
  subcatchment == "78" |
  subcatchment == "79" |
  subcatchment == "89" |
  subcatchment == "94" ~ "Hotspot"))

common_peak$hotspot <- as.factor(common_peak$hotspot)

top20_peak_map <- tm_basemap("Hydda.Base") +
  tm_shape(common_peak, unit = "Miles") +
  tm_polygons("hotspot", title = "Legend", textNA = "Subcatchment", palette="#006d2c",
              alpha = 0.8)+
  tm_layout(inner.margins=c(.05, .05, .05, .52), legend.position =  c(.56,.8),
            legend.title.size = 1.4, legend.text.size = 1) +
  tm_text("subcatchment", size = 0.3) +
  tm_scale_bar(position = c(.56,.75), breaks = c(0, 0.2, 0.4, 0.6, 0.8,1)) +
  tm_compass(position = c(.54,.68))
```

```r
tmap_save(top20_peak_map, here("5.Results_Maps", "output_maps","top20_peak_map.png"))
```

Export the results as shapefiles (e.g. For use in other map software like ArcGIS or Google Earth Pro)

```r
#Keep the common hotspots only
common_peak_only <- subcatch_dry %>%
  filter(
  subcatchment == "1" |
  subcatchment == "2" |
  subcatchment == "3" |
  subcatchment == "7" |
  subcatchment == "11" |
  subcatchment == "23" |
  subcatchment == "28" |
  subcatchment == "38" |
  subcatchment == "42" |
  subcatchment == "58" |
  subcatchment == "62" |
  subcatchment == "63" |
  subcatchment == "74" |
  subcatchment == "75" |
  subcatchment == "76" |
  subcatchment == "78" |
  subcatchment == "79" |
  subcatchment == "89" |
  subcatchment == "94" )

#Export as .shp
##st_write(common_peak_only, here("5.Results_Maps", "output_shapefiles", "common_peak.shp"))

#Keep the common hotspots only
common_total_only <- subcatch_dry %>%
  filter(
  subcatchment == "21" |
  subcatchment == "22" |
  subcatchment == "23" |
  subcatchment == "29" |
  subcatchment == "40" |
  subcatchment == "45" |
  subcatchment == "46" |
  subcatchment == "47" |
  subcatchment == "49" |
  subcatchment == "51" |
  subcatchment == "54" |
  subcatchment == "59" |
  subcatchment == "60" |
  subcatchment == "63" |
  subcatchment == "65" |
  subcatchment == "67" |
  subcatchment == "68" |
  subcatchment == "71" |
  subcatchment == "89")
```

```
#Export as .shp
##st_write(common_total_only,  here("5.Results_Maps", "output_shapefiles","common_total.shp"))
```