LOW IMPACT DEVELOPMENT PRACTITIONER'S GUIDE FOR HAWAIʻI

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EXECUTIVE SUMMARY

The **Low Impact Development Practitioner's Guide for Hawai'i** provides informational guidance on how to **plan** for and **implement** Low Impact Development (LID) practices for new development and redevelopment in Hawai'i. LID consists of nature-based solutions aiming to preserve or enhance the natural hydrology of a place that existed prior to development. LID is intended to protect the quality, health, and supply of Hawai'i's water resources and the environment.

Implementing LID offers substantial environmental, economic, and community benefits to the developer, municipality, and the wider community which include:

- Protection of sensitive forests, wetlands, and nearshore habitats.
- Reduced impacts from flooding and erosion.
- Lower long-term life cycle costs.
- Increased property values.
- More aesthetically pleasing and naturally attractive landscapes within urban areas.
- Improved effects on public health.

The LID Practitioner's Guide is intended to be used by the:

- General public
- Developers, engineers, planners, and architects
- State and county government staff
- Elected officials
- Businesses
- Conservation professionals and natural resource managers
- Educators

This update to the 2006 *LID Practitioner's Guide* includes discussions of new and updated LID site design strategies and Best Management Practices (BMPs) and provides guidance for selecting the most appropriate LID for a development or redevelopment project. These LID BMPs include:

- Infiltration Basins
- Infiltration Trenches
- Dry Wells
- Rain Gardens
- Permeable Pavements
- Green Roofs
- Tree or Planter Boxes
- Vegetated Swales
- Vegetated Filter Strips
- Detention Basins

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ABBREVIATIONS

BMP	Best Management Practice
CCH	City and County of Honolulu
CF	cubic feet or foot
CWA	Clean Water Act of 1972
DCIA	Directly Connected Impervious Area
DEQ	Michigan Department of Environmental Quality
DFM	Department of Facility Maintenance
DIA	Diameter
DLNR	State of Hawaiʻi Department of Land and Natural Resources
ENR	Engineering News Record
EPA	US Environmental Protection Agency
ESC	Erosion and Sediment Control
ft	feet or foot
ft/ft	feet per foot
ft/yr	feet per year
ft^2	square feet or foot
ft^3	cubic feet or foot
HAR	Hawaiʻi Administrative Rules
HDOT	State of Hawaiʻi Department of Transportation
HDPE	High Density Polyethylene
HRS	Hawaiʻi Revised Statutes
IMP	Integrated Management Practices
in	inch(es)
in/hr	inches per hour
IPCC	Intergovernmental Panel on Climate Change
LID	Low Impact Development
MAX	Maximum
MCC	Maui County Code
MIN	Minimum, minutes
mm/yr	millimeter(s) per year
MS4	Municipal Separate Storm Sewer System

NOAA National Oceanic and Atmospheric Administration

NPDES National Pollutant Discharge Elimination System

NRCS Natural Resources Conservation Service

O&M Operation and Maintenance

PCBs Polychlorinated Biphenyls

RRWQ Rules Relating to Water Quality of the City and County of Honolulu

SCM Storm Control Measure

SF square feet or foot

SOH State of Hawaiʻi

TSS Total Suspended Solids

TYP Typical

UNH University of New Hampshire

1 INTRODUCTION

1.1 INTRODUCTION

From the rain above us, to the ocean around us, and to the waters in the ground below us, we in Hawaiʻi are surrounded by water. In this unique collection of watersheds that make up the Hawaiian Islands, nestled within are our homes, communities, and places of work, worship, and play. Our island life revolves around water. For hundreds of years before us, these watersheds facilitated the movement of rainwater which shaped the environment we call home (see **Figure 1-1**). The way we have developed these places within our unique watersheds has led to disruptive impacts on our environment, the natural systems that regulate water, the health of our communities, and the socioeconomic factors that affect each of us. Therefore, all of us living in Hawaiʻi have a collective responsibility to preserve and protect the quality, health, and supply of these precious water systems which are critical to our survival and prosperity.

So how can we continue to develop responsibly while preserving the effectiveness of our islands' natural water systems? Incorporating Low Impact Development practices to manage stormwater within our own developments is one effective way to do this.

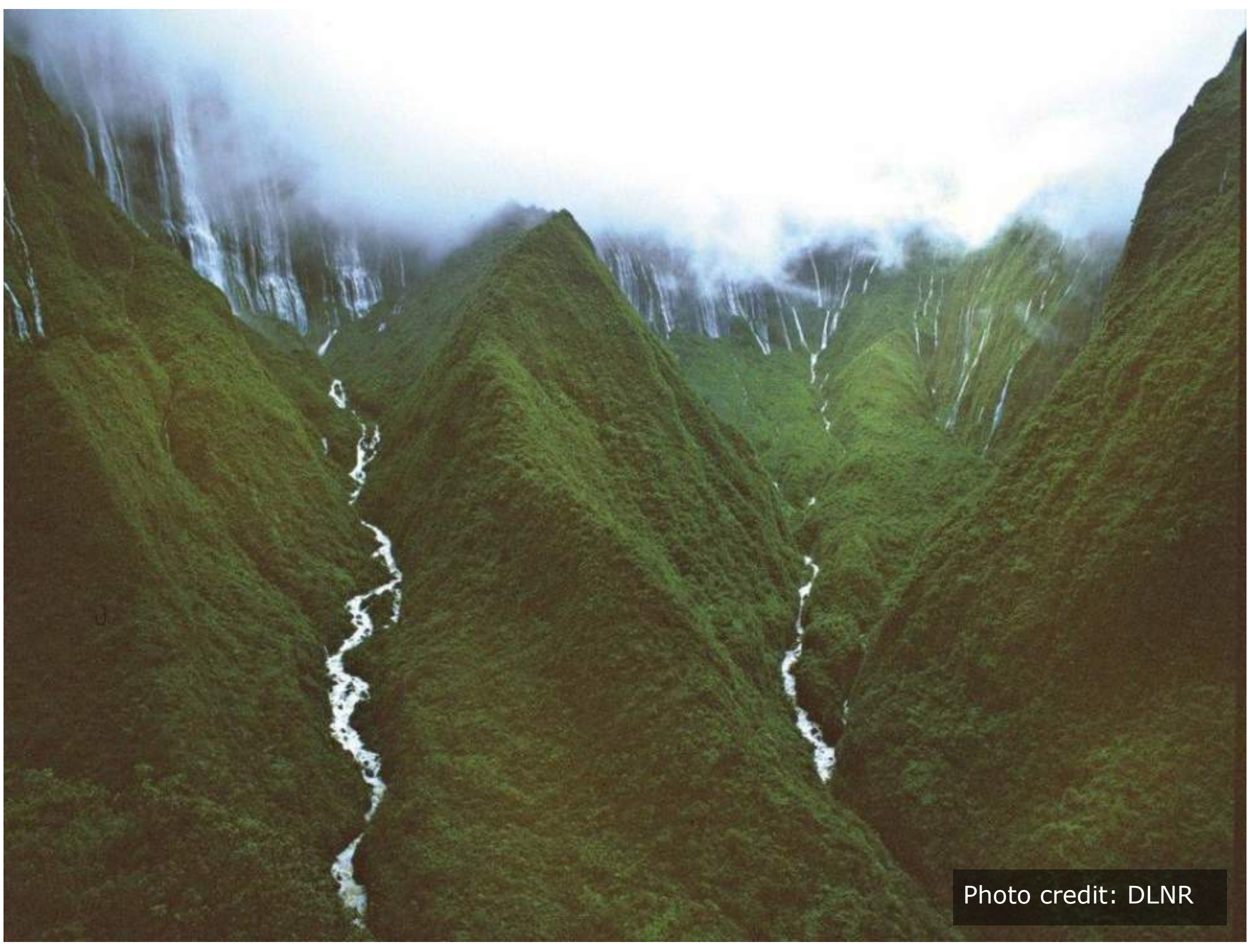


Figure 1-1: West Maui Watershed

1.2 BACKGROUND

Hawaiʻi's water resources are a vital part of our way of life. These resources provide habitats for our native fish and wildlife, provide residents with fresh water, support traditional practices of fishing and agriculture, support our recreational activities, and are a significant aspect of Hawaiʻi's economy. Residents and visitors rely heavily on the abundance of healthy water resources within our state. Due to the many ways that we all depend on our water resources, it is essential for all to protect these resources. An important way to protect these resources is by finding new ways to manage stormwater.

Photo credit: GoHawaii.com

What is a Watershed?

A watershed is an area of land, such as a mountain or valley, that catches and collects rainwater which usually drains into the soil or to the ocean through a river or stream. *(Source: DLNR)*

Hawaiʻi has seen a noticeable decrease in the quality of natural environmental conditions since the growth and development of our communities and neighborhoods within our watersheds. Many natural streams and wetlands that have been important in maintaining the natural hydrology of our islands have been paved over or diverted, resulting in disruptive impacts to local climate, nearshore environments, and the ability of our groundwater supplies to recharge unencumbered. The fragmentation of the watershed from *mauka* (towards the mountains) to *makai* (towards the ocean) due to land development has substantially impacted these critical water resources (SOH 2023).

Conventional neighborhood site design can exacerbate this fragmentation when large areas of impervious surfaces (such as wide roads and parking lots), segregated land uses, and enclosed stormwater drainage systems prevent water from infiltrating into the soil and instead quickly convey untreated stormwater runoff into nearby water bodies.

Furthermore, as climate change impacts on Hawaiʻi increase in the future, the frequency and intensity of large storm events is expected to increase. Thus, the need for alternative approaches to manage stormwater becomes critical to reducing the impacts that storm events have on existing stormwater systems. With local mean sea levels also expected to rise, stormwater systems would also be threatened by the backflow of seawater into these systems. This phenomenon is already occurring in low-lying areas such as Waikīkī and Māpunapuna on Oʻahu, leading to inland flooding with pools of brackish water. These threats emphasize the need to address our current stormwater management practices.

What has resulted from conventional stormwater management designs in Hawai‘i?

Murky and Hazardous Waters in the Ala Wai Canal.
(Photo credit: Elyse Mallams, Honolulu Magazine)

Invasive Algae in Maunalua Bay.
(Photo credit: Honolulu Star Advertiser)

Flooding of Roadways in Kahului.
(Photo credit: The Maui News)

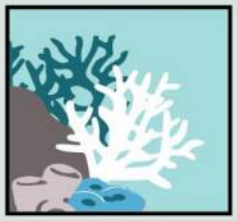
Flooding of Properties in Ha‘ena.
(Photo credit: Jamm Aquino, Honolulu Star Advertiser)

Polluted runoff into oceans off Kona.
(Photo credit: Laura Ruminski, West Hawaii Today)

Conventional stormwater management designs have contributed to environmental issues and disruptions throughout Hawai‘i that include:

Flooding of properties and roadways

Pollution of nearshore environments



Damage to coral reefs

Increased cleanup costs after storm events

Impacts to public health

1.3 WHAT IS LOW IMPACT DEVELOPMENT?

Low Impact Development (LID) is a planning and development approach that is more environmentally sustainable than conventional development. LID integrates landscaping and stormwater management design strategies to preserve or enhance the natural hydrology of a site, mimicking the watershed patterns that existed before development (see **Figure 1-2**). LID Best Management Practices (BMPs) emphasize the conservation and use of natural features within a site, reducing stormwater runoff and promoting natural processes such as infiltration, evapotranspiration, or reuse of stormwater where it is generated to protect the water quality of streams and the ocean. An essential principle of LID is recognizing that stormwater isn't just a by-product to be discarded but rather a valuable resource to be conserved, protected, and reused.

Figure 1-2: Infiltration Trench located at Punahou School in Honolulu

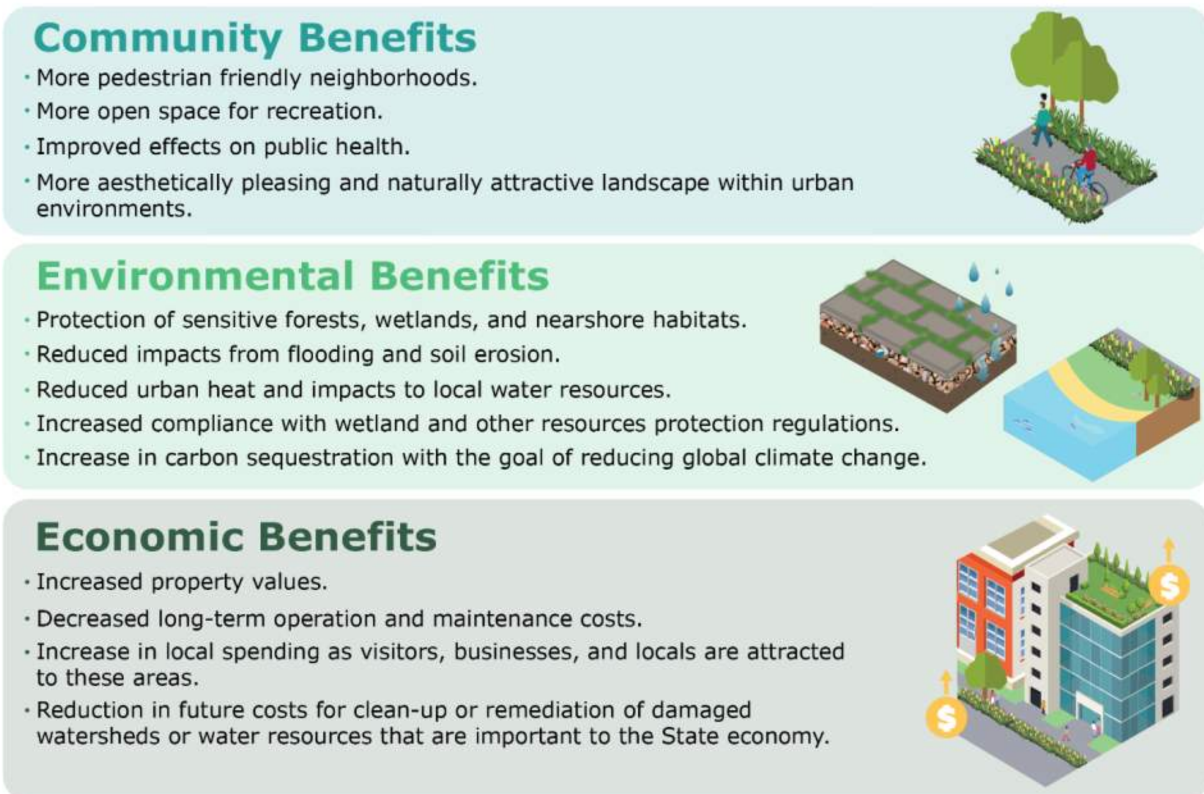
1.4 GOALS AND BENEFITS OF LID

LID's objective is to minimize the environmental impact of development on water resources while upholding the developer's intended purpose and vision for the site. Numerous LID concepts involve on-site treatment methods that don't rely on physical structures; leading to lower infrastructure expenses and potentially raising the property's value compared to typical development systems that require costly maintenance. The goals of LID include:

- Prevent environmental impacts rather than having to mitigate them;
- Manage water quantity and quality as close to the source as practicable and minimize the use of large or regional collection and conveyance systems;
- Preserve natural areas, native vegetation, and reduce impacts on watershed hydrology;
- Use natural drainage pathways as a framework for site design;
- Utilize less complex, nonstructural methods for stormwater management that are lower cost and require lower maintenance than conventional structural controls; and
- Create a multifunctional landscape.

LID offers substantial advantages to the municipality, developer, and the wider community. Employing a more compact design with more permeable surface and smaller infrastructure (such as stormwater drainage systems) leads to cost savings for developers. Less impermeable surface area also results in decreased surface runoff, thereby alleviating strain on municipal drainage systems. Furthermore, these practices curtail nonpoint source pollution in drinking water sources, recreational waters, and wetlands, ultimately preserving valuable water resources and avoiding the need for costly future restoration efforts. Other LID benefits are listed in **Figure 1-3**.

Figure 1-3: LID Benefits



1.5 ABOUT THE LOW IMPACT DEVELOPMENT PRACTITIONER'S GUIDE

The *Low Impact Development Practitioner's Guide for Hawaiʻi* provides our local communities, government agencies, developers, businesses, and others informational guidance on **how** to plan for and implement LID practices for new developments and redevelopments in Hawaiʻi.

This update to the 2006 *Low Impact Development A Practitioner's Guide* includes new and updated LID design and stormwater management strategies that have been deployed in Hawaiʻi or other places with similar topographical and environmental conditions along with an improved understanding of each strategy to make educated stormwater management decisions for a development project. This LID Practitioner's Guide has been developed with input from various state and county government agencies and organizations with regulatory or administrative responsibilities or experience in the deployment of LID. This Guide is intended to facilitate a range of LID techniques for various locations throughout Hawaiʻi and provide a wide range of stakeholders with a reference, tool, and technical guide for those planning for and integrating LID strategies.

Sections 2–4 of this Guide provide further discussions on stormwater management, site design strategies, and LID BMPs. A range of BMPs is provided within these sections, along with a decision-making process to assist in selecting the appropriate LID BMP for each development.

Developers, Engineers, Planners, & Architects	Use the Guide's technical design standards to support the planning and design of innovative LID approaches within their development projects.
State & County Government Staff	Use the Guide to develop, update, or change existing plans, rules, and regulations related to LID and to determine the best placement and design of capital improvement projects to receive the economic and environmental benefits of LID.
Elected Officials	Use the Guide to learn LID basics to craft and support a regulatory environment that considers the use of LID to protect our islands' natural resources.
Businesses	Use the Guide to incorporate innovative solutions that promote thriving businesses and environmental sustainability.
Conservation Professionals & Natural Resource Managers	Use the Guide to support the planning, design, and promotion of innovative LID approaches to achieve conservation and natural resource management goals.
Teachers	Use the Guide as a resource to educate and raise awareness about various LID designs to protect vital water resources, environments, and climate.
General Public	Use the Guide to learn about, advocate for, and implement LID on their own properties.

To proactively preserve and protect our local water resources, it is important for all stakeholders to put LID into practice. Each user of this Guide is responsible for working within their capabilities and, if needed, is suggested to seek advice and consultation from appropriate experts. **Figure 1-4** provides information on who should use this Guide and how to use it.

Figure 1-4: Who Should Use This Guide and How to Use It

1.6 LID PRACTICES IN HAWAIʻI

Since 2006, the number of LID BMPs employed throughout the state has increased, most notably on Oʻahu and Maui. This increase in LID can be attributed to the adoption of state and county stormwater management rules and regulations that require the use of LID for new development and redevelopment and the voluntary actions of many property owners and conservation groups (see **Figure 1-5**). Although LID practices may be required for some development or redevelopment projects in Hawaiʻi, LID BMPs can be installed voluntarily within any property to take advantage of the environmental, economic, and aesthetic benefits of LID. Every effort to manage stormwater with LID benefits everyone in Hawaiʻi.

Figure 1-5: Green Roof on the Hawai'i Convention Center

To ensure that LID BMPs remain effective, proper management and maintenance techniques are needed which include public education to deter the premature deterioration of LID BMPs and transparency on the effort required to operate and maintain LID systems. **Section 4** of this Guide discusses recommended operations and maintenance for each LID BMP.

1.7 REGULATORY REQUIREMENTS RELATED TO STORMWATER AND LID

Federal, state, and county regulations and programs regulate the discharge of stormwater into our waterways and encourage the use of LID BMPs. These programs protect water quality by encouraging or requiring the treatment of runoff where it is generated, thereby decreasing water pollution and stormwater volume at the source.

Federal Regulations

Two of the main federal regulations for managing stormwater runoff include: **Clean Water Act of 1972:** This law established requirements for the control of stormwater pollutants into the nation's waters and water quality standards for surface waters.

These federal regulations would be most applicable to federally funded projects or projects occurring on federally owned lands!

- **National Pollutant Discharge Elimination System (NPDES) program:** This is a permit program, under the Clean Water Act, which regulates stormwater discharge from three potential sources: municipal separate storm sewer systems (MS4s), construction activities, and industrial activities. The US Environmental Protection Agency (EPA) authorizes each state to administer the NPDES program for their state. However, not all states have their own NPDES permit program. For those states, the EPA administers the NPDES permit program.

Other federal regulations related to stormwater runoff include:

- **Section 10 of the Rivers and Harbors Act of 1899**: This act relates to construction of any structure in or over any navigable water of the United States.
- **Coastal Zone Management Act of 1972**: This program helps states in planning and managing the development and protection of coastal areas.
- **Section 303(d) of the Clean Water Act of 1972**: This section relates to the establishment of Total Maximum Daily Loads for impaired water bodies.
- **Section 401 of the Clean Water Act of 1972**: This section relates to Water Quality Certification for any activity that may discharge into waters of the United States and that requires a federal permit, license, certificate, approval, registration, or statutory exemption.
- **Section 404 of the Clean Water Act of 1972:** This section relates to the regulation of the discharge of dredged or fill material into waters of the United States.
- **Endangered Species Act of 1973:** The primary law in the US for the protection, recovery, and conservation of fish, wildlife, and plants that are listed as threatened or endangered.

State of Hawaiʻi Regulations

At the Hawaiʻi State level, the main program regulating the discharge of stormwater and pollutants into our state waterways is through the administration of the NPDES permit program. The US EPA has designated the State of Hawaiʻi Department of Health as the authority to manage the NPDES permitting program in Hawaiʻi.

These state regulations would be most applicable to state-funded projects, projects occurring on state-owned lands, or large development projects!

An **NPDES permit** is required for a development or redevelopment project if the project is:

- a development greater than or equal to 1 acre;
- an industrial facility; or
- an activity that would discharge stormwater pollutants into state waters from point sources.

State laws and other state regulations related to stormwater runoff include:

- Hawaiʻi Revised Statutes (HRS)
  - **HRS Chapter 180C:** Soil Erosion and Sediment Control
  - **HRS Chapter 205A:** Coastal Zone Management Program
  - **HRS Chapter 342D:** Water Pollution
  - **HRS Chapter 342E:** Nonpoint Source Pollution Management and Control
- Hawaiʻi Administrative Rules (HAR)
  - **HAR Chapter 11-53:** Section 401 Water Quality Certifications

  - **HAR Chapter 11-54: Water Quality Standards**
  - **HAR Chapter 11-55: Water Pollution Control**
  - **HAR Chapter 11-56:** Nonpoint Source Pollution Control
- State of Hawaiʻi Department of Transportation (HDOT) Permanent BMP Requirements
  - These requirements are most applicable to HDOT Highways projects and relate to the **implementation** of permanent LID BMPs to applicable new HDOT developments and redevelopment projects, highway base yards, and maintenance facilities statewide. These requirements can be found in the HDOT Stormwater Post-Construction BMP Manual (2022).

County Regulations

Several county regulations and plans either require or encourage the use and integration of LID BMPs for a development or redevelopment project in their respective counties.

Most regulations that require permanent LID BMPs apply to projects within the City and County of Honolulu (CCH) and the County of Maui. In addition, all counties have adopted an Erosion and Sediment Control (ESC) ordinance conforming to HRS Chapter 180C and a set of standard specifications for public works construction on each island for the protection of water resources resulting from land-disturbing activities.

Although no regulations are currently in place requiring LID BMPs on Kauaʻi and Hawaiʻi Island, property owners could still receive the economic and environmental benefits from the integration of LID BMPs within their development or redevelopment project.

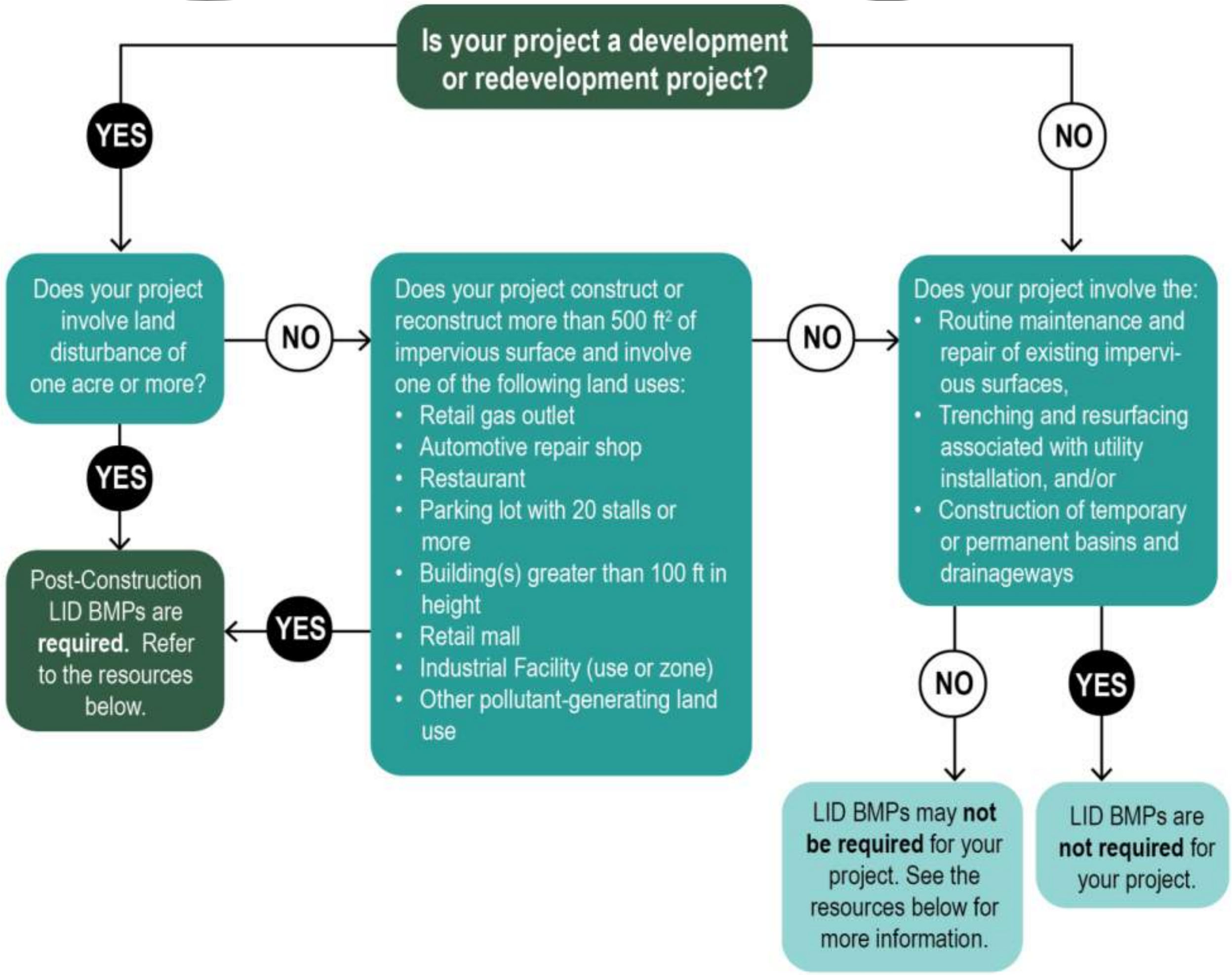
Projects in the City & County of Honolulu

As required under the CCH Charter, the *Oʻahu General Plan* (updated in 2021) is a foundational comprehensive set of objectives and policies for the long-range development of the island and is used to guide subsequent community development and policy plans. Implementation of ordinances and regulations must be consistent with the General Plan. The use of LID is a concept that aligns and supports the objectives for natural environment and resource stewardship, transportation and utilities, and physical development and urban design within the *Oʻahu General Plan*.

According to the CCH Administrative Rules Relating to Water Quality (§20-3) administered by the Department of Planning and Permitting, development or redevelopment projects on Oʻahu may be required to install permanent LID BMPs (see **Figure 1-6**).

Figure 1-6: Flowchart of Projects in the CCH Requiring LID

Does your development, redevelopment, or activity require the installation of post-construction LID BMPs?



Source: CCH Post-Construction Water Quality Requirements Booklet

Resources and regulations in support of the implementation of LID in the CCH include:

- O'ahu General Plan (adopted in 2021)
- City & County of Honolulu Administrative Rules Section 20-3: Rules Relating to Water Quality (2017)
- City & County of Honolulu Post-Construction Water Quality Requirements Booklet (2019)
- City & County of Honolulu Stormwater BMP Guide for New and Redevelopment (2017)

Projects in the County of Maui

The County of Maui 2030 General Plan (adopted in 2010) is a foundational set of goals, objectives, policies, and implementing actions that portray the desired direction for the county’s future. All Maui County implementation ordinances and regulations must be consistent with the General Plan. The use of LID is a concept that aligns and supports the goals, objectives, and policies for protecting the natural environment, improving physical infrastructure, and promoting sustainable land uses and growth management within the County of Maui 2030 General Plan.

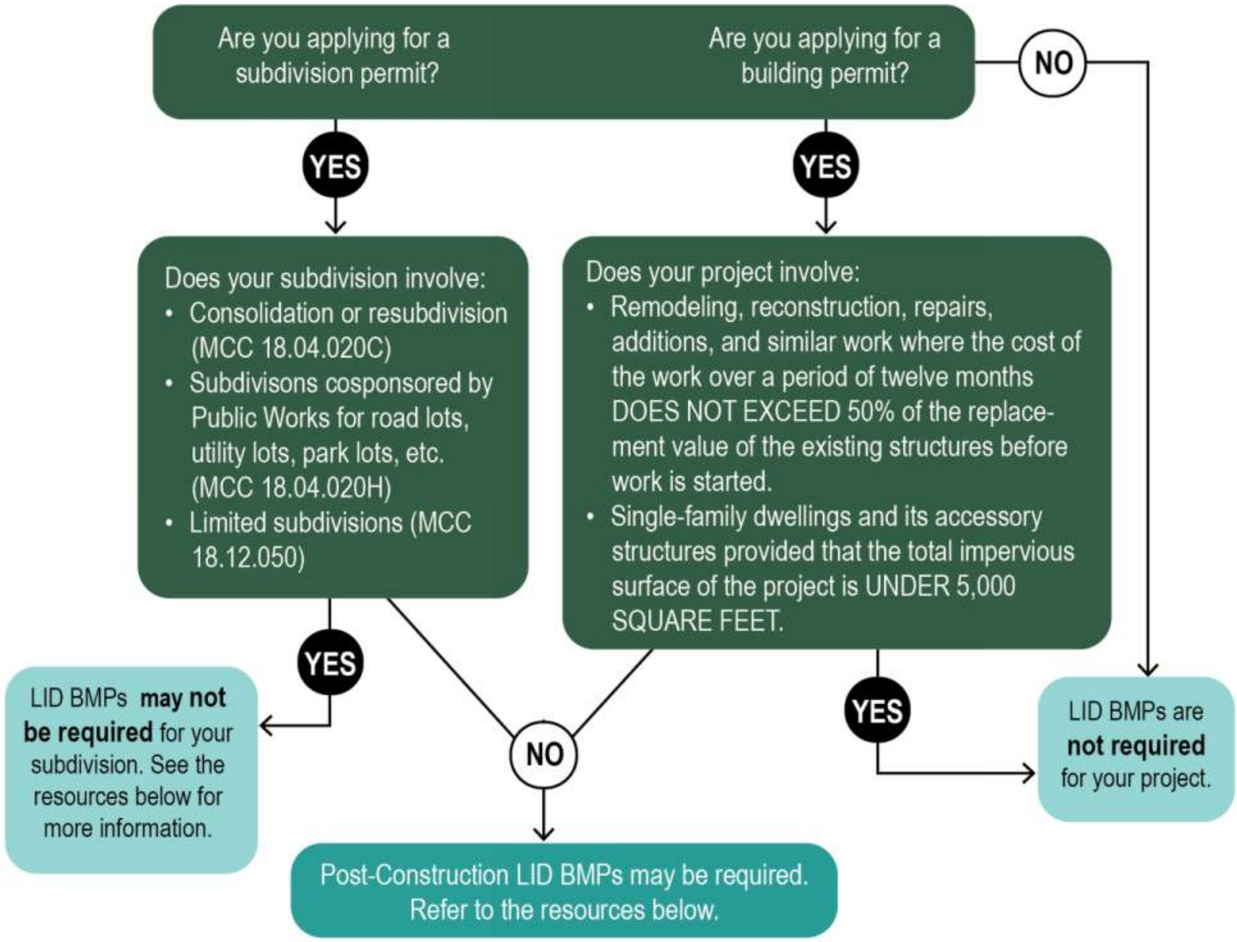
According to the Maui County Code (MCC) and the *Rules for the Design of Stormwater Treatment Best Management Practices* (Chapter 15-111) enforced by Maui County’s Department of Public Works, projects that require building or subdivision permits in the county may be required to install permanent LID BMPs (see **Figure 1-7**).

Who needs a building permit?
A building permit is required for anyone constructing, altering, moving, demolishing, repairing, and using any building or structure within the county (MCC Chapter 19.500).

Who needs a subdivision permit?
A subdivision permit is required for anyone who wishes to subdivide or reconsolidate land within Maui County (MCC Chapter 18.04).

Figure 1-7: Flowchart of Projects in Maui County Requiring LID BMPs

Does your development, redevelopment, or activity require the installation of post-construction LID BMPs?



Source: Maui County Information Sheet for Stormwater Quality BMP Plan and Maintenance Plan

Resources and regulations in support of the implementation of LID BMPs in Maui County include:

- Maui County 2030 General Plan (adopted in 2010)
- Rules for the Design of Stormwater Treatment Best Management Practices (Maui County Administrative Rules Chapter 15-111) (effective since 2012)
- Information Sheet for Stormwater Quality Best Management Practices Plan and Maintenance Plan (revised in 2023)
- Maui County Code
  - Section 16.26B.3900 (Post-construction Stormwater Quality Best Management Practices) which mandates compliance as part of the building code.
  - Section 18.20.135 (Post-construction stormwater quality best management practices) which mandates compliance as part of subdivision development.

- Section 18.04.020 (Related to subdivision requirements)

Projects Within the County of Hawaiʻi

The County of Hawaiʻi 2045 General Plan (anticipated to be adopted by County Council in 2024) is the primary policy document to be used by Hawaiʻi County agencies, planning commissions, elected officials, landowners, developers, and citizens to guide the land use policies and development of Hawaiʻi County. Ordinances and regulations of the County must be consistent with the policies and objectives of the General Plan.

At the time of publication of this Guide, the only regulation in support of the implementation of LID BMPs in the County of Hawaiʻi is applicable to subdivision storm drainage systems:

- Hawaiʻi County Code Section 23-92: Subdivision projects must construct stormwater disposal systems using drywells, infiltration basins, or other infiltration methods to contain runoff.

However, as mentioned throughout the County's 2045 General Plan draft dated September 2023, prioritizing and promoting stormwater management and the implementation of green infrastructure and LID BMPs on the island are critical elements to a resilient and sustainable island that the County strives to achieve in the future. Objectives and policies in the General Plan encourage the use of LID BMPs in the design of roads, rights-of-way, drainage systems, parking areas, and other development sites.

Resources in support of the implementation of LID BMPs in the County of Hawaiʻi include:

- County of Hawaiʻi General Plan 2045: Planning for a Sustainable Future (September 2023 Draft)
- Nonpoint Pollution Control Field Guide: Best Management Practices for the Operation and Maintenance of Hawaiʻi County Roads, Highways, and Bridges (2020)

Projects Within the County of Kauaʻi

The County of Kauaʻi General Plan (approved in 2018) is the county's guiding policy framework built upon a set of key objectives and actions to manage growth, land use, and development. County ordinanaces and regulations must be consistent with the policies and objectives of the General Plan.

At the time of publication of this Guide, the County of Kauaʻi does not yet have regulations requiring the use of permanent LID BMPs for development or redevelopment projects. The only regulations in support of the implementation of LID BMPs in the County of Kauaʻi are applicable to subdivision storm drainage systems:

- Kauaʻi County Code Section 9-2.6(4): Storm drainage systems for subdivisions must assure that waters drained from the subdivision are substantially free of pollutants, including sedimentary materials, to protect watercourses and shorelines.

However, as mentioned in the County’s General Plan, green infrastructure is encouraged to be used for watershed management and for the desired design of new communities and drainage systems in lieu of traditional methods of development. In addition, the General Plan supports permitting and code changes at the County level to encourage LID to support water savings and conservation.

Resources in support of the implementation of LID BMPs in the County of Kauaʻi include:

- Kauaʻi Kākou: County of Kauaʻi General Plan (adopted in 2018)

2 STORMWATER MANAGEMENT

2.1 WHY STORMWATER MATTERS

The Hawaiian Islands are home to numerous microclimates—some areas receive a lot of rain, while some areas are very dry. The average annual rainfall exceeds 300 inches per year in many mountainous areas. These climatic conditions combined with the region's unique volcanic and coral geologic formations, sensitive water resources, and significant land development make stormwater a very significant environmental and economic issue.

Historically, stormwater has been viewed as strictly a drainage issue and a waste to be disposed of. Because of this, stormwater runoff is usually directed to the nearest discharge location, infiltrated with little or no pretreatment, or conveyed directly to receiving waters via large concrete channels or piped by the shortest route practicable.

Development usually increases the total area of impervious surfaces at a project site, preventing the natural infiltration of rainwater into the underlying groundwater system. As a result, the groundwater lens (which serves as the principal drinking water source) will become depleted without adequate recharge or water conservation. Or, if stormwater is infiltrated without adequate pretreatment, groundwater quality is degraded.

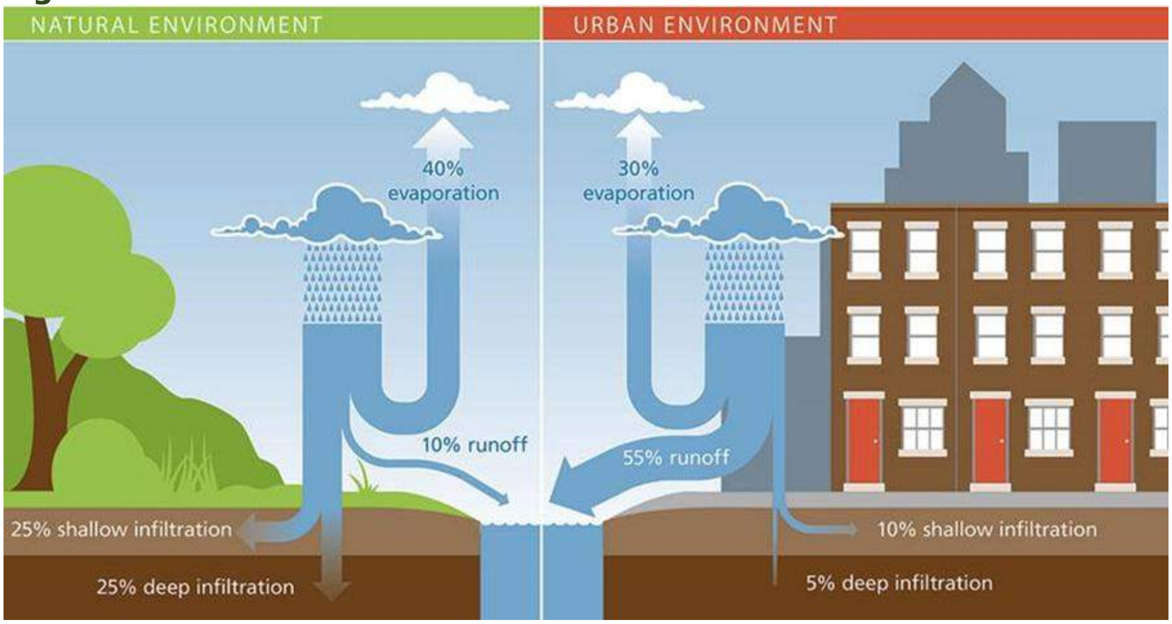
2.1.1 IMPACT OF STORMWATER RUNOFF ON HAWAIIAN WATERSHEDS

Urban development has a profound influence on the quality of the waters of Hawaiʻi. Development dramatically alters the local hydrologic cycle (see **Figure 2-1**). The hydrology of a site changes starting from the initial clearing and grading that occurs during construction. Trees that intercepted rainfall are removed and natural depressions that had temporarily ponded water are graded to a uniform slope. The spongy humus layer of native vegetation that had blanketed the ground and absorbed rainfall is scraped off, eroded, or severely compacted. Having lost its natural stormwater storage capacity, a cleared and graded site can no longer prevent rainfall from being rapidly converted into runoff.

The situation worsens after construction. Rooftops, roads, parking lots, driveways, and other impervious surfaces no longer allow rainfall to soak into the ground. Consequently, most rainfall is directly converted into stormwater runoff.

The increase in stormwater runoff can be too much for natural drainage systems to handle. As a result, the drainage system is often "improved" to rapidly collect runoff and quickly convey it away (using curbs, gutters, enclosed storm sewers, and lined channels) from properties. The stormwater runoff is subsequently discharged to downstream waters, such as streams, wetlands, lagoons, or nearshore bays.

Figure 2-1: Natural vs. Urban Stormwater



2.1.2 IMPACTS TO NATURAL STREAM CHANNELS

As pervious rangelands and forests are converted into less pervious urban soils or pavement, both the frequency and magnitude of storm flows increase dramatically. As a result, the bank-full event (when a stream or river overtops its banks) occurs two to seven times more frequently after development occurs (Leopold 1994). In addition, the discharge associated with the original bank-full storm event can increase by up to five times (Hollis 1975).

Overbank floods are ranked in terms of their statistical return frequency. For example, a flood that has a 50% chance of occurring in any given year is called a "two-year" flood. The two-year storm has been frequently designated as the "bank-full flood," as researchers have demonstrated that most natural stream channels on the islands have just enough capacity to handle the two-year flood before spilling out into the floodplain. This rainfall depth is called the two-year design storm. Similarly, a rain event that has a 10% chance of occurring in any given year is called a "ten-year storm."

2.1.3 IMPACTS TO WATER QUALITY

Impervious surfaces accumulate pollutants windblown in from adjacent areas, leaked from vehicles, or deposited from the atmosphere. During storm events, these pollutants are quickly washed off and rapidly delivered to downstream waters. Water quality impacts are numerous, and pollutants include sediments (measured as total suspended solids or TSS), nutrients (nitrogen and phosphorus), and pathogens (bacteria and viruses).

2.1.3.1 Sediment (Suspended Solids)

Sediment includes particles that are deposited on impervious surfaces and washed off by a storm event as well as the erosion of stream banks and construction sites.

Sediments can harm aquatic life in streams, ponds, and nearshore marine waters by causing turbidity, or cloudiness in the water. The cloudiness can reduce light penetration aquatic vegetation needs for growth and increase water temperatures. Sediment can smother benthic organisms. In addition, other pollutants can attach to sediment and discharge into our water resources.

2.1.3.2 Nutrients

Runoff from developed land has elevated concentrations of phosphorus and nitrogen, which can cause eutrophication, or the excessive enrichment of water habitats that eventually lead to low levels of oxygen in these water bodies. Significant sources of nutrients include fertilizer, atmospheric deposition, sewage (e.g., from overflows and faulty septic systems), animal waste (both domesticated and feral), organic matter, and stream bank erosion. Data from the mainland US suggest that lawns are a significant contributor, with concentrations as much as four times higher than other urban land uses (Steuer et al. 1997; Waschbusch et al. 2000; Bannerman et al. 1993). Nutrients are a major source of degradation in some of the islands' waters.

2.1.3.3 Bacteria

Bacteria levels in stormwater runoff routinely exceed public health standards for water-based activities, such as surfing, swimming, and diving. Sources include pet waste, urban wildlife, sanitary sewer overflows, wastewater, and illicit connections to the storm drain system. Bacteria are a leading contaminant in state waters and have led to many beach closures.

2.1.4 ENVIRONMENTAL RESOURCE AREAS AND SENSITIVE RECEPTORS

The Hawaiian Islands contain a broad range of environmental resource areas which are sensitive to stormwater discharges. Critical resource areas include groundwater, streams, ponds, wetlands, beaches, and coral reefs. Both the hydrology and water quality in these areas are impacted by stormwater runoff, as were discussed above. This section explains the sensitivity of the various resource areas and evaluates their potential response to alternate stormwater management strategies and practices.

2.1.4.1 Groundwater

Groundwater serves as the primary source of drinking water in Hawaiʻi. The largest source of groundwater recharge is rainfall, which infiltrates the ground and recharges the underlying water table (the upper surface of the groundwater system). A significant portion of this rainfall is lost to evapotranspiration, some is lost to surface runoff, and the remaining portion is available as "recharge" to groundwater.

As land development occurs, impervious surfaces preclude the natural infiltration of this rainwater, thereby reducing the recharge rate. This reduced recharge results in a lowering of the water table and a reduction of the thickness of the drinkable groundwater lens. Ultimately, development can lead to a depletion of groundwater resources, increased saltwater intrusion to drinking water wells and aquifers, and increased concentrations of other pollutants derived from urban runoff.

Water withdrawals for drinking water and irrigation also deplete the groundwater lens and result in declining water table elevations and corresponding decreases in the thickness of the freshwater lens. The Ghyben-Herzberg principle suggests that for each foot that the water table declines, the freshwater lens thickness decreases by 40 feet (based upon a 1:40 density ratio between fresh and salt water). Therefore, reductions in recharge and the water table can significantly affect the potable groundwater system.

One potential remedy for this impact is to collect and infiltrate stormwater runoff and to help restore (or enhance) natural recharge rates. To some degree, this already occurs in current stormwater management implementation. It is possible to collect and infiltrate enough stormwater to match the natural (predevelopment) recharge rates. This strategy may be a viable option to mitigate and compensate for other sources of groundwater consumption, such as withdrawals for drinking water and irrigation.

However, the infiltration of stormwater raises important water quality issues. Stormwater is commonly degraded with a broad range of pollutants collected from the land surface or accompanying rainfall. Secondly, aquifers can be highly permeable and, therefore, very susceptible to contamination. Thus, depending on the land use, stormwater can require significant pretreatment prior to infiltration to protect the quality of groundwater resources. In addition to pretreatment, wellhead protection areas have been delineated, showing the specific groundwater areas that contribute to the drinking water supply. These wellhead protection areas require the highest level of protection to ensure a safe drinking water supply. Currently, recharge is not a requirement for development projects but can be an effective stormwater management tool if designed properly.

2.1.4.2 Freshwater Streams, Ponds, and Wetlands

Numerous streams (perennial and intermittent), ponds, and wetlands are throughout Hawaiʻi. They provide important aquatic habitat for a broad range of fish, amphibian, mammal, and bird species. They also serve as recreational and food resources for people. Suface water provides more than 50% of the irrigation water in Hawaiʻi, and on some islands, is the main source of drinking water. Streams are also a source of hydroelectric power and support certain traditional Native Hawaiian gathering customs and taro production (Oki 2003).

Stream flow is derived from overland runoff and baseflow from groundwater, which discharges into streambeds. If baseflow is continuous throughout the year, the stream is perennial. If groundwater elevations fall below the natural streambed, the stream is intermittent. In either case, stream ecosystems are very dependent upon the maintenance of natural groundwater levels and corresponding groundwater discharges to the streams.

Each stream ecosystem is adapted to its natural flow regime, which is a mixture of surface runoff and groundwater baseflow. Stormwater management practices associated with land development within watersheds can significantly alter the timing and rates of surface flow and groundwater discharge, thereby impacting stream ecosystems. In some cases, naturally occurring perennial streams may dry up seasonally in a developed watershed, significantly altering the habitat. Similarly, water quality impacts caused by increased nutrients and sedimentation can significantly impact streams ecosystems. Finally, streams, particularly small first- and second-order streams, are especially susceptible to increased channel erosion associated with altered hydrology and land development.

Ponds, including nearshore fishponds, provide unique habitats and are also sensitive to stormwater discharges within their watersheds. Eutrophication is a common problem in freshwater ponds and is the result of excessive nitrogen and phosphorus loading, which can cause excessive weed or algal growth and ultimately can cause depleted oxygen levels, fish kills, and noxious odors. Common sources of phosphorus include phosphate-containing cleaners or detergents, human and animal waste, and lawn fertilizers. Common sources of nitrogen include human and animal waste, and lawn fertilizers.

Wetlands provide a broad range of habitat and recreational value. They too are susceptible to impacts from stormwater in terms of both hydrology and water quality changes. Wetlands are defined and entirely dependent upon surface and near surface hydrologic conditions (water levels to within 12 inches of the surface of the ground), which support hydrophytes (wetland vegetation) and hydric soils. Like the other freshwater resource areas discussed above, wetlands are very sensitive to water level changes and alterations in water inputs. Therefore, stormwater must be managed within the watersheds to wetlands in a manner that preserves natural flow regimes. Wetlands are also susceptible to pollutant loading increases, particularly phosphorus and nitrogen.

2.1.4.3 Coastal Waters

Coastal waters surround each of the Hawaiian Islands and serve as the ultimate discharge area for all surface runoff. Nearshore waters are valuable for the support and propagation of shellfish and other marine life, conservation of coral reefs, and oceanographic research and serve as a very significant recreational resource for people. Coastal water quality issues include eutrophication, damage to coral reefs (primarily through sedimentation), bacterial/viral pollution of swimming beaches, and increased erosion. Sediments cause physical damage, including decreased water clarity and smothering of coral and other marine resources (Fukuda 2004). Nutrients (typically nitrogen and phosphorous for coastal environments) cause eutrophication, which results in excessive algae and weed growth, depleted dissolved oxygen levels, and foul odors. Coastal erosion is projected to increase as sea levels rise. Erosion will cause loss of habitat (e.g., beaches for monk seals and turtle nesting), negative impacts to benthic habitat (e.g., sedimentation on coral reefs), and degradation of water quality (e.g., increased turbidity and exposure of existing cesspools).

Cesspools pose a significant risk to nearshore water and groundwater quality because cesspools do not treat wastewater. Cesspools merely dispose of wastewater. Over 80,000 cesspools are in the state; over half of them pose a significant risk to water resources. In 2017, the Hawaiʻi State legislature passed Act 125, which requires the replacement of all cesspools by 2050. The replacement of all cesspools will benefit our water resources and the public for years to come.

2.2 SEA LEVEL RISE

Global mean sea level is the average height of the entire ocean surface. The present rate of change in the global mean sea level is +3.1 millimeters per year (mm/yr) (Sweet et al. 2022). Global mean sea level rise has accelerated over preceding decades compared to the mean of the 20th century. Regional effects cause sea levels to increase in some parts of the planet while decreasing or remaining relatively stable in other areas. In the contiguous US, sea level has risen on average by 6.5 inches (in) since 1950 (Sweet et al. 2018). Factors contributing to the observed rise in sea level include melting of land-based glaciers and ice sheets and thermal expansion of the ocean water column.

Sweet et.al. (2017 and 2022) identify specific regions that are susceptible to a greater-than-average rise in sea level. Hawaiʻi thus far has seen a rate of sea level rise (+1.54 mm/yr) less than the global average (+3.1 mm/yr); however, this rate is expected to change in the future. Hawaiʻi is in the "far field" regarding the effects of melting land ice. This means that the effects of melting land ice have been significantly less in Hawaiʻi compared to areas nearer to the ice melt. Over the next few decades, these effects are expected to spread to Hawaiʻi, which is then projected to experience a sea level rise greater than the global average.

Future scenarios and projections for sea level rise vary and are dependent upon a variety of factors. The Intergovernmental Panel on Climate Change (IPCC) provides projections on future sea levels under a range of possible global emissions and temperature scenarios. The IPCC projections estimate that Hawaiʻi will experience 0.6 to 0.8 feet (ft) of sea level rise by 2050 and 1.3 to 2.5 ft of sea level by 2100. The IPCC AR6 Sea Level Projection Tool allows users to view both global and regional sea level projections from 2020 to 2150.

The US Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force (Task Force) also provides sea level change projections through 2150 for all US states and territories. The Task Force projections are based on targeted elevation thresholds for sea level rise at specific times in the future. The Task Force projections estimate that Hawaiʻi will experience 0.5 to 1.4 ft of sea level rise by 2050, and 1.0 to 6.0 ft of sea level by 2100. The Interagency Sea Level Rise Scenario Tool allows users to view both global and regional sea level projections from 2020 to 2150.

Technical information about sea level rise is available in the following documents:

- National Oceanographic and Atmospheric Administration. 2023. "Relative Sea Level Trends."
- Intergovernmental Panel on Climate Change. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
- Sweet et al. 2022. *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines*.

Sea level rise is not uniform throughout the Hawaiian Islands and rates of sea level rise rates vary by island. Current sea level trends in Hawaiʻi range from +1.54 mm/yr (Honolulu) to +3.51/mm/yr (Kawaihae). The primary impacts of sea level rise are coastal erosion and flooding, which are not uniformly distributed throughout the islands. The University of Hawaiʻi estimated the potential impacts that sea level rise would have on passive flooding, annual high wave flooding, and coastal erosion. The footprints of these three hazards were combined to map the projected extent of chronic flooding due to sea level rise, referred to as the Sea Level Rise Exposure Area (SLR-XA). The modeling results are available through the State of Hawaiʻi Sea Level Rise Viewer.

Coastal erosion refers to the gradual wearing away of land primarily due to wave action and flooding. Coastal erosion is the dominant shoreline change trend in Hawaiʻi. The beaches of Kauaʻi, Oʻahu, and Maui are eroding at an average long-term rate of -0.56 ± 0.03 feet/year (ft/yr) and an average short-term rate of -0.20 ± 0.03 ft/yr (Fletcher et.al. 2012). Annual erosion is greatest on Maui followed by the islands of Kauaʻi and Oʻahu (Fletcher et al. 2012). Erosion and beach loss in Hawaiʻi are expected to increase significantly as rates of sea level rise increase. Average shoreline recession in Hawaiʻi by 2050 is projected to be nearly twice historical rates and by 2100 nearly 2.5 times historical rates (Anderson et al. 2015).

Technical information about coastal erosion is available in the following documents:

- Fletcher et al. 2012. National assessment of shoreline change: Historical shoreline change in the Hawaiian Islands: U.S. Geological Survey Open-File Report 2011–1051.
- Anderson et al. 2015. Doubling of coastal erosion under rising sea level by mid-century in Hawaiʻi.

Sea level rise is exacerbating the impacts of flooding in Hawaiʻi, particularly in low-lying coastal areas. Marine flooding refers to flooding caused by high tides and high wave events in areas that are hydrologically connected to the ocean. Groundwater inundation refers to subaerial flooding in low-lying areas that are not hydrologically connected to the ocean. Flooding caused by groundwater inundation has the potential to more than double the area of flooding solely by marine inundation (Rotzoll and Fletcher 2013).

Technical information about flooding is available in the following documents:

- Sweet et al. 2018. *2017 State of U.S. High Tide Flooding with a 2018 Outlook*.
- Sweet et al. 2018. *Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold*.
- Paoa et al. 2023. Probabilistic sea level rise flood projections using a localized ocean reference surface.
- Rotzoll, K., and C. H. Fletcher. 2013. Assessment of groundwater inundation as a consequence of sea-level rise.
- Shellie Habel et al. 2024. Hidden threat: the influence of sea-level rise on coastal groundwater and the convergence of impacts on municipal infrastructure.
- Rotzoll, K., C. Fletcher. 2013. Assessment of groundwater inundation as a consequence of sea-level rise.

Government agencies and communities have recognized the potential impacts of climate change and sea level rise and established guidance and objectives for sea level rise planning and adaptation with an emphasis on reducing vulnerability and increasing community resilience.

There are three general approaches for adapting to sea level rise: protection, accommodation, and retreat. Within these approaches, there are various structural and nonstructural alternatives that may be appropriate, depending on a variety of factors. These factors include the coastal setting, wave climate, topography, existing development patterns and intensity, existing land uses, criticality of infrastructure, adaptive capacity, resilience potential, project budget, and project objectives.

Protection options primarily consist of structural adaptations to mitigate the impacts of coastal hazards (e.g., seawalls, revetments, berms, levees). Accommodation options include structural adaptations (e.g., freeboard, post-on-pier construction, flood-resistant materials), nonstructural adaptations (e.g., shoreline setbacks), and nature-based solutions (e.g., beach and dune restoration). Retreat involves locating future development and/or relocating existing development away from areas that are vulnerable to coastal hazards and sea level rise.

Sea level rise has the potential to reduce the effectiveness and design life of LID BMPs. The assessment and planning phase of a project should include a detailed characterization of subsurface conditions (i.e., geology and hydrology) to evaluate groundwater depths and soil porosity. The assessment phase should also evaluate adjacent properties and land uses to identify potential external sources of flooding that could impact the project site. Depending on the nature of the project, the site conditions, and the development timeframe, additional BMPs may be required to accommodate sea level rise, coastal erosion, and flooding. The planner or designer should consider the following measures to adapt LID BMPs that may be impacted by sea level rise:

- Flood-resistant materials.
- Special additives and admixtures to make concrete more resistant to corrosion.
- Stainless steel, coated, or plastic reinforcing bar in concrete structures.
- Anti-flotation design for structures subject to periodic or continuous exposure to high water tables.
- Salt-tolerant vegetation.
- Plants that can withstand periodic inundation and flooding.
- Berms and other protection measures, devices, or structures such as riprap or articulated concrete block to withstand high tides and wave action.
- Relocation outside projected sea level inundation areas.
- Structures or overflow devices that allow for quick draining of BMPs.

Guidance for sea level rise adaptation is available in the following documents:

- Hawaiʻi Climate Change Mitigation and Adaptation Commission. 2017. *Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report*.

- Romine, B. et al. 2020. *Guidance for Using the Sea Level Rise Exposure Area in Local Planning and Permitting Decisions*.
- Codiga, D., and K. Wager. 2011. *Sea-Level Rise and Coastal Land Use in Hawaiʻi: A Policy Tool Kit for State and Local Governments*.

2.3 INTEGRATED STORMWATER MANAGEMENT

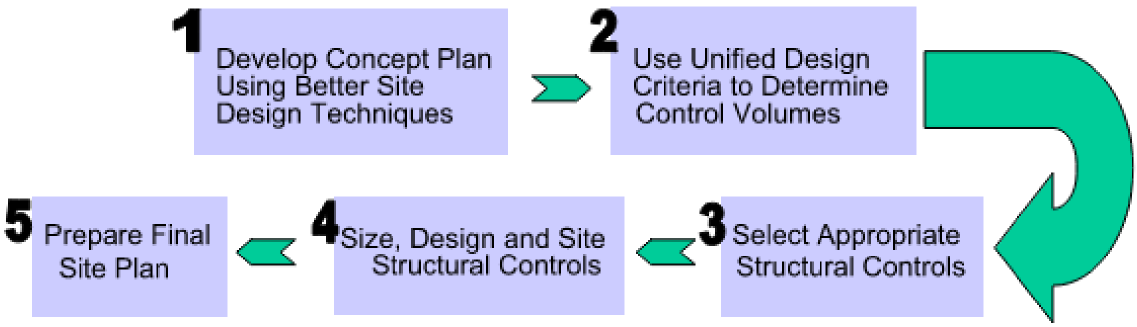
Integrated stormwater management design involves combining site design strategies with the design and layout of stormwater infrastructure to attain stormwater quality and quantity management goals. The planner or designer uses the various site design strategies and physical infrastructure to address stormwater holistically across the site. Each design strategy and stuctural practice work together to treat water quality and reduce the overall runoff from the site. Several structural practices and different types of structural practices may need to be constructed throughout the project site to comprehensively manage the runoff generated from storms.

The integrated stormwater management concept uses the following elements or steps:

1. LID Practices and Techniques—Protect and utilize natural features of the site to reduce runoff and pollutants.
2. Design Criteria for Stormwater Control Requirements—Calculate the volume of runoff to be controlled for water quality, as described below in **Section 3.3**. Water quantity shall be designed to meet local county drainage and flooding ordinances and regulations.
3. Downstream Assessment—If necessary or desired, perform a downstream analysis to ensure that the proposed development is not adversely impacting downstream properties after the volumes calculated in Step 2 above have been controlled.
4. Selection and Sizing of Structural Stormwater Controls and Conveyance—Structural control measures are selected using a screening process, then sized, designed, and located on a development plan. The reader of this Guide can use the tables found in **Section 4.1** to identify the most appropriate BMP or group of practices to use at a site.
5. Preparation of Final Site Plan—The last step in the process is the preparation of a final site plan that meets all of the construction and stormwater criteria and preserves or even enhances the water quality and natural infiltration of the site.

The aim of these steps is to provide a process that will address the comprehensive stormwater management goals presented in **Section 3.3** while at the same time providing ease of application for the land developer and a streamlined process for the review of a project. The integrated design process is illustrated in **Figure 2-2**.

Figure 2-2: Integrated Stormwater Management Site Design Process



The following principles should be kept in mind when using the integrated stormater management site design process to prepare a stormwater management plan for a development site:

- Site design should utilize an integrated approach to deal with stormwater quantity, quality, and protection of downstream properties and/or stream banks.
- The stormwater management infrastructure for a site should be designed to integrate drainage and water quantity control, water quality protection, and downstream property and channel protection. Site design should be done in unison with the design and layout of stormwater infrastructure to attain stormwater management goals. Together, the combination of integrated site design practices and effective infrastructure layout and design can mitigate adverse stormwater impacts of most urban developments while preserving or enhancing water quality and aesthetics.
- Stormwater management practices should strive to utilize natural drainage design principles and require as little maintenance as practicable.
- Almost all sites contain natural features that can be used to help manage and mitigate runoff from development. Features on a development site might include natural drainage patterns, depressions, permeable soils, wetlands, floodplains, and undisturbed vegetated areas that can be used to reduce runoff, provide infiltration and stormwater filtering of pollutants and sediment, recycle nutrients, and maximize on-site storage of stormwater. Site design should seek to improve the effectiveness of natural systems rather than to ignore or replace them. Furthermore, natural systems typically require low maintenance and will continue to function for many years if properly designed and maintained.
- Structural stormwater controls should be implemented after site design and nonstructural options have been exhausted.

  Operationally, economically, and aesthetically, conservation site design and the use of natural techniques offer significant benefits over structural stormwater controls. Therefore, all opportunities for utilizing these methods should be explored before implementing structural stormwater controls such as engineered wet ponds and sand filters.

- Structural stormwater solutions should attempt to be multipurpose and be aesthetically integrated into the site design.

  A structural stormwater facility need not be an afterthought or ugly nuisance on a development site. A parking lot, soccer field, or city plaza can serve as a temporary storage facility for stormwater. In addition, water features such as ponds and wetlands when correctly designed and integrated into a site can increase the aesthetic value of a development.

- "One size does not fit all" in terms of stormwater management solutions.

  Although the basic challenges of stormwater runoff and the need for its management remain the same, each site, project, and watershed presents different opportunities. For instance, an infill development in a highly urbanized town center or downtown area will require a much different set of stormwater management solutions than a low-density residential subdivision in a largely undeveloped watershed. Therefore, local stormwater management needs to consider differences between development sites, different types of development and land use, various watershed conditions and priorities, the nature of downstream lands and waters, and community desires and preferences.

3 LID PRINCIPLES & SITE DESIGN STRATEGIES

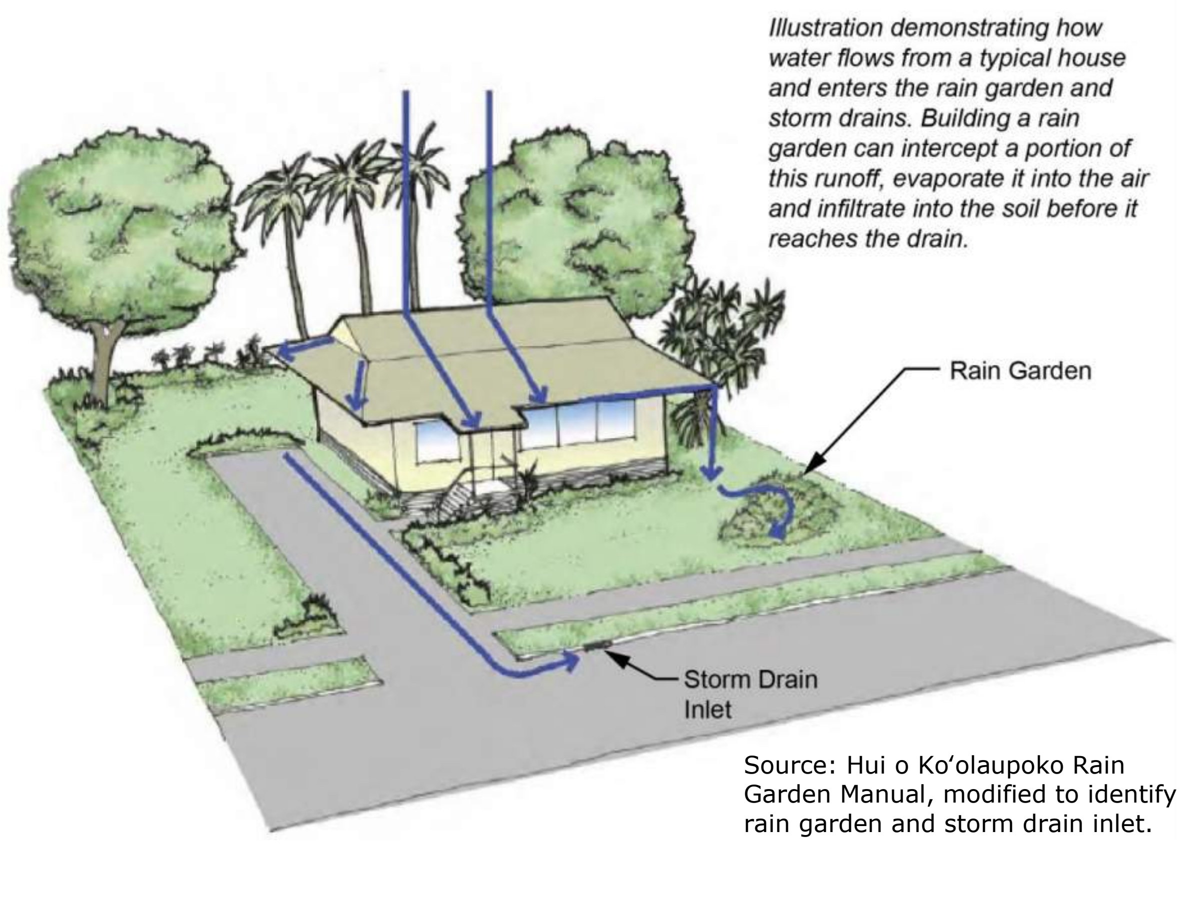
3.1 SITE ASSESSMENT

A site assessment is a fundamental starting point in the development of an LID site design. Two critical components when assessing a site are the on-site drainage patterns and the existing soils. Other important site characteristics to evaluate include topography, vegetation, water features, the depth to groundwater, setbacks, climate, sensitive archaeological or environmental areas, existing development, and sea level rise. Sea level rise has the potential to significantly alter flood patterns, drainage patterns, and groundwater elevations. The evaluation of these characteristics of the property is integral in determining which LID principles, strategies, and BMPs can or should be implemented.

3.2 INCORPORATING LID INTO THE SITE DESIGN PROCESS

After the site assessment has been completed, site planning and design can begin. Site planning and design should consider how road design, lot configuration, and construction practices can utilize the existing natural features on the property to retain beneficial natural hydrologic functions.

Figure 3-1: Stormwater Flows at a Residential Lot Using LID Practices



Source: Hui o Koʻolaupoko Rain Garden Manual, modified to identify rain garden and storm drain inlet.

Low impact development can broadly be divided into two categories: LID principles and LID BMPs. LID principles are used to reduce the causes of the hydrologic impacts of the project while LID BMPs help mitigate unavoidable hydrologic impacts of the project. Incorporating LID principles early in the planning process is the most efficient and cost-effective way to successfully implement LID. When used properly, LID principles can greatly reduce the magnitude of adverse impacts that must be mitigated by BMPs. The below LID principles and site design strategies help to maintain or restore the property's predevelopment hydrologic and hydraulic functions. In short, these principles will minimize runoff volume and preserve the existing runoff drainage patterns.

A project should attempt to incorporate LID site design strategies to the maximum extent practicable; however, the unique features at the project site, as determined during the site assessment, will help determine the applicability of each site design strategy to the project.

3.2.1 CONSERVE NATURAL AREAS, SOILS, AND VEGETATION

The conservation of natural areas, soils, and vegetation is critical to retaining the functions of predevelopment site hydrology, such as rainfall interception, evapotranspiration, and infiltration. Maximizing these functions reduces the quantity of runoff that is required to be treated.

Existing trees and vegetation intercept and capture a significant portion of rainfall. Soils with thick, undisturbed vegetation have a much higher capacity to store and infiltrate runoff compared to that of disturbed soils. Mature trees and vegetation also present the added benefits of providing habitat, preventing erosion, and providing shade. Conservation of soil is desirable at a project site because the upper soil layers of a natural area contain organic material, soil biota, vegetation, and a configuration favorable for storing and slowly conveying stormwater.

Figure 3-2: Native Tree Preservation

Photo Credit: Tomoko Naka, Bowers + Kubota Consulting

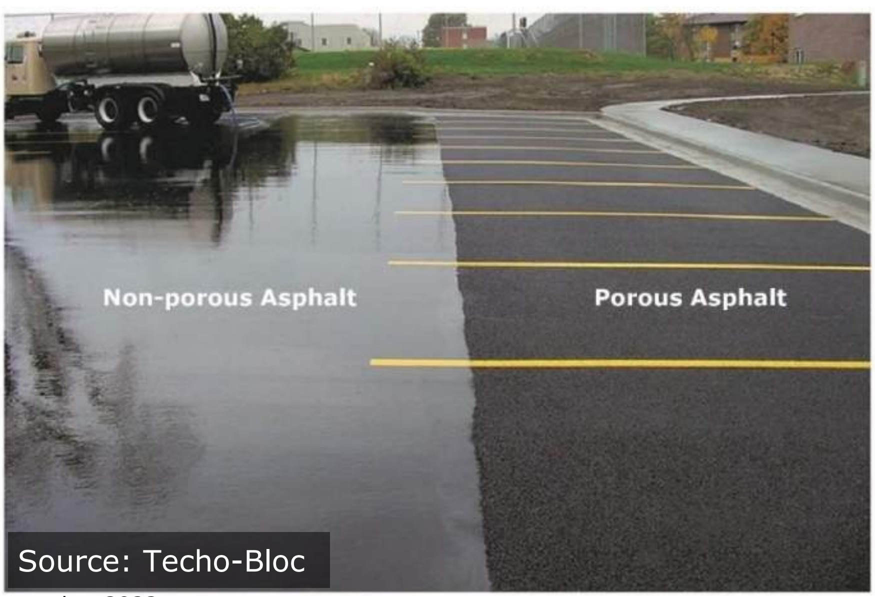
Specific measures include the following:

- Preserve riparian buffers.
- Preserve wetlands.
- Preserve natural flow pathways.
- Preserve and protect steep slopes.
- Protect sensitive environmental areas.
- Preserve undisturbed vegetated areas.
- Preserve native trees and restrict disturbance of soils beneath tree canopies.
- Limit construction activities and disturbance to areas with previously disturbed soils.
- Avoid disturbing vegetation and soil on slopes and near surface waters.
- Leave an undisturbed buffer along both sides of natural streams.

3.2.2 MINIMIZE IMPERVIOUS SURFACES

One of the principal causes of environmental impacts due to development is the creation of impervious surfaces. Impervious land coverage is a fundamental characteristic of the urban and suburban environment. Impervious surfaces come in the form of rooftops, roadways, parking areas, sidewalks, and other impermeable surfaces that do not allow rainfall to infiltrate into the ground. The extent of impervious land in a watershed is an important indicator of not only the stormwater quantity but also the stormwater quality in that watershed. An undeveloped watershed would naturally filter the rainwater to prevent degradation of the receiving waters. With impervious surfaces in a watershed, pollutants are washed off rooftops and roadways untreated into storm drains, channels, and streams to be discharged to the ocean or other receiving water bodies with the load of pollutants captured during the storm event. This sequence can lead to degradation of the quality of the receiving water bodies.

Figure 3-3: Photo of Porous and Non-porous Asphalt



Source: Techo-Bloc

Minimizing impervious surfaces has other beneficial effects such as increased groundwater recharge; reduced flooding; prevention of erosion and loss of habitat in streams, riparian areas, and shoreline areas; and reduced urban heat island effect, in which the air temperature in cities is higher than the temperature in rural or undeveloped areas.

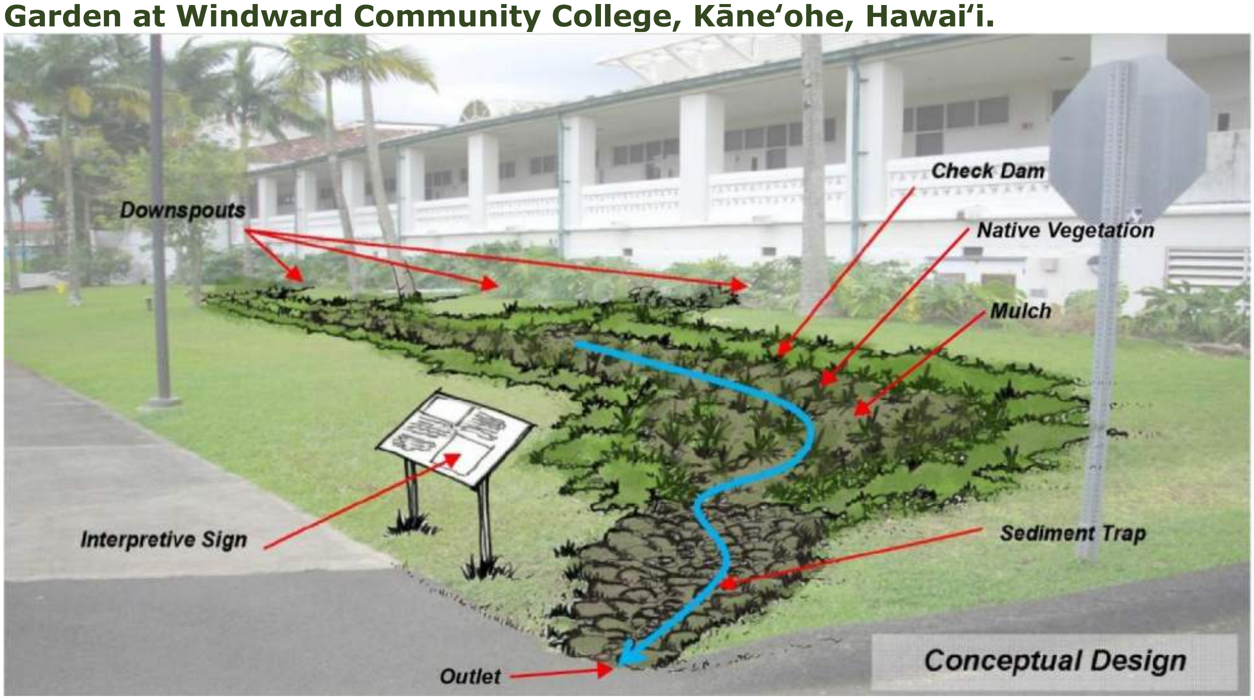
Specific strategies used to reduce the amount of impervious area created as part of a project include the following:

- Use minimum allowable roadway and sidewalk widths, driveway lengths, and parking stall sizes.
- Minimize building footprint by constructing vertically rather than horizontally.
- Cluster buildings so that they require less driveways and pathways.
- Use green roofs instead of conventional roofing materials.
- Maximize the utilization of compact car spaces in parking areas.
- Use alternative materials such as pervious pavers, permeable pavement, or turf blocks on light duty roads, parking lots, driveways, and sidewalks.

3.2.3 DISCONNECT IMPERVIOUS AREAS

Establishing permeable surfaces between impermeable surfaces is an effective way to intercept urban runoff and reduce runoff volumes. This site design strategy can be achieved by disconnecting continuously paved or impervious areas with landscaping or permeable materials. One of the best-known examples of disconnecting impervious areas is directing roof runoff to a landscaped area. This technique results in reduced peak storm flows and filtered runoff prior to entering the storm drainage system or natural waterway. The volume of runoff that leaves the site and enters the storm drain is also reduced as a result of some of the runoff infiltrating into the soil at the site.

Figure 3-4: Conceptual Design of Multiple Downspouts Discharging to Rain Garden at Windward Community College, Kāneʻohe, Hawaiʻi.



Source: Hui o Koʻolaupoko Windward Community College Low Impact Retrofit, modified to identify relevant features of the rain garden.

Any impervious surface that drains into a storm drain system is considered a "Directly Connected Impervious Area" (DCIA). DCIAs are the greatest contributor to nonpoint source pollution. When runoff flows across building roofs, roadways, and parking lots, pollutants such as oils, sediments, metals, and other chemicals are picked up by the flows. If the runoff flows along a gutter and then directly into a drainage system, there is no opportunity for the pollutants to be filtered out by plant material or infiltrated into the soil. One of the key site design strategies to use for stormwater quality protection is the reduction of DCIAs. Specific site design strategies for the disconnection of impervious surfaces are the following:

- Design roof downspouts to flow to landscaped areas or planter boxes.
- Direct flow from paved areas to landscaped areas.
- Grade paved areas to achieve sheet flow to landscaped areas.
- Break up flow directions from large, paved areas.
- Use permeable paving materials on driveways, sidewalks, and parking areas.

Figure 3-5: Downspout Disconnection into Vegetated Area

Source: Prince George's County, MD, Department of Environmental Resources

3.2.4 MINIMIZE SOIL COMPACTION

Minimizing soil compaction is the practice of protecting and minimizing damage to existing soil quality caused by land development. Undisturbed soil has voids or spaces between soil particles. These voids or space have water carrying and holding capacity. When soil is overly compacted, the soil voids are destroyed; and permeability is reduced significantly.

Clearing and grubbing exposes and compacts the underlying soil, which will significantly alter the hydrologic characteristics of the site. Therefore, disturbance should be avoided in planned green spaces and proposed landscaped areas where feasible. During construction, these areas should be restricted so vehicles and construction equipment do not inadvertently compact the area. Minimizing soil compaction at urban sites may be challenging due to limited construction area. In areas planned for landscaping and where compaction cannot be avoided or minimized, tilling of the soil and/or adding soil amendments should be performed to improve the soil's infiltration capacity. However, the original infiltration capacity of the soil most likely will not be restored. Specific site design strategies to minimize soil compaction are the following:

- Avoid extensive and unnecessary clearing and stockpiling of topsoil.
- Limit areas that may be accessed by heavy equipment.
- Minimize the size of construction easements and material storage areas.
- Prohibit working on wet soils with heavy equipment.
- Avoid and/or minimize soil compaction in open spaces, landscaped areas, and proposed LID BMP areas.
- Restore the infiltration rate of compacted open space areas with tilling and soil amendments.

3.2.5 PROTECT NATURAL FLOW PATHWAYS AND RIPARIAN BUFFER AREAS

The identification, use, and protection of natural drainage features is a main component of LID. Natural drainage features such as swales, depressions, and watercourses can minimize stormwater impacts from development and help protect water quality. Using natural drainage features can eliminate or reduce the need for structural drainage systems at a development.

Vegetated drainage features tend to slow down runoff which reduces the peak flow, improves water quality through filtration, and allows for infiltration and evapotranspiration. Other benefits include additional wildlife habitat, improved site aesthetics, and higher property values. When determining the development footprint of the site, natural drainage features should be avoided wherever practicable.

Riparian buffer areas, which are the vegetated areas between developed land and surface water, are critical to the biological, chemical, and physical integrity of a waterway. They protect water quality by stabilizing banks, cooling water, mitigating flow rates, and filtering pollutants from overland sheet flow before it enters the waterway. When planning for the protection of a riparian buffer, consider that the wider the riparian buffer, the greater the water quality protection and habitat value that the buffer can provide.

Specific site design strategies to minimize disturbance to natural flow pathways and riparian buffer areas are the following:

- Maintain existing surface flow patterns of undeveloped sites.
- Maintain existing water body alignments, sizes, and shapes.

- Limit site disturbance, clearing, and grading to the smallest area practicable.
- Minimize and control construction traffic areas.
- Minimize and control construction stockpiling and storage areas.
- Use construction fencing to identify areas where no disturbance is allowed.

3.3 HYDROLOGY

Frequently, designers and planners immediately gravitate towards BMPs when implementing low impact development. LID manuals also tend to focus much of their content on BMPs, also known as storm control measures (SCMs) or integrated management practices (IMPs) in other areas of the United States.

So why talk about hydrology? The first question we need to ask is "what is hydrology?"

Hydrology is the study of the volume or rate of stormwater that runs off a site or onto a site. Many technical references, such as *Urban Hydrology for Small Watersheds* Technical Release 55 (TR-55) by the Natural Resources Conservation Service (NRCS) or *Low-Impact Development Hydrologic Analysis* by Prince George's County, Maryland, describe in detail theories, concepts, methodologies, equations, and graphs to estimate the amount of stormwater runoff. This section does not discuss those technical references or provide detailed calculations or methodologies. Rather, this section focuses on fundamental concepts in hydrology that impact all LID planning and design.

To understand the role and importance of hydrologic principles in LID, contrasting conventional site development against LID is a helpful exercise. This contrast will clearly demonstrate the paradigm shift in LID planning and design. Conventional site development treats stormwater runoff as a hazard. Conventional site design removes runoff as quickly as practicable from property and people to reduce property damage and promote safety. LID views stormwater as a resource. Instead of removing runoff as quickly as practicable from a site, LID keeps stormwater within a site for as long as practicable to reduce the amount of stormwater that leaves the site.

Figure 3-6: Rain Garden on 11th Ave. and Harding Street, Honolulu, Hawaiʻi

Photo Credit: Trees for Kaimukī

Figure 3-7: Terraced Detention Cells at Hāʻena State Park, Kauaʻi, Hawaiʻi

Photo: Lauren Roth Venu

Essentially, LID manipulates the time of concentration to extend this time as long as practicable to match the predevelopment hydrologic condition. The time of concentration is a concept in hydrology that describes the amount of time that runoff flows from the most remote part in a drainage area or watershed to the outlet of the drainage area/watershed. As the time of concentration increases, the rainfall intensity in runoff equations decreases resulting in reduced runoff flow rate. Every LID BMP/IMP/SCM and site design strategy is based on this fundamental concept. Reducing the amount of impervious area and preserving existing vegetation promotes infiltration and retards the runoff flow rate. Installing a rain garden or a rain barrel promotes treatment and infiltration of stormwater while also detaining or retaining rainwater on-site. Elimination of channelization and avoiding steep slopes reduces the runoff rate. Without even calculating a site-specific hydrograph, planners and designers can be assured that employing LID methods will result in reduced post-development runoff when compared to conventional site design. Specific LID hydrologic analyses would be needed to optimize the site design and determine the overall impact of the various LID BMPs on a particular development.

Hydrologic methods encourage the planner or designer to consider an integrated systems approach to LID. Runoff volume is influenced by many factors, such as rainfall intensity, site topography or slope, soil infiltration rate, and surface roughness. During the hydrologic analysis phase of a project, the planner or designer needs to account for all these various factors across the entire site. By manipulating these factors, LID attempts to mimic the existing predevelopment hydrologic condition, which typically has less runoff volume than that of the post-development hydrologic condition.

Figure 3-8 Detention Basin at Ala Wai Golf Course, Honolulu, Hawai'i

Source: Bowers + Kubota Consulting

3.4 EROSION & SEDIMENT CONTROL

Initially, planners and designers may wonder why this Guide has a section on erosion and sediment control (ESC). At first glance, LID and ESC measures appear to have no relationship. However, during any development there will be earth-disturbing activities that could lead to increased erosion and sedimentation. In addition, many of the concepts of ESC are paralleled in LID.

Erosion is the dislodging of soil particles from the soil matrix. Sedimentation is the suspension of soil particles in stormwater runoff that are then deposited in a different area on or off a project site. Controlling erosion is always cheaper than controlling sedimentation.

The rate of erosion can be modeled with a few different equations such as the universal soil loss equation, modified universal soil loss equation, and revised universal soil loss equation. These equations incorporate factors that account for soil characteristics, the length and steepness of slopes, the type of surface cover, and the implementation of BMPs. By manipulating these factors, the planner or designer can minimize the amount of erosion yielded by a specific storm or annually at a project site.

Similar strategies employed in LID are also used in ESC during construction. For example, preservation of the existing hydrologic condition is essential to reducing erosion. Preservation of existing vegetation and pervious areas retards runoff velocity and promotes infiltration, respectively, which yields a lower time of concentration. Phasing grading operations allows the contractor to preserve the existing hydrologic condition of different areas of the site until previously disturbed areas are fully stabilized with temporary or permanent cover. Controlling the locations where construction equipment is used minimizes compaction at the site and fosters infiltration. Minimizing steep slopes and the length of slopes also reduces runoff velocity, which results in a lower time of concentration.

ESC BMPs may be used to protect LID BMPs during construction. For example, bioretention cells need to be protected from sediment and compaction from construction equipment. Silt fences and/or filter socks can be installed around the bioretention cells to prevent sediment and equipment from entering the cells and allow for the cells to become fully vegetated.

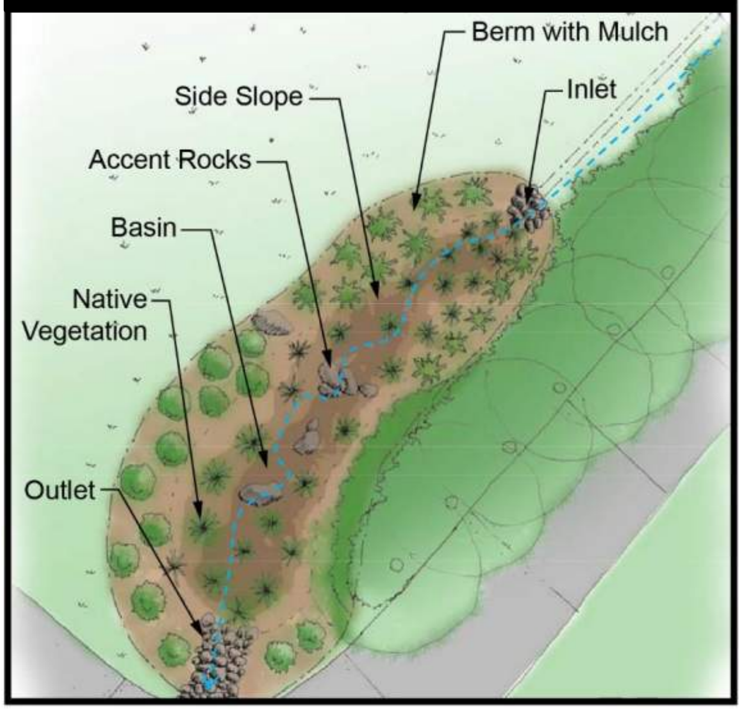
ESC BMPs can also be converted into permanent post-construction BMPs. For example, a detention or sediment basin could be converted into a bioretention cell or rain garden after removing accumulated materials and scarifying the top layer of soil. A grassed buffer strip used to treat sediment-laden runoff can also be used after construction is complete to treat stormwater runoff.

Technical ESC resources are available in the following documents:

- *Developing Your Stormwater Pollution Prevention Plan A Guide for Construction Sites*, EPA-833-R-06-004, May 2007, by the US Enviromental Protection Agency
- Draft *City and County of Honolulu Stormwater Best Management Practice Manual Construction*, August 2017
- *Interim Best Management Practices (BMP's) for Sediment and Erosion Control for the County of Kauaʻi*, April 2004
- *Construction Best Management Practices Field Manual*, October 2021, by the State of Hawaiʻi Highways Division
- *Stormwater Management Program Plan Daniel K. Inouye International Airport Section C: Construction Site Runoff Control Program*, August 2020, by the State of Hawaiʻi Airports Division
- *Final Construction Site Runoff Control Program Manual*, September 2021, by the State of Hawaiʻi Harbors Division

4 LID STRUCTURAL BEST MANAGEMENT PRACTICES

Figure 4-1: Rain Garden Conceptual Plan and Photos of Constructed Rain Garden at He‘eia State Park, Kāne‘ohe, Hawai‘i



Source: Hui o Ko‘olaupoko Rain Garden Manual

This Section focuses on structural BMPs, sometimes referred to as treatment control BMPs, SCMs, or IMPs. After LID site design strategies have been implemented, the next step is to select the most environmentally sound and cost-effective array of structural LID BMPs to satisfy LID goals. The structural BMPs in this section are separated into three broad categories based on their primary treatment mechanism: infiltration, retention, or biofiltration, as shown in **Table 4-1**. However, LID BMPs often employ multiple treatment mechanisms. For example, a bioretention basin promotes infiltration and retention but also is planted with vegetation that filters pollutants. An enhanced swale can be designed with an engineered soil to promote infiltration while also filtering contaminants. An example of an infiltration BMP is illustrated in **Figure 4-1**. **Figure 4-1** shows the conceptual plan and constructed rain garden at He‘eia State Park in Kāne‘ohe, Hawai‘i. A fourth category labeled “Other” is included in **Table 4-1** for BMPs that do not fall into the first three categories. For this Guide, the only BMP in the Other category is detention basins. This type of basin is usually not considered an LID BMP because detention basins typically do not retain and infiltrate stormwater at the source. Rather, detention basins attenuate the flow of stormwater. Detention basins are included in the Guide because of their widespread use in stormwater management and ability to reduce the flow rate of runoff, which can be a useful way to mimic predevelopment hydrology.

Table 4-1: BMP Categories

BMP	Infiltration	Retention	Biofiltration	Other
Infiltration Basin	X			
Infiltration Trench	X			
Dry Well	X			
Bioretention Basin (Rain Garden)	X			
Permeable Pavement	X			
Harvesting / Reuse		X		
Green Roof			X	
Tree / Planter Box (Vegetated Biofilter)			X	
Enhanced Swale			X	
Vegetated Swale			X	
Vegetated Filter Strip			X	
Detention Basin				X

Reference: This table is modified from a similar table included in the **City and County of Honolulu Administrative Rules, Title 20 Department of Planning and Permitting, Chapter 3 Rules Relating To Water Quality** (RRWQ).

4.1 LID BMP SELECTION PROCESS

LID involves planning that first looks to reduce stormwater runoff as much as practicable through the use of LID site design strategies and then to mitigate the stormwater runoff as effectively as practicable through the use of LID BMPs. Selecting the proper BMPs that fit within the site and achieve the water quality objectives is an important aspect of LID.

Sometimes a project will require multiple types of BMPs used together to meet water quality objectives. Using several structural BMPs together in series is called a "treatment train." A treatment train might first filter the runoff before entering another BMP that would allow the runoff to infiltrate into the ground. A treatment train can also provide redundancy to ensure that if one BMP fails, there is a backup to treat the stormwater.

Not every BMP will be appropriate for each site because site characteristics and land use vary widely throughout the Hawaiian Islands. Selecting LID BMPs can be complex because many factors must be considered. This section provides information on the most relevant factors with which to evaluate and then select LID BMPs. These factors include land use, physical feasibility, stormwater quantity, pollutant removal, community acceptance, environmental impacts, construction cost, and ease of maintenance. The most appropriate BMPs are those that are feasible and cost-effective and achieve the maximum benefits for watershed protection.

This section presents a series of tables **(4-2 to 4-4, 4-6, and 4-7)** that can be used to evaluate and select BMPs. Screening factors in these tables include:

- Land use
- Physical feasibility
- Stormwater quantity
- Pollutant removal
- Community, habitat, safety, cost, and maintenance

The tables presented here are not exhaustive. Additional criteria may be incorporated into a site-specific evaluation, depending on local knowledge of the site and resource protection goals.

4.1.1 LAND USE

This section helps determine which BMPs are best suited for the proposed land use at the site. Some land uses lend themselves to certain BMPs. For example, low-density residential developments lack large parking areas conducive to permeable pavement. Conversely, rain barrels are especially well-suited for residential use, but green roofs are unlikely to be used on single-family homes. Successful LID projects match the BMP to land use. **Table 4-2** allows the planner or designer to initially screen BMPs most appropriate for a given land use.

Table 4-2: BMP per Land Use

BMP	RESIDEN-TIAL	ROADS/ HIGHWAYS	COMMER-CIAL	ULTRA URBAN	RETROFITS
Infiltration Basin	Yes	Limited	Yes	Limited[1]	Limited
Infiltration Trench	Yes	Yes	Yes	Yes	Yes
Dry Well	Yes	No	Yes	Yes	Yes
Bioretention Basin (Rain Garden)	Yes	Yes	Yes	Limited	Yes
Permeable Pavement	Yes[2]	Limited[2]	Yes	Yes	Yes[2]
Harvesting / Reuse	Yes	No	Yes	Yes	Yes
Green Roof	Limited	No	Yes	Yes	Yes
Tree / Planter Box (Vegetated Biofilter)	Yes	Yes	Yes	Yes	Yes
Enhanced Swale	Yes	Yes	Yes	Limited[1]	Limited

BMP	RESIDEN-TIAL	ROADS/ HIGHWAYS	COMMER-CIAL	ULTRA URBAN	RETROFITS
Vegetated Swale	Yes	Yes	Yes	Limited[1]	Limited
Vegetated Filter Strip	Yes	Yes	Yes	Limited[1]	Yes
Detention Basin	Limited	Limited	Limited	No	Yes

Notes:
[1]Difficult to apply due to space limitations usually associated with the land use.

[2]Applicable with special design considerations.

4.1.2 PHYSICAL FEASIBILITY

Each site should be evaluated for key physical characteristics, such as soil type, depth to the groundwater table, slopes, and general space available. The planner or designer must determine if there are any physical constraints at the project site that may restrict or preclude the use of a particular BMP. The planner or designer can use **Table 4-3** to determine if some of the physical conditions present at a site might limit the use of a BMP. The four primary physical site factors to evaluate are the following:

1. Soil Types. The soil types in **Table 4-3** are related to the Natural Resources Conservation Service (NRCS) classification system of hydrologic soil groups. The four groups of soils in the NRCS system are A, B, C, and D, which are based on their runoff and percolation potential. Type A soils have the highest infiltration rates while Type D soils have the lowest infiltration rates. Many infiltration BMPs require soils with infiltration rates of 0.5 inches per hour (in/hr) or greater, which generally correlate to Type A or B group soils. The use of NRCS hydrologic soil groups is a good planning tool for an initial evaluation of feasible BMPs. In the design phase, more detailed geotechnical tests are usually required to determine the actual infiltration rate of the soil at the site.
2. Depth to Water Table. This column in **Table 4-3** indicates the minimum depth to the seasonally high water table from the bottom elevation, or invert, of a BMP. As the depth to the water below the BMP decreases, the rate at which a BMP can infiltrate rainwater decreases because the soil under the BMP becomes saturated with water.
3. Slope. This column in **Table 4-3** provides guidance as to the flatness of the area where the BMP is proposed to be located. The maximum allowable slope for each BMP is listed.
4. General Space Requirements. This column in **Table 4-3** lists the general area needed to install the BMP as Low, Medium, or High. These terms are qualitative and relative. BMPs that are small and compact, like dry wells and infiltration trenches, would be rated Low, which means that these BMPs do not need a lot of land area to be installed. BMPs that are large, like infiltration basins and detention basins, would be rated High, which means

that these BMPs tend to need a lot of area to be constructed. BMPs that are not compact but do not require a large amount of land area would be rated Medium, which means that these BMPs cannot fit in very small sites but still need a sufficient amount of land area to funciton effectively. BMPs rated Medium may be challenging to construct on sites with parking lots while still meeting the required number of parking spaces per county codes and regulations.

Table 4-3: BMP per Physical Feasibility

BMP	SOIL TYPE	DEPTH TO WATER TABLE (FEET)	MAXIMUM SLOPE	GENERAL SPACE REQUIREMENTS
Infiltration Basin	A or B	≥ 3	≤ 20%	High
Infiltration Trench	A or B	≥ 3	≤ 15%	Low
Dry Well	A or B	≥ 3	≤ 15%	Low
Bioretention Basin (Rain Garden)	A or B	≥ 3	≤ 20%	Medium
Permeable Pavement	A or B	≥ 3	≤ 5%	Medium
Harvesting/ Reuse	n/a	n/a	n/a	Low
Green Roof	n/a	n/a	10° Roof Slope	Medium
Tree/Planter Box (Vegetated Biofilter)	A/B/C/D	≥ 3	n/a	Low
Enhanced Swale	A/B/C/D	≥ 3	≤ 5%	Medium
Vegetated Swale	A/B/C/D	≥ 2	≤ 6%	Medium
Vegetated Filter Strip	A/B/C/D	n/a	≤ 15%	Medium
Detention Basin	A/B/C/D	≥ 3	≤ 20%	High

4.1.3 STORMWATER QUANTITY OBJECTIVES

The physical nature of LID BMPs limit their effectiveness in addressing stormwater quantity objectives, namely reducing the stormwater runoff volume or flow rate or recharging the groundwater aquifer. For example, tree filter boxes are usually compact. Consequently, they can only treat a small amount of runoff. In contrast, infiltration or detention basins can be several hundred feet in length and width, resulting in a large overall volume with the ability to treat a large amount of runoff. **Table 4-4** will help the planner or designer decide if one or more BMPs are needed to address the following objectives:

1. Stormwater Volume. This column indicates whether the BMP can effectively manage stormwater runoff volumes.
2. Groundwater Recharge. This column indicates whether the BMP can provide groundwater recharge. Groundwater recharge is not a formal criterion, but often a design goal to help replenish groundwater supplies.
3. Peak Flow Rate. This column indicates whether the BMP can effectively reduce stormwater peak flow rates.

Low means that the BMP has the little potential to address the stormwater quantity objective while High indicates that the BMP, if properly planned, designed, and operated, and maintained, could effectively address the stormwaer quantity objective. Because drainage area is directly related to stormwater quantity, BMPs rated Low tend to treat the runoff from small drainage areas while BMPs rated High are capable of treating the runoff from much larger drainage areas. The planner or designer should employ an integrated approach to address stormwater quantity by using multiple LID BMPs distributed throughout the project site. When combined, the multiple LID BMPs (instead of a single or a few large detention basins) would have the overall effect of reducing the amount of runoff from the site.

Table 4-4: BMP per Stormwater Quantity Objective

BMP	VOLUME	GROUNDWATER RECHARGE	PEAK RATE
Infiltration Basin	High	High	High
Infiltration Trench	Medium	High	Low/Med
Dry Well	Medium	High	Medium
Bioretention Basin (Rain Garden)	Medium/High	Medium/High	Medium
Permeable Pavement	High	High	Medium/High
Harvesting/ Reuse	High	Low	Low
Green Roof	Medium/High	Low	Medium
Tree/Planter Box (Vegetated Biofilter)	Low/Medium	Low/Medium	Medium
Enhanced Swale	Low/Medium	Low/Medium	Low/Medium
Vegetated Swale	Low/Medium	Low/Medium	Low/Medium
Vegetated Filter Strip	Low	Low	Low
Detention Basin	High	Low	High

4.1.4 POLLUTANT REMOVAL

In addition to stormwater quantity, LID BMPs should address anticipated pollutants of concern, which include nutrients, sediment, trash, pathogens, pesticides, oil and grease, metals, and organic compounds. Pollutants will vary depending on the land use, as shown in **Table 4-5.**

As mandated by the Section 303(d) of the Clean Water Act, the State of Hawaiʻi Department of Health maintains a list of marine and inland water bodies that are impaired due to pollution. The pollutants identified in the "303(d) list" are based on the State's Water Quality Standards described in HAR Chapter 11-54 and include the pollutants listed in **Table 4-5**. In addition to land use, the planner or designer should identify the receiving water to which the runoff will discharge and identify pollutants of concern based on the 303(d) list.

Table 4-5: Typical Pollutants Associated with Land Uses

Land Use	Nutrients	Sediment	Trash	Pathogens	Pesticides	Oil & Grease	Metals	Organic Compounds
Residential Development	X	X	X	X	X	X		
Commercial Development	P	P	X	P	P	X	X	P
Industrial		X	X			X	X	X
Roadway	P	X	X	X	P	X	X	X
Automotive Repair Shop			X			X	X	X
Restaurant			X	X	P	X		
Parking Lot	P	P	X		P	X	X	
Retail Gasoline Outlet			X			X	X	X
Buildings taller than 100'	X	X	X	X	X	X		

X=anticipated, P=potential

Source: CCH Stormwater BMP Guide for New and Redevelopment, July 2017

After identifying the pollutants of concern, the planner or designer should then evaluate BMPs to see which ones are well-suited to remove those pollutants. **Table 4-6** lists the anticipated ability of each BMP to remove specific pollutants from stormwater runoff. The expected pollutant removal rates are rated High (H), Medium (M), Low (L), or Unknown (U). More detailed information with numerical capture rates for specific pollutants is available in the fact sheets for each LID BMP in **Section 4.2** and **Appendix A**.

Table 4-6: BMP per Expected Pollutant Removal

BMP	Nutrients	Sediment	Trash	Pathogens	Pesticides	Oil & Grease	Metals	Organic Compounds
Infiltration Basin	H	H	H	H	H	H	H	H
Infiltration Trench	H	H	H	H	H	H	H	H
Dry Well	H	H	H	H	H	H	H	H
Bioretention Basin (Rain Garden)	H	H	H	H	H	H	H	H
Permeable Pavement	H	H	L	H	H	H	H	H
Harvesting/ Reuse	H	H	L	H	H	H	H	H
Green Roof	M	H	H	M	M	H	M	M
Tree/Planter Box (Vegetated Biofilter)	M	H	H	M	U	H	H	H
Enhanced Swale	M	H	H	U	U	M	M	U
Vegetated Swale	L	M	L	L	U	M	M	U
Vegetated Filter Strip	L	M	M	L	U	M	M	M
Detention Basin	L	M	H	L	U	M	L/M	U

Key: Low | Medium | High | Unknown

4.1.5 COMMUNITY, HABITAT, SAFETY, COST AND MAINTENANCE

This last step in weeding out BMPs that do not match the goals and needs of the development, and selecting the most appropriate BMP involves assessing the important factors of community acceptance, habitat quality, safety, construction cost, and ease of maintenance as shown in **Table 4-7**. A brief description of each factor is listed below:

1. Community Acceptance. This indicates whether members of the community are likely to have issues with the BMP. This factor is generally measured by reported nuisance problems, aesthetics, and visual prominence (i.e., is the BMP easy to see or is it out of sight underground or screened by vegetation).
2. Habitat Quality. BMPs are evaluated on their ability to provide wildlife or wetland habitat, assuming that the BMP is landscaped appropriately. Objective criteria include size, water features, wetland features, and vegetative cover of the BMP and directly adjacent area.
3. Safety. Safety is always a vital concern and is especially emphasized in residential settings.
4. Construction Cost. The BMPs are rated according to their construction cost relative to each other. The cost excludes design and land acquisition. BMP costs are rated either low, medium, or high.
5. Ease of Maintenance. This factor indicates the relative maintenance needed for a BMP in terms of three criteria: frequency of scheduled maintenance, chronic maintenance problems (such as clogging), and reported failure rates. All BMPs require routine inspection and maintenance.

Table 4-7: BMP per Community, Habitat, Safety, Cost & Maintenance Factors

BMP	COMMUNITY ACCEPTANCE	HABITAT QUALITY	SAFETY CONCERNS	COST	MAINTENANCE
Infiltration Basin	Medium	Medium	Medium	Medium / High	Medium
Infiltration Trench	High	Low	Low	Low/ Medium	Low/Medium
Dry Well	High	Low	Low	Low	Low
Bioretention Basin (Rain Garden)	Medium	Medium	Low	Medium	Medium
Permeable Pavement	High	Low	Low	Medium	Medium/High
Harvesting/ Reuse	Medium	Low	Low	Low	Low
Green Roof	High	Medium	Medium	Medium / High	Medium
Tree/Planter Box (Vegetated Biofilter)	High	Medium	Low	Medium	Low

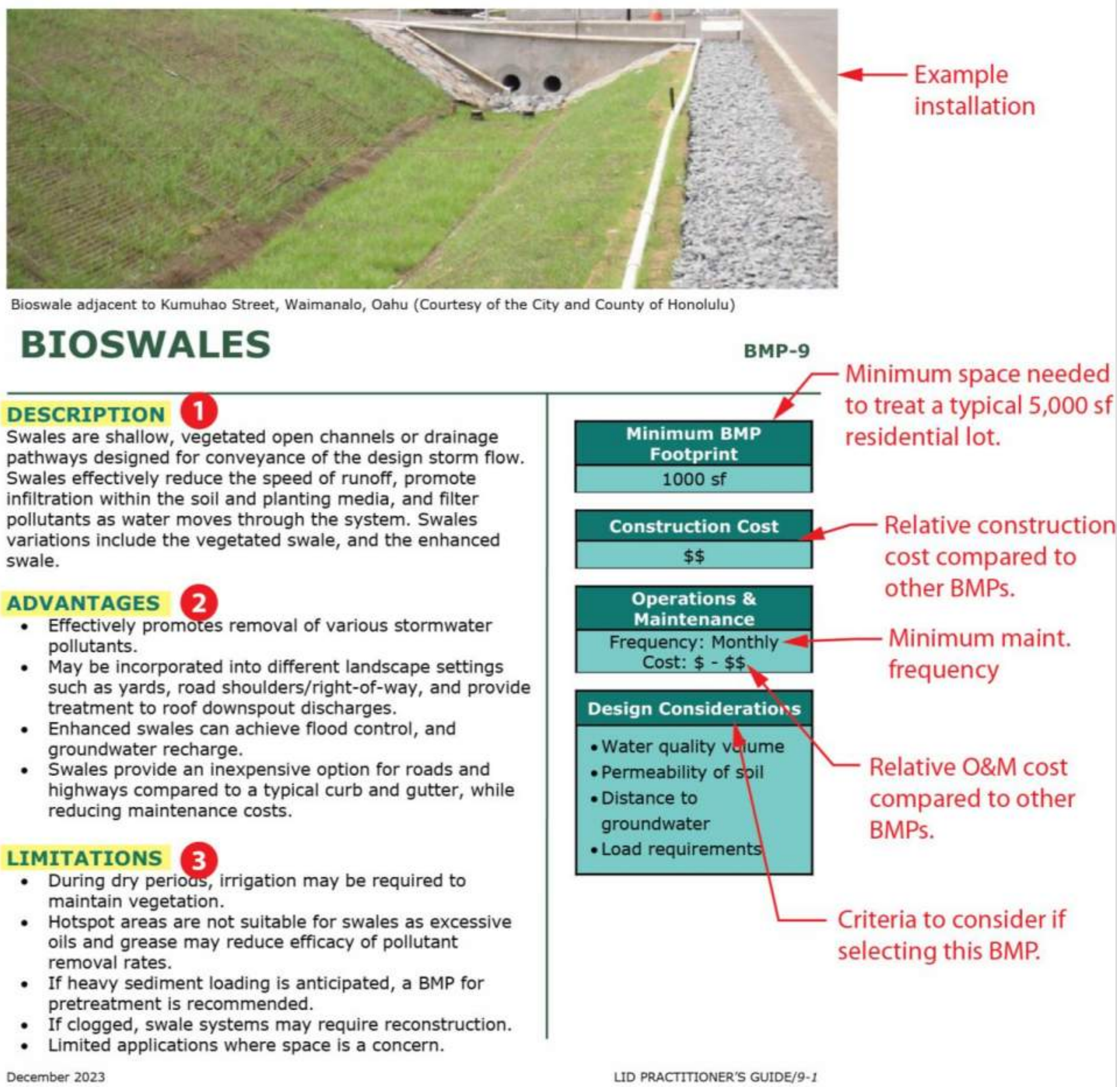
BMP	COMMUNITY ACCEPTANCE	HABITAT QUALITY	SAFETY CONCERNS	COST	MAINTENANCE
Enhanced Swale	High	Medium	Low	Medium	Low/Medium
Vegetated Swale	High	Medium	Low	Medium	Low/Medium
Vegetated Filter Strip	High	Medium	Low	Low	Low
Detention Basin	Medium	Medium	Medium	Medium / High	Low

4.2 LID BMP FACT SHEETS

A fact sheet has been provided for each BMP included in this Guide. Each fact sheet provides a quick overview of the BMP on the first page and more detailed information on the subsequent pages. Two versions of the fact sheets are included in this Guide. **Section 4.2.2** includes abridged versions of the fact sheets with only basic information on the BMPs. The casual reader of this Guide can refer to the versions in **Section 4.2.2** to gain a basic understanding of how each BMP functions and under what conditions the BMP should be implemented. **Appendix A** includes expanded versions of the fact sheets with detailed technical information on the BMPs. The detailed fact sheets are intended to be used by engineers, landscape architects, and other technical experts.

4.2.1 HOW TO READ THE FACT SHEETS

Each fact sheet includes the following information.



Bioswale adjacent to Kumuhao Street, Waimanalo, Oahu (Courtesy of the City and County of Honolulu)

BIOSWALES BMP-9

DESCRIPTION ❶

Swales are shallow, vegetated open channels or drainage pathways designed for conveyance of the design storm flow. Swales effectively reduce the speed of runoff, promote infiltration within the soil and planting media, and filter pollutants as water moves through the system. Swales variations include the vegetated swale, and the enhanced swale.

ADVANTAGES ❷

- Effectively promotes removal of various stormwater pollutants.
- May be incorporated into different landscape settings such as yards, road shoulders/right-of-way, and provide treatment to roof downspout discharges.
- Enhanced swales can achieve flood control, and groundwater recharge.
- Swales provide an inexpensive option for roads and highways compared to a typical curb and gutter, while reducing maintenance costs.

LIMITATIONS ❸

- During dry periods, irrigation may be required to maintain vegetation.
- Hotspot areas are not suitable for swales as excessive oils and grease may reduce efficacy of pollutant removal rates.
- If heavy sediment loading is anticipated, a BMP for pretreatment is recommended.
- If clogged, swale systems may require reconstruction.
- Limited applications where space is a concern.

Minimum BMP Footprint
1000 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Monthly Cost: $ - $$

Design Considerations
• Water quality volume • Permeability of soil • Distance to groundwater • Load requirements

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❶ What the BMP is comprised of, how it functions, and what it is intended to do.

❷ List of the most beneficial attributes of the BMP.

❸ Highlights potential problems that may make it infeasible or undesirable at a site.

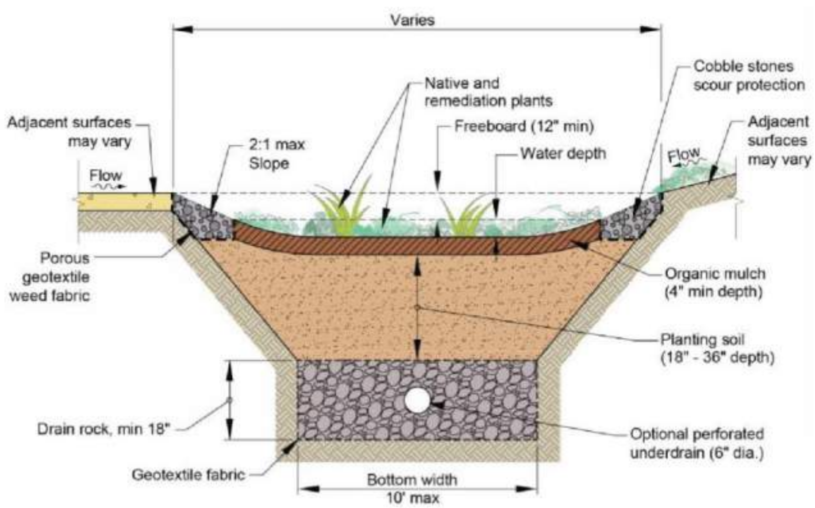
BMP FACT SHEET **BMP-9**
BIOSWALES

1 VARIATIONS

Variations include a vegetated swale, or an enhanced swale. A vegetated swale typically has runoff entering one side of the swale and exit at the other end of the swale. It is designed to reduce runoff velocities to allow pollutants to be removed via sedimentation, adsorption, and infiltration through the soil. A vegetated swale does not have planting media or an underdrain system. An enhanced swale is similar to a vegetated swale but differs by featuring a permeable planting media and underdrain system beneath the swale to allow for capture and treatment of the water quality volume. Enhanced swales promote groundwater recharge while reducing runoff volume that enters the storm drainage system.

2 APPLICATIONS

- Residential – Swales can be used for side and backyard areas to minimize runoff volume and slow runoff flow.
- Commercial/Industrial – swales can provide drainage around the site and slow discharge from other BMPs that drain to the swale.
- Highway/Road – vegetated swales can provide an excellent alternative to curb and gutter systems.



Bioswale Section View (Source: Bowers + Kubota Consulting)

3 SITE CONSIDERATIONS

- Enhanced Swale
  - An enhanced swale requires a footprint equivalent to roughly 8% - 40% of its contributing impervious drainage area.
  - Enhanced swales require a bottom width of roughly 2-8 feet.

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1. Potential variations to the BMP which could include design alternatives that can increase storage capacity or infiltration rate.

2. Type of land use that is most applicable or feasible for installation of the BMP.

3. Various physical characteristics of a particular property that would be reviewed for the selection of the BMP.

BMP FACT SHEET
BIOSWALES **BMP-9**

- Check dams are only required if the longitudinal slope is greater than 2% but must be less than 5%.
- Requires minimum of 3-feet from bottom of swale to seasonally high water table.

- Vegetated Swale
  - A vegetated swale requires a footprint equivalent to roughly 2% - 4% of its contributing impervious drainage area.
  - The flow velocity must not exceed 1 foot/second.
  - Vegetated swales must not have a bottom width greater than 10 feet.
  - Requires minimum of 2-feet from bottom of swale to seasonally high water table.

❶ DESIGN GUIDELINES AND CONSIDERATIONS

- Enhanced Swale
  - Landscape design should specify proper grass species based on specific site, soils, and hydrologic conditions. Vegetation should be chosen to only require maintenance no more than semi-annually.
  - The underdrain diameter must be a minimum of 6 inches and must be placed at a minimum slope of 0.5%.
- Vegetated Swale
  - Check dams may be used to achieve velocity requirements, decrease runoff volume, rate, and velocity, and promote filtration and settling of nutrients and other pollutants.
  - Dense turf grass is recommended to promote sedimentation, filtration, and nutrient uptake to limit erosion and maintain reduced flow velocities.
  - Does not require pretreatment.

❷ EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	83-92%
Total Phosphorus	29-80%
Nitrogen	39-89%
Copper	46%
Metals	88-90%
Zinc	63%
Oil/Grease	75%

Sources: [1,8]

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❶ Technical options and procedures to be considered when designing the BMP. Specific design criteria are presented which can assist planners and designers in incorporating LID techniques into the site design and determining how best to utilize the BMP.

❷ List of the most commonly targeted pollutants and the anticipated pollutant capture rate of the BMP.

BMP FACT SHEET
BIOSWALES **BMP-9**

1 **COST CONSIDERATIONS**

Costs will vary between the different variations of swales; however, an estimated construction cost of vegetated swales is roughly between $0.85 to $2.30 per cubic foot of storage capacity, or between $25,000 - $50,000 per acre of impervious surface treated. Operation and Maintenance costs are roughly 3% of construction costs between $500 - $1,500 per acre of impervious surface treated. A 2012 Study by the San Diego Stormwater Urban Mitigation Plan estimated that annual maintenance costs for a vegetated swale ranged from $1,476 to $2,623.

2 **OPERATION AND MAINTENANCE**

Maintenance primarily involves litter control and maintaining vegetation and plant cover. Other maintenance activities include the following:

- Inspect pretreatment areas for clogging, clean as necessary.
- Remove accumulated trash and debris.
- Inspect and correct erosion problems in the soil of the swale.
- Remove sediment buildup from the bottom of the swale if accumulation reaches 25% of the original design volume.
- Mow grass to maintain a height of 3 – 4 inches.

3 **SIZING PROCEDURE**

Enhanced Swale

1. Determine the Water Quality Volume (WQV) that will need to be treated by the LID BMP.

   $$WQV = P \, x \, C \, x \, AT \, x \, 3630$$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. C = 0.05 + 0.009I

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. Pretreatment is critical to capture sediment that may clog the soil media. Size the pretreatment forebay assuming a volume equal to 10% of the WQV. The forebay's volume counts toward the WQV requirement.

   $$VP = 0.1 \, x \, WQV$$

   Where V_P = Pretreatment Forebay Volume (ft^3)
   WQV = Water Quality Volume (ft^3)

December 2023 LID PRACTITIONER'S GUIDE/9-4

1 General cost information for comparison purposes. The section includes both installation cost of the BMP and the annual maintenance cost of the BMP in 2023 dollars.

2 Guidance on suggested maintenance procedures for the BMP, including the frequency with which to perform the recommended maintenance.

3 Formula(s) to calculate the water quality volume or water quality flow rate that will need to be treated by the BMP and then a step-by-step procedure to size the BMP to mitigate the calculated volume or flow rate.

4.2.2 BMP FACT SHEETS

Ala Wai Golf Course Infiltration Basin (Courtesy of Bowers + Kubota Consulting)

INFILTRATION BASIN

BMP-1

DESCRIPTION

An infiltration basin is a shallow impoundment, where stormwater runoff is captured, stored, and infiltrated through the basin floor into the soil. The basin is generally vegetated with simple grass cover.

ADVANTAGES

- Cost-effective BMP for controlling both stormwater quantity and quality.
- Reduces peak discharge and runoff volume.
- Mitigates downstream flooding.
- Controls channel erosion.
- Provides water quality benefits by reducing the amount of pollutants in receiving waters.
- Provides groundwater recharge.

LIMITATIONS

- Works best for drainage areas under 5 acres but can go up to 10 acres under the right conditions.
- Infeasible in locations with a high groundwater table.
- Excavation may disturb archaeological resources.
- Basin has a large footprint.

Minimum BMP Footprint
1,000 sf

Construction Cost
$$–$$$

Operations & Maintenance
Frequency: Semi-Annually Cost: $$

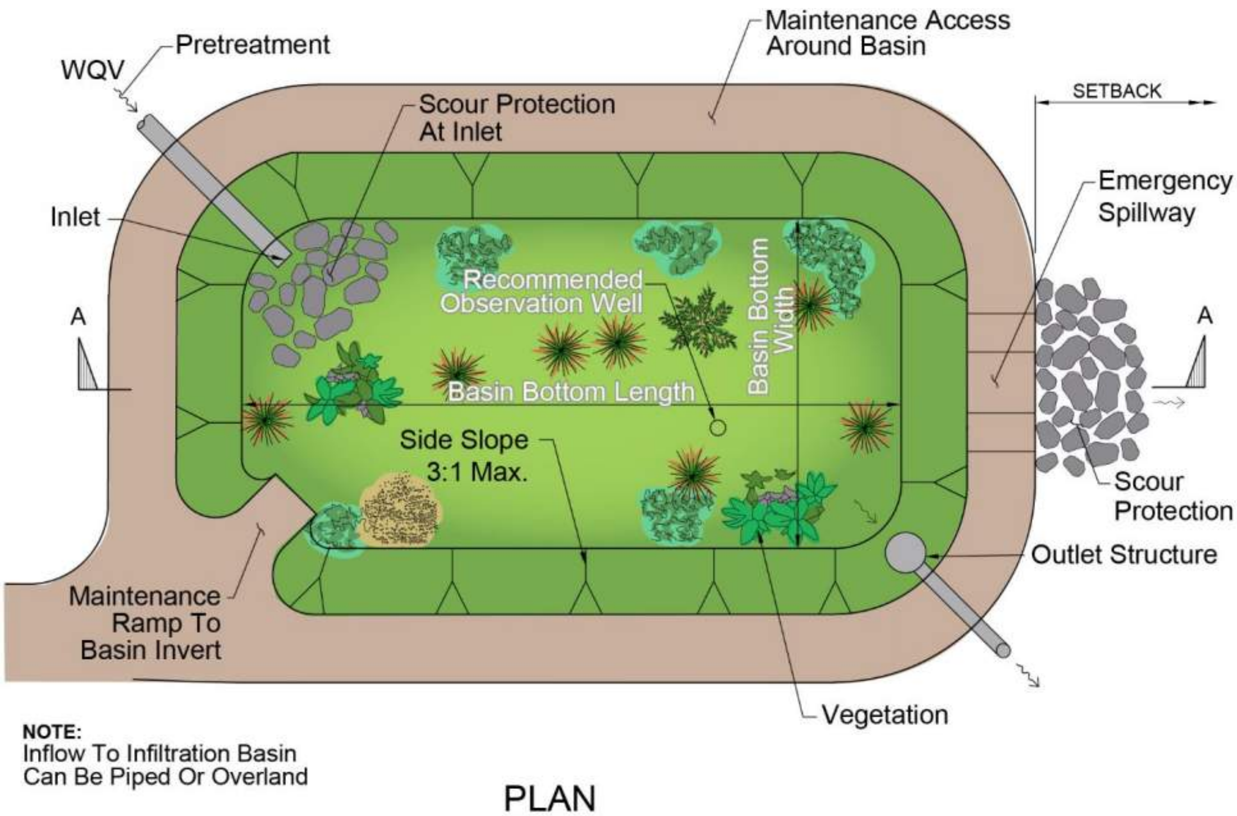
Design Considerations
• Soil infiltration rate • Interior side slope • Length to width ratio • Time to drain basin • Basin invert slope • Water quality volume

VARIATIONS

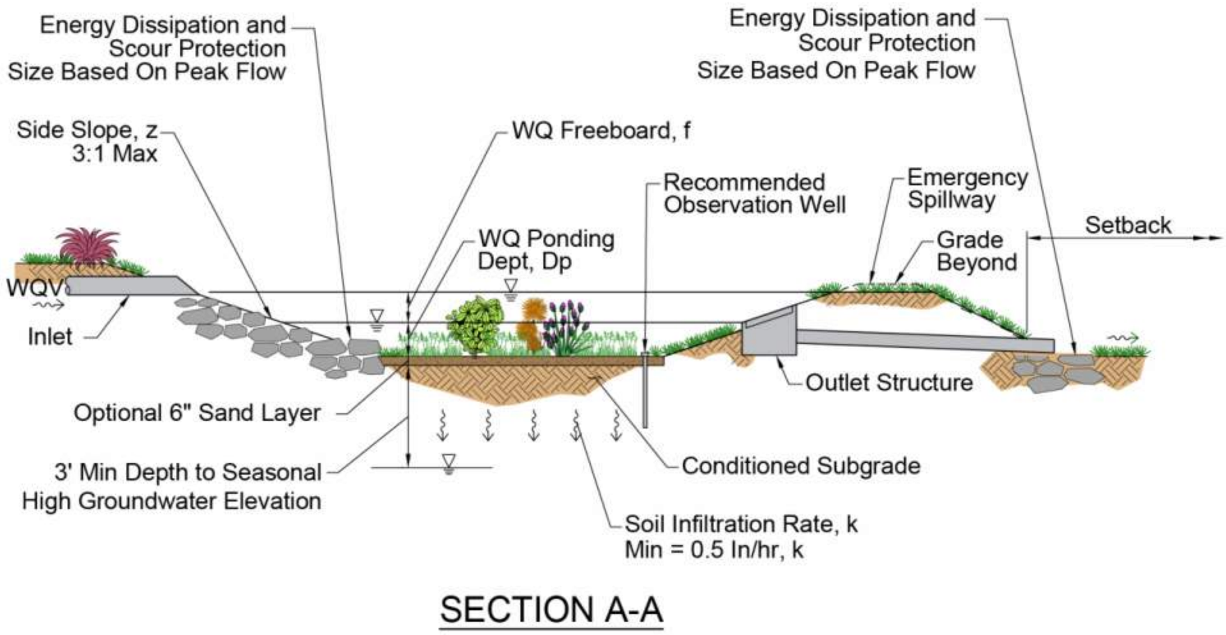
Infiltration basin variations include a subsurface infiltration system and an infiltration berm. A subsurface infiltration system is a rock (or premanufactured material) storage bed beneath surfaces like parking lots, lawns, and playfields, designed for temporary storage and infiltration of stormwater runoff. Infiltration berms are vegetated features aligned with site contours in moderately sloped areas. They are earthen embankments with sloping sides, serving to retain, infiltrate, slow, or redirect stormwater.

APPLICATIONS

Infiltration basins are often applicable in rural areas as well as in residential, industrial, and commercial developments, provided there is ample space. Their implementation may be constrained in densely urbanized areas and certain redevelopment endeavors, primarily due to space constraints.



Source: Bowers + Kubota Consulting



Source: Bowers + Kubota Consulting

Infiiltration Trench at Punahou School (Courtesy of the City and County of Honolulu)

INFILTRATION TRENCH

BMP-2

DESCRIPTION

An infiltration trench is a rock-filled trench designed for stormwater infiltration and conveyance. Stormwater runoff flows onto the rock and infiltrates through the bottom into the underlying soil. Designs may include an overflow drain, an underdrain, or vegetation.

ADVANTAGES

- Reduces volume of stormwater runoff.
- Reduces peak runoff rate.
- Increases groundwater recharge.
- Linear design makes it suitable for roadway applications.

LIMITATIONS

- Pretreatment recommended upstream to capture sediment loadings to avoid clogging and premature failure.
- The tributary drainage area should be less than five acres.
- Soil infiltration rate should be a minimum of 0.5 inch/hour to provide adequate treatment.
- Should not be used for treatment at industrial sites to avoid groundwater contamination.

Minimum BMP Footprint
80 sf

Construction Cost
$–$$

Operations & Maintenance
Frequency: Monthly Cost:$–$$

Design Considerations

- Utilize pretreatment
- Permeability of soil
- Distance to groundwater
- Install observation wells

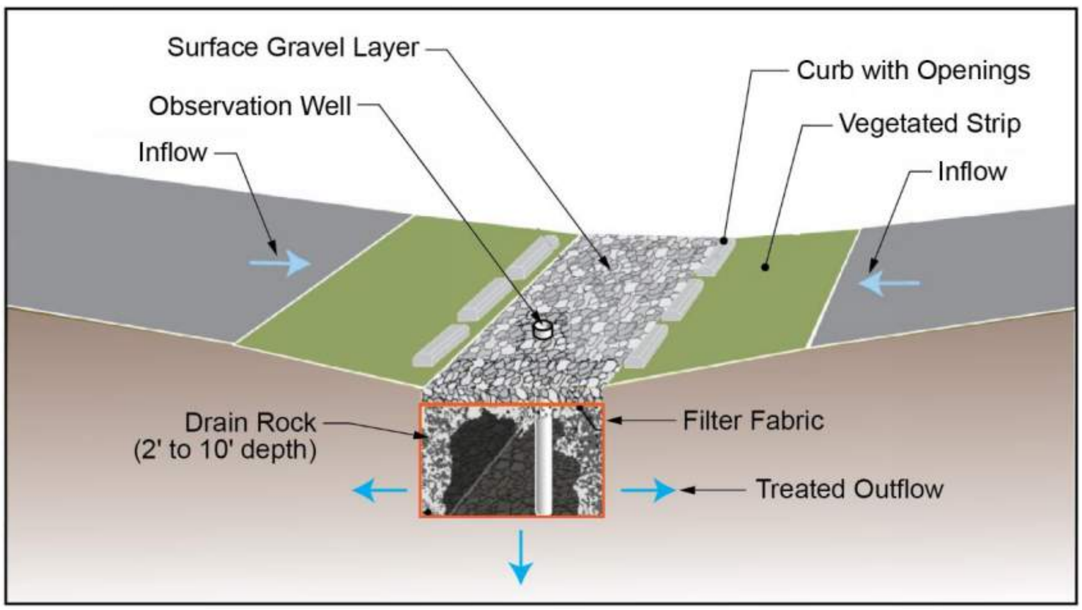
VARIATIONS

Infiltration trenches are linear stormwater BMPs designed for runoff infiltration. Infiltration trenches can be a part of a conveyance system with other pretreatment systems upstream to reduce sediment loading and clogging.

APPLICATIONS

- Urban/commercial areas especially when paired with other stormwater controls.
- Residential
- Retrofit
- Highway/road

See the figure below for a schematic of an infiltration trench. Water flows through vegetated strip towards the gravel layer where it is drained underground.



Source: CalTrans

Dry Well on Ane Keohokalole Highway, Hawaiʻi Island (Courtesy of Bowers + Kubota Consulting)

DRY WELL

BMP-3

DESCRIPTION

Dry wells are subsurface storage and infiltration facilities used to capture and temporarily store runoff. A dry well is constructed by excavating a hole in the ground and filling it with open graded aggregate, or a prefabricated perforated storage chamber or pipe segment. Dry wells may be used to aid groundwater recharge and reduce stormwater runoff volume. They are commonly used to accept roof runoff. When designing dry wells, the underlying soil's rate of infiltration and the distance from the dry well bottom to the groundwater table should be taken into consideration.

ADVANTAGES

- Reduces volume of stormwater runoff.
- Reduces peak stormwater runoff rate.
- Improve water quality.
- Visually unobtrusive.

LIMITATIONS

- May not be suitable for roofs with high concentrations of nutrients and other contaminants.
- Not appropriate for soil types C or D or soils with infiltration rates less than 0.5 inch/hour.
- A minimum of 3 feet from the bottom of the dry well to the groundwater table to allow an adequate infiltration rate.

Minimum BMP Footprint
30 sf

Construction Cost
$

Operations & Maintenance
Frequency: Quarterly Cost: $

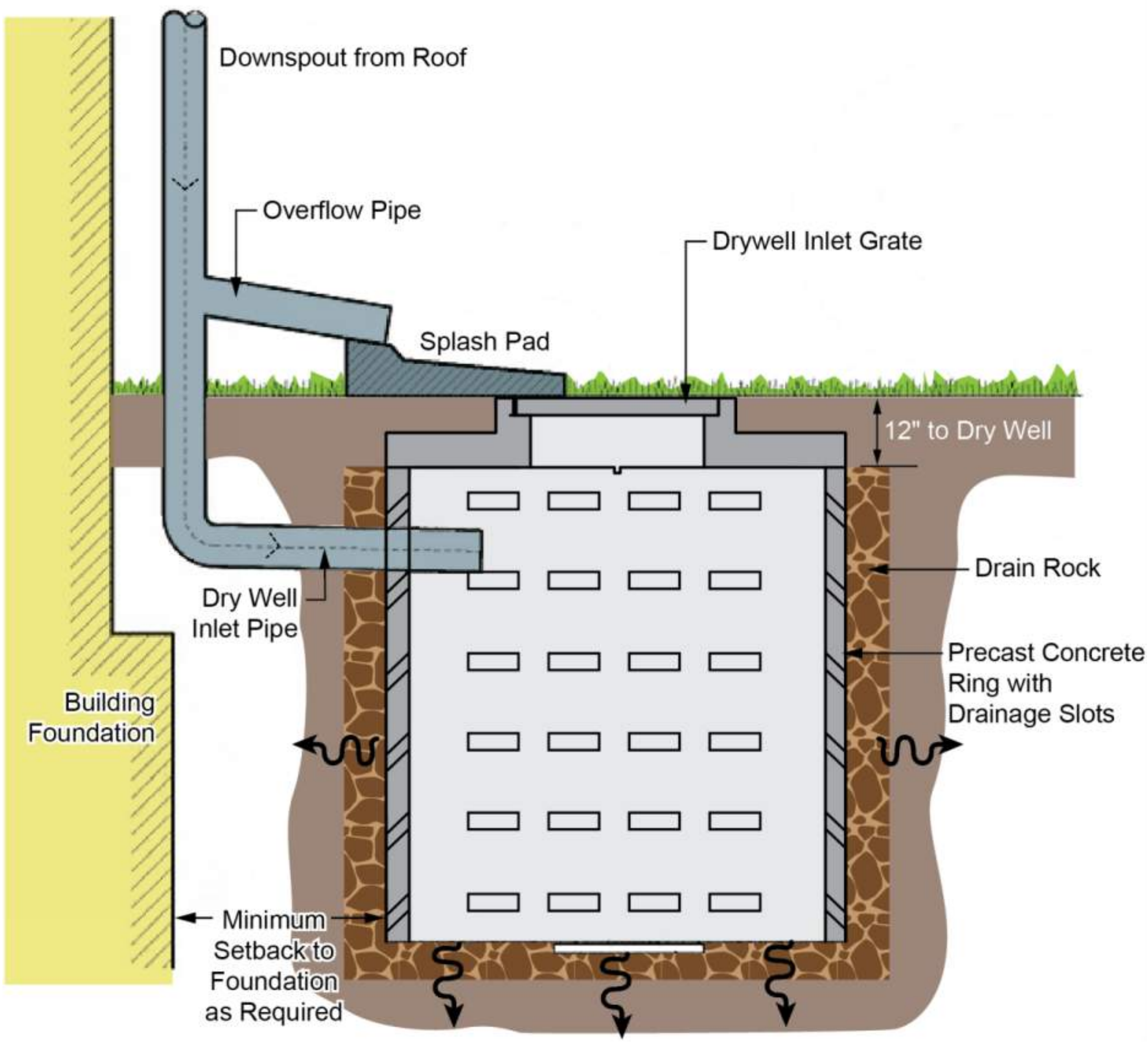
Design Considerations
• Water quality volume • Permeability of soil • Distance to groundwater

VARIATIONS

- Intermediate "Sump" Box—runoff flows through an intermediate box to allow sediments to filter out. Water then flows through a screen into the dry well.
- Prefabricated Dry Well—using prefabricated dry wells in place of aggregate dry wells can increase storage capacity and lower associated costs.

APPLICATIONS

Dry wells are most often used in a residential setting, particularly to capture roof runoff. However, because of their small footprint, dry wells can also be used for commercial areas, ultra urban areas, and retrofits.



Source: American Groundwater Solutions LLC with revisions by Bowers + Kubota Consulting

Left: Residential Rain Garden in Kailua, O'ahu; Right: Rain Garden in Wahikuli Wayside Park, Maui Photos (Courtesy of Hui o Ko'olaupoko)

BIORETENTION BASIN (RAIN GARDEN)

BMP-4

DESCRIPTION

Rain gardens or bioretention basins are landscaped depressions adapted to provide on-site treatment of stormwater runoff. Rain gardens collect runoff and filter it through a mixture of soil, sand, and/or gravel. The infiltrating stormwater also provides water to the plants in the rain garden. These BMPs function as soil-based and plant-based filtration devices that remove pollutants through physical, biological, and chemical treatment processes.

ADVANTAGES

- Pollutant removal effectiveness is typically high.
- Versatile with broad applicability
- Provides shade and windbreaks.
- Absorbs noise and improves aesthetic vegetated appearance.
- Reduces peak discharge and runoff volume.
- Pretreatment for downstream drainage structures and BMPs.

LIMITATIONS

- In areas with prolonged dry periods, installation of an irrigation system may be required.
- Not recommended for areas with slopes greater than 20% or where tree removal would be required.
- Not suitable at locations where the water table is within 3 feet of the bottom of the bioretention facility.
- Potential to create breeding habitat for mosquitoes.

Minimum BMP Footprint
600 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Semi-Annually Cost: $$

Design Considerations

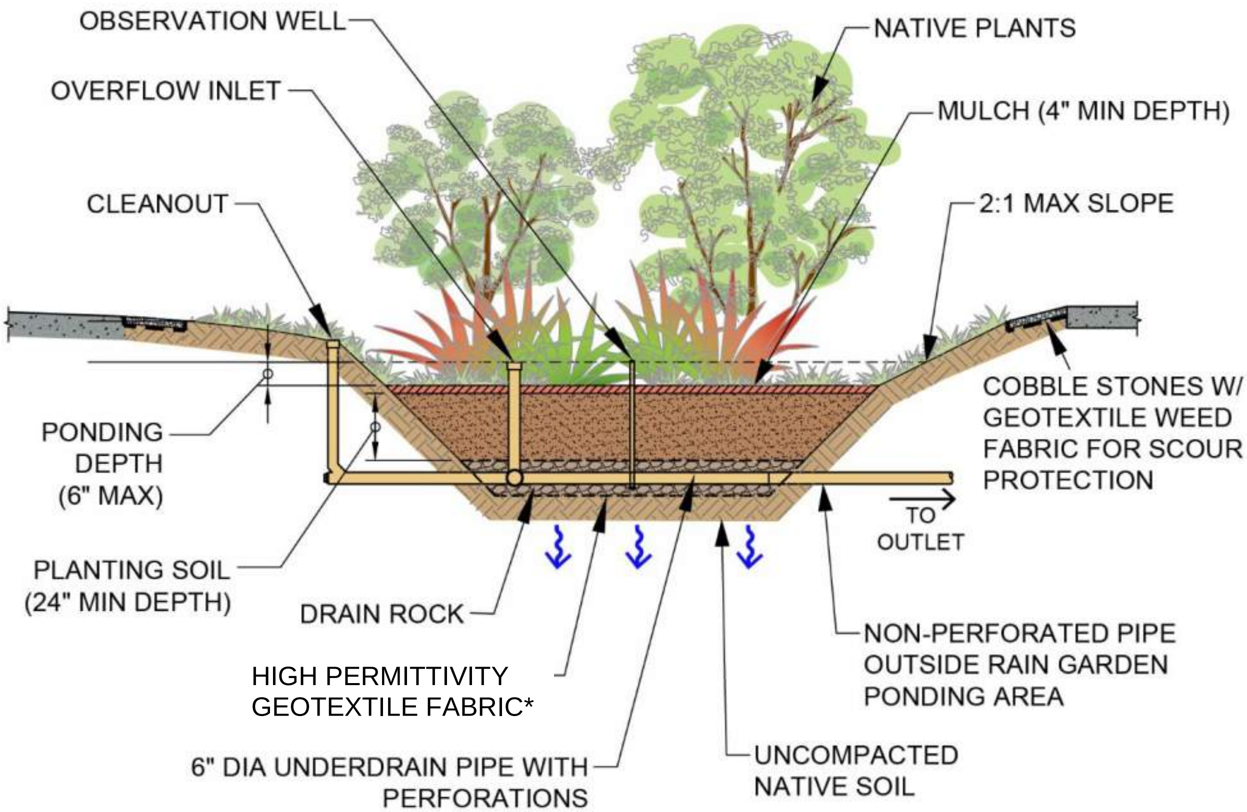
- Plant selection
- Side slope
- Soil infiltration rate
- Ponding depth
- Hydraulic residence time

VARIATIONS

- Subsurface storage/infiltration bed
- Use of an underdrain
- Use of impervious liner
- Designed for either infiltration, infiltration/filtration, or filtration

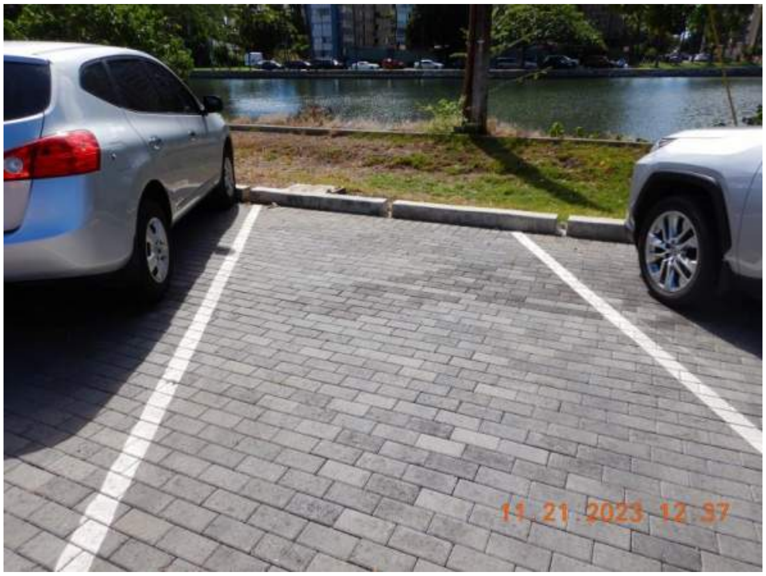
APPLICATIONS

- Urban areas such as parking lot islands, along roads, at intersections, or other landscaped areas as a retrofit, redevelopment, or new construction.
- Bioretention basins can be tailored to treat hot spots with high pollutant concentrations by adding an impervious liner to the bottom to prevent groundwater or surface water contamination.
- Bioretention basins are suitable for residential areas because it can add beauty to the landscape, resulting in an increase in property value.



*WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC

Source: Bowers + Kubota Consulting



Permeable Pavers at Ala Wai Golf Course, Honolulu, O'ahu,
Courtesy of Bowers + Kubota Consulting

PERMEABLE PAVEMENT

BMP-5

DESCRIPTION

Permeable pavement consists of pavement or interlocking paver blocks designed to allow stormwater infiltration into an underlying aggregate layer until the water infiltrates into the soil matrix. The underground aggregate reservoir layer is designed for surface vehicle load requirements. Permeable pavement can also be referred to as pervious pavement or porous pavement. Permeable pavement is durable with a life span of approximately 20 years, and possibly more with proper maintenance.

ADVANTAGES

- Captures surface stormwater runoff volume based on the design storm event.
- Underground infiltration inhibits mosquito breeding.
- Reduces or eliminates space needed for other BMPs.
- Infiltration addresses all pollutants, except litter.
- Microbial growth in aggregates promotes biodegradation of oils and organic materials and adsorption of heavy metals.
- Dual use for pavement structure and stormwater management.

LIMITATIONS

- Low soil permeability will decrease efficiency resulting in higher surface runoff volumes.

Minimum BMP Footprint
600 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Quarterly Cost: $$–$$$

Design Considerations
• Water quality volume • Permeability of soil • Distance to groundwater • Load requirements

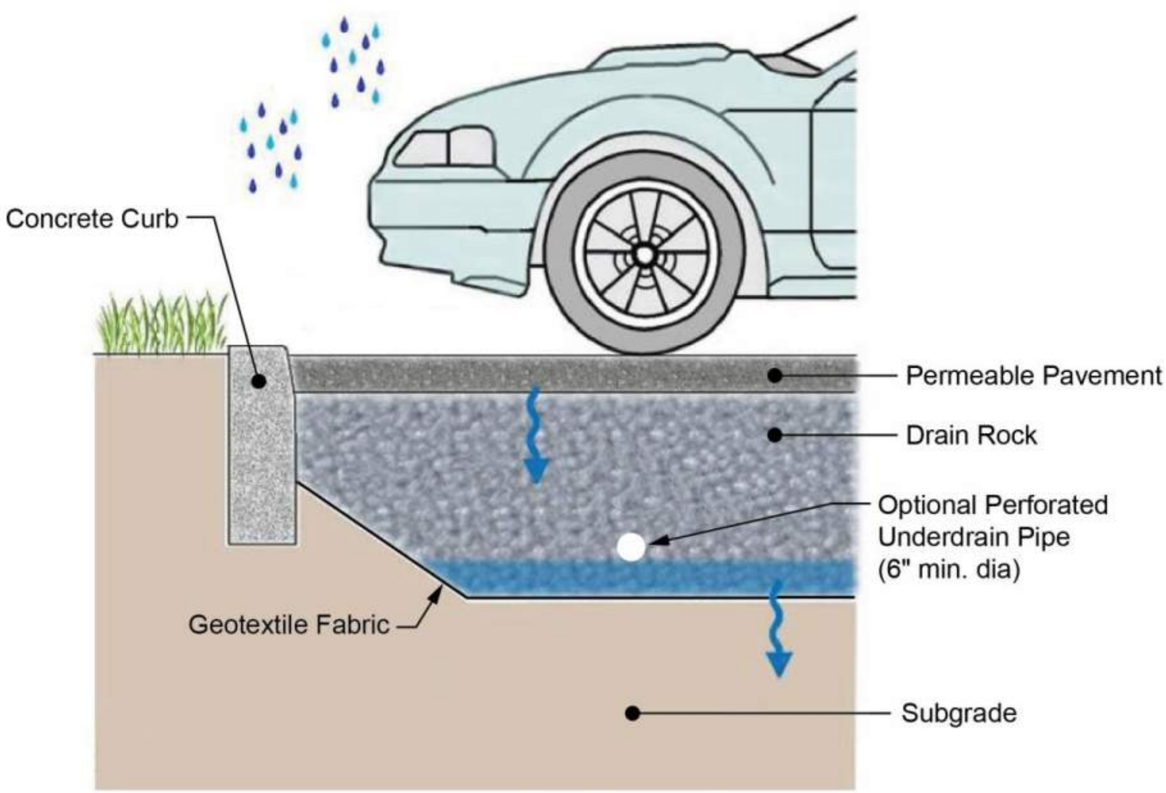
- Higher initial cost than conventional pavement.
- Not applicable for use on highways and high-volume roads due to heavy traffic and sediment loads.
- Not applicable for materials storage areas where silt, sediment, or spillage may occur.

VARIATIONS

Permeable pavement can be used in different variations including the use of interlocking paver blocks, pervious concrete, porous asphalt, or grass pavers. This BMP can also be used with an underdrain system if the native soil within the subgrade has a low infiltration rate.

APPLICATIONS

Applications include low-volume, low-speed areas, such as driveways, parking lots, minor roads and roadway shoulders. Permeable pavement is also applicable for sidewalks, patios, and deck areas. In highly developed areas with little open space, permeable pavement can be applied in retrofit situations when existing conventional pavement is being replaced. Residential properties commonly use permeable pavers due to their customizable options in shape, size, color, and layout. Pavers are also commonly used in walkways, plazas, and parking areas for large-scale projects.



Source: Cahill Associates


Left: Cistern at a residence. Right: Rain barrel at a residence. (Courtesy of Honolulu Board of Water Supply)

RAINWATER HARVESTING

BMP-6

DESCRIPTION

Rainwater harvesting is the capture and temporary storage of roof runoff in rain barrels or cisterns for non-potable outdoor purposes like irrigation and washing vehicles. Rain barrels, which are often aboveground plastic tanks, capture smaller runoff volumes. Cisterns, with greater capacity and pressurized distribution, can be aboveground or underground.

ADVANTAGES

- Recycles roof stormwater runoff for non-potable water uses.
- Provides runoff volume and pollutant reduction.
- Reduced water demands and cost for landscape irrigation.
- Wide applicability.

LIMITATIONS

- Periodic maintenance and cleaning to ensure effective stormwater storage while reducing algae growth and limiting mosquito breeding.
- If captured water is not used as anticipated or excessive rainfall occurs, the extra water collected must be managed to prevent overtopping and erosion of areas below the rain barrel or cistern.
- Improper or infrequent use, such as the rain barrel or cistern not being emptied between storm events, may result in unintended discharges.

Minimum BMP Footprint
Varies

Construction Cost
$

Operations & Maintenance
Frequency: Semi-Annually Cost: $

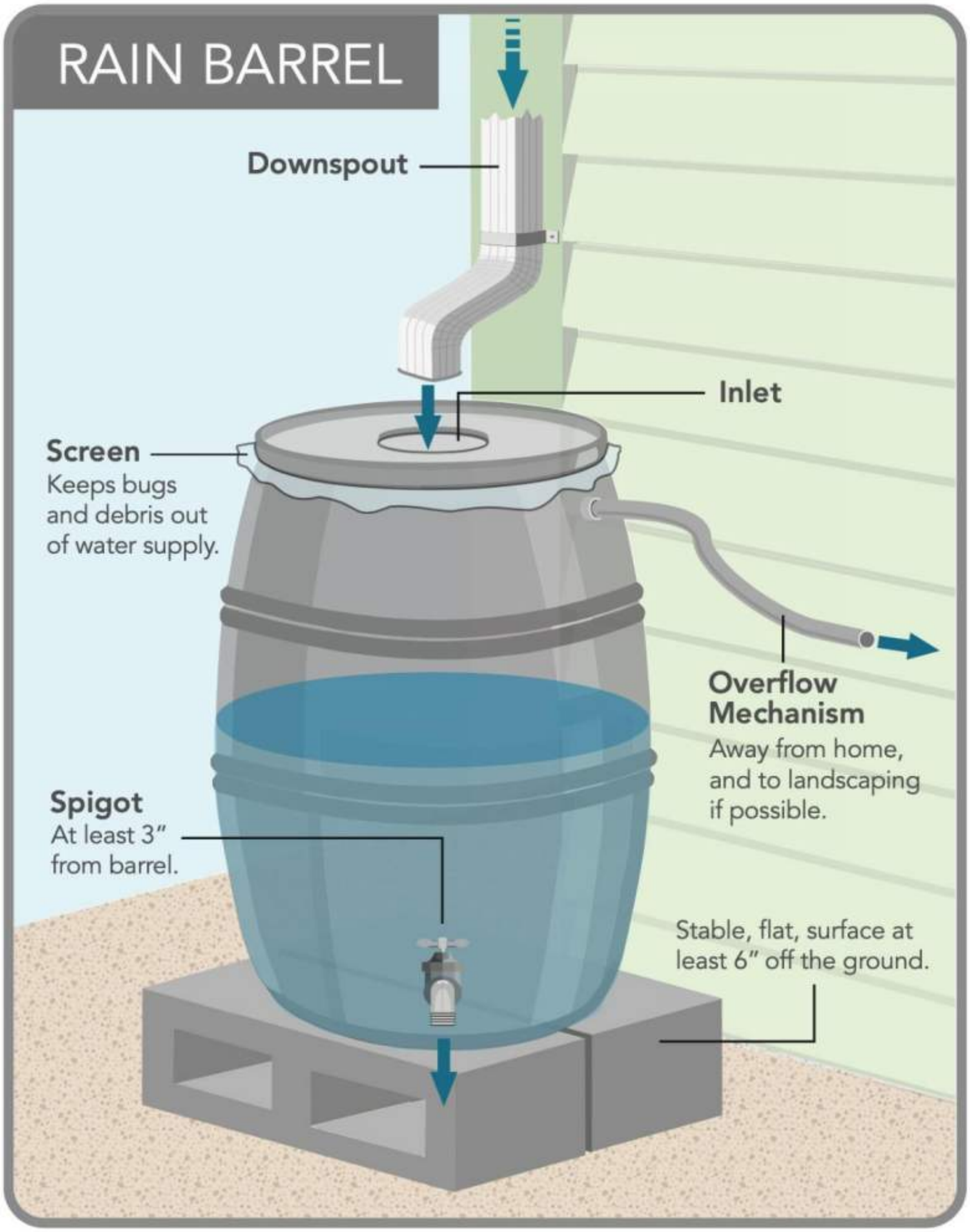
Design Considerations
• Location • Storage capacity • Structural support • Evaporation Rate • Rainfall

VARIATIONS

- Rain barrels
  - Typically, rooftop downspouts link to rain barrels, gathering and storing water for future use. These barrels are prevalent in households, where water is repurposed for garden irrigation. They also find application in smaller-scale commercial and institutional settings.
- Cisterns
  - A cistern is a storage tank with greater capacity compared to a rain barrel. Typically, cisterns reuse stormwater for irrigation. Cisterns are available in various materials (fiberglass, concrete, etc.) and can be installed aboveground or underground. Sizes range from 200 to 10,000 gallons and larger.
- Vertical Storage Tank
  - A vertical storage tank is a large-scale structure designed to store large amounts stormwater. These tanks are the largest among stormwater capture and reuse containers, and their application depends on drainage area and water demand. Vertical storage tanks are most suitable for extensive irrigation or fire suppression and should be planned by a licensed expert. They are typically used at commercial, educational, or institutional facilities with substantial water requirements.
- Underground Storage Systems (using manufactured modular products)
  - Stormwater runoff can be stored underground using structural plastic units beneath pavements and landscaped areas. These modular units offer significant storage capacity in a compact space and do not require additional structural support. Implementing an underground storage system is ideal for institutional or commercial applications. These systems are more intricate than other types of stormwater storage systems, necessitating professional engineering design and requiring pumps supply irrigation systems.

APPLICATIONS

Harvesting/Reuse is applicable to many types of projects. The only caveat is that there must be a roof or area with which nearby to capture the stormwater. Rain barrels are mostly used in residential areas. Rainwater collected through rainwater harvesting can substitute potable water for purposes like irrigation, mechanical systems, or toilet flushing, primarily in rural areas.



Source: City of Palo Alto Stormwater Program

Left: Turtle Bay (Courtesy of Sea Grant); Right: Frank Fasi Municipal Building Parking Structure (Courtesy of CCH-DFM)

GREEN ROOFS

BMP-7

DESCRIPTION

Green roofs are an eco-friendly alternative to standard roofs, effectively reducing stormwater runoff and offering various environmental and aesthetic advantages. By utilizing innovative design strategies, they make productive use of spaces typically unused for stormwater management. Unlike traditional roofing materials, green roofs absorb, store, and naturally disperse stormwater, also acting as thermal regulators for the building.

ADVANTAGES

- Effective stormwater management and energy conservation.
- Alleviation of the urban heat island effect.
- Prolonged lifespan of roofing materials.
- Enhanced visual appeal for living and working environments.

LIMITATIONS

- Cost (intensive systems).
- Careful design and construction required.
- Maintenance requirements until plants are established.
- Difficult to keep plants alive with green roof soil shallower than 4 inches.

BMP Footprint Size
350 sf

Construction Cost
$$ - $$$

Operations & Maintenance
Frequency: Quarterly Cost: $$

Design Considerations
• Location • Storage capacity • Structural support • Evaporation Rate • Rainfall

VARIATIONS

- Depending on the plant material and planned usage for the roof area, vegetated roofs can be categorized as systems that are intensive, semi-intensive, or extensive. Intensive systems allow for more variety but are expensive and require more maintenance. Intensive systems require the deepest soil and can accommodate many types of plantings, including large shrubs and trees. Semi-intensive systems also require a deeper soil layer and form a transition from extensive to intensive greening. Semi-intensive systems require moderate maintenance and occasional irrigation depending on the location. A typical growing medium depth for a semi-intensive green roof is 6 to 10 inches.
- Among green roof systems, extensive vegetated roofs are the most popular. Extensive green roofs excel in reducing stormwater runoff and are cost-effective compared to other options. Extensive systems have three variations of assemblies that can be considered in design.
    - Single media assemblies find common use in pitched roof applications and in situations where a lightweight installation is needed. These systems typically feature drought-resistant plants and employ coarse engineered media with excellent permeability.
    - Dual media assemblies employ two distinct types of non-soil growth media. In this setup, a fine-grained media with some organic content is layered atop a base of course, lightweight aggregate. This design omits a geocomposite drain. The aim of this design is to enhance drought resistance. These assemblies are usually 4 to 6 inches thick.
    - Dual media with synthetic retention/detention layer systems incorporate non-permeable plastic panels with cup-like depressions on the top surface (essentially, a modified geocomposite drain sheet). These panels are filled with coarse lightweight aggregate. The cups capture and hold water while also creating an air pocket at the base of the assembly.

APPLICATIONS

Green roofs are not commonly used for residential structures. They are suitable for various types of buildings including commercial and industrial buildings. They are suitable in ultra urban environments, where available space is at a premium. Green roofs can be installed either during initial construction or added as a retrofit.

Kuono Marketplace, Kahala, O‘ahu (Courtesy of Bowers + Kubota Consulting)

TREE AND PLANTER BOX FILTERS BMP-8

DESCRIPTION

Tree and planter box filters, also known as vegetated biofilters, are stormwater treatment devices filled with engineered soil media, and are typically located in a sidewalk, parking lot, or median. Runoff flows from adjacent impervious areas into the device and infiltrates through the soil media before being directed back into the drainage system. Pollutant removal is accomplished by filtration from the soil media and by evapotranspiration and phytoremediation from the vegetation.

ADVANTAGES

- Pollutant removal effectiveness is typically high.
- Provides an aesthetic vegetated appearance.
- Standardized design and layout.
- Ease of construction and maintenance.
- Pretreatment for downstream structures and BMPs.

LIMITATIONS

- In areas with prolonged dry periods, installation of an irrigation system may be required.
- Not applicable downstream of landscaped or pervious areas where heavy sediment loadings may lead to premature failure.
- Width of sidewalk or right-of-way may limit tree box size.
- Areas with high density of underground utilities may limit use of trees and planter box filters.
- Tree roots may damage sidewalks.

Minimum BMP Footprint
16 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Annually Cost: $

Design Considerations

- Bioretention area and depth
- Bioretention media
- Ponding depth
- Underground drain system
- Vegetation
- Water quality volume

VARIATIONS

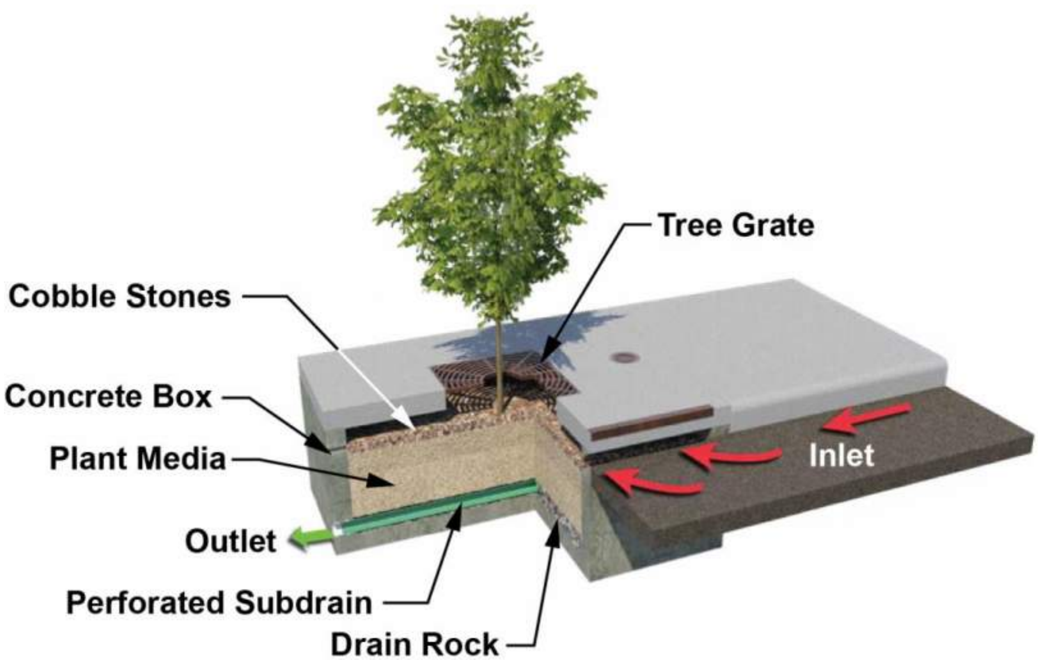
Tree and planter box BMPs have several variations that include contained, infiltration, or flow-through systems. The contained systems are generally traditional planters that capture rainwater and have weep holes to drain the excess water from the planter. This type of planter box can be installed to retrofit an existing urban streetscape or large area of pavement such as at an entryway to a building.

The second variation is an infiltration system designed to filter stormwater runoff through the planter's soil, capturing pollutants in the process, and then infiltrating into the native soil beneath the planter. Typically, these planters are constructed to be level with the surrounding paved surfaces. The planter is sized to accept runoff and temporarily store the water in a reservoir on top of the soil. This variation does not have an underdrain system.

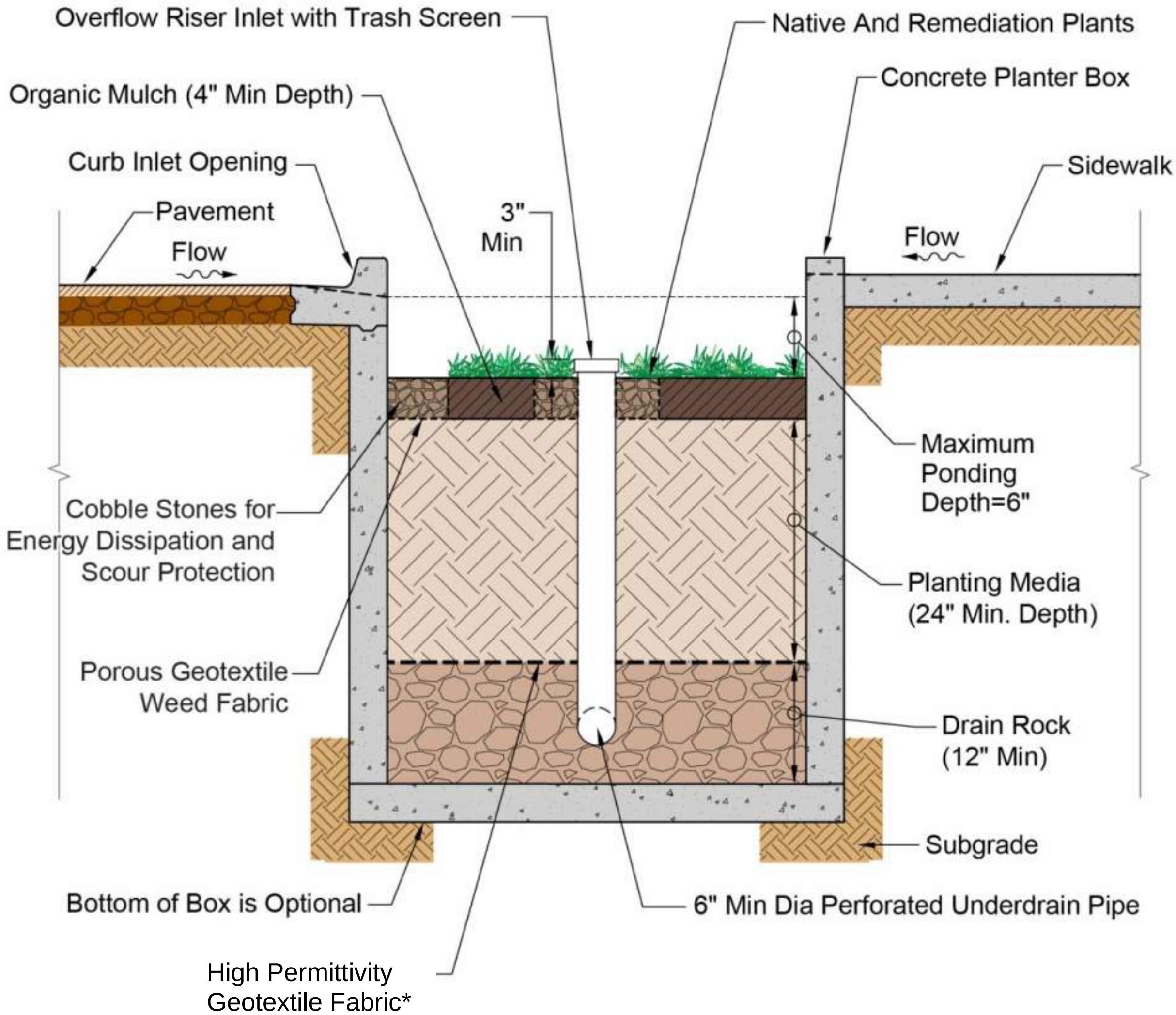
The third variation is a flow-through box system. This variation is completely contained with an impervious bottom and drains to the stormwater system. Pollutant reduction is achieved as the water filters through the soil media. Flow control is achieved by temporarily ponding runoff above the soil and in a gravel layer below it. Once the stormwater has filtered through the soil, the stormwater exits through a perforated underdrain system that flows to the downstream drainage system.

APPLICATIONS

Planter and tree box filters are typically applied in urban areas. They can handle high pollutant loadings. They have a relatively small footprint and can accommodate vertical elevation drops along its edges. Often tree box filters are used in series to treat the entire water quality volume. Areas that work well with a box filter system include sidewalks, urban streetscapes, and residential, commercial, and light industrial buildings.



Tree Box Filter (Source: Contech)



*Well-graded filter or drain rock may be used in lieu of high permittivity geotextile fabric

Planter Box Filter Section View (Source: Bowers + Kubota Consulting)

Bioswale adjacent to Kumuhao Street, Waimanalo, O'ahu (Courtesy of the City and County of Honolulu)

BIOSWALES

BMP-9

DESCRIPTION

Swales are shallow, vegetated open channels or drainage pathways designed for conveyance of the design storm flow. Swales effectively reduce the speed of runoff, promote infiltration within the soil and planting media, and filter pollutants as water moves through the BMP. Swale variations include the vegetated swale and the enhanced swale.

ADVANTAGES

- Effectively promotes removal of various stormwater pollutants.
- May be incorporated into different landscape settings such as yards, road shoulders, rights-of-way, and provides treatment to roof downspout discharges.
- Enhanced swales can achieve flood control and groundwater recharge.
- Swales provide an inexpensive option for roads and highways compared to a typical curb and gutter, while reducing maintenance costs.

LIMITATIONS

- During dry periods, irrigation may be required to maintain vegetation.
- Hotspot areas are not suitable for swales as excessive oils and grease may reduce efficacy of pollutant removal rates.
- If heavy sediment loading is anticipated, a BMP for pretreatment is recommended.
- If clogged, swale systems may require reconstruction.
- Limited applications where space is a concern.

Minimum BMP Footprint
1000 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Monthly Cost: $ - $$

Design Considerations

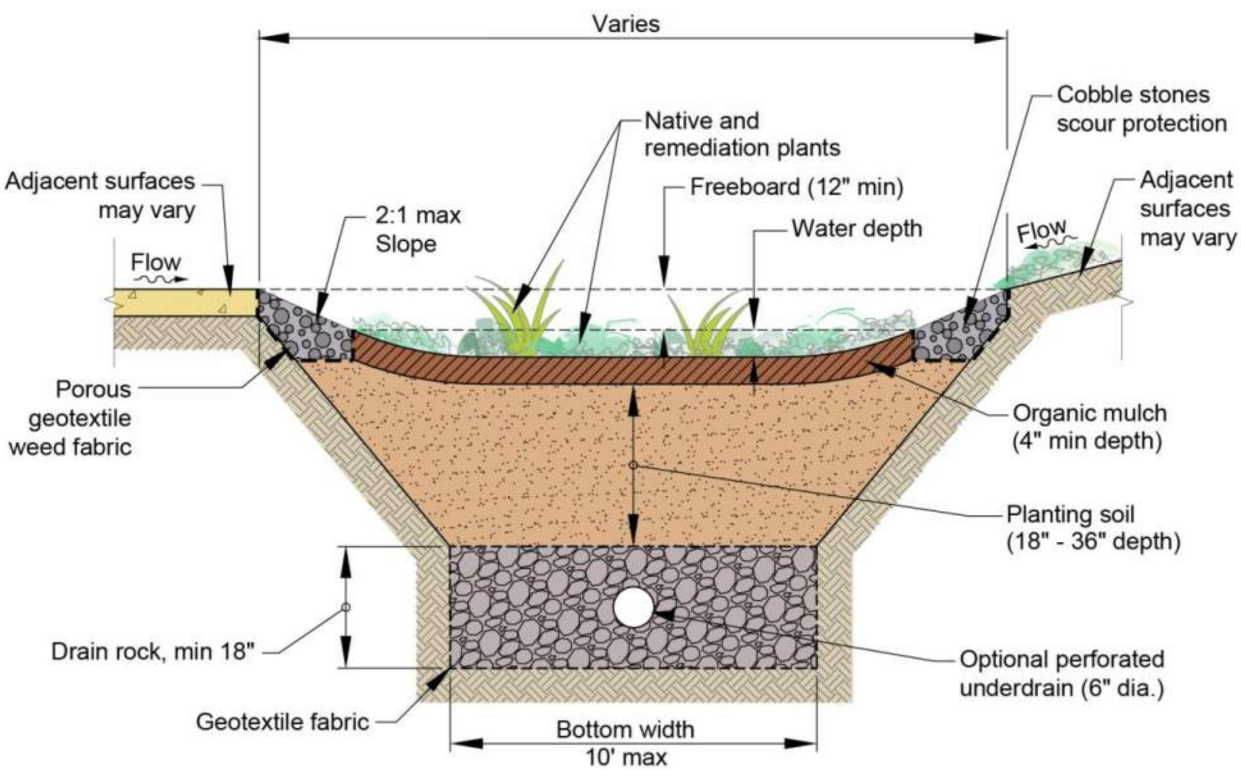
- Water quality volume
- Permeability of soil
- Distance to groundwater
- Load requirements

VARIATIONS

Variations include a vegetated swale or an enhanced swale. A vegetated swale typically has runoff entering one side of the swale and exiting at the other end of the swale. Vegetated swals are designed to reduce runoff velocities to allow pollutants to be removed via sedimentation, adsorption, and infiltration through the soil. A vegetated swale does not have engineered planting media or an underdrain system. An enhanced swale is similar to a vegetated swale but differs by featuring a permeable planting media and underdrain system beneath the swale to allow for capture and treatment of the water quality volume. Enhanced swales promote groundwater recharge while reducing runoff volume that enters the storm drainage system.

APPLICATIONS

- Residential—Swales can be used for side and backyard areas to minimize runoff volume and slow runoff flow.
- Commercial/Industrial—swales can provide drainage around the site and slow discharge from other BMPs that drain to the swale.
- Highway/Road—vegetated swales can provide an excellent alternative to curb and gutter systems but vehicle and pedestrian safety must be considered during design of the swales.



Bioswale Section View (Source: Bowers + Kubota Consulting)

Courtesy of State of Hawai'i Department of Transportation

VEGETATED FILTER STRIP

BMP-10

DESCRIPTION

A vegetated filter strip, sometimes referred to as a vegetated buffer strip, is a well-maintained strip of vegetation located adjacent and typically parallel to roadways or other impervious areas. They are typically vegetated with turf or native grasses and function by reducing the velocities of stormwater runoff and filtering out sediment and other pollutants via sedimentation. These strips rely on sheet flow across them, often achieved with level spreaders. Vegetated filter strips are commonly designed as pretreatment BMPs to treat runoff from impervious surfaces before reaching other BMPs such as a vegetated swale or bioretention basin.

ADVANTAGES

- Ability to filter and infiltrate stormwater runoff.
- Provides wildlife habitat while limiting cost and improving aesthetics.
- Promotes natural hydrologic balance and maintains groundwater recharge while reducing sediment load.
- Relatively easy to install and requires low maintenance.
- Effective at removing certain chemicals or heavy metals.

LIMITATIONS

- Not intended for treatment of concentrated flows.
- May be better suited in treatment trains for comprehensive stormwater management.
- Not suitable for high velocity runoff or areas with steep slopes, which may lead to erosion or damage of filter strip.
- Filter strips are not recommended in areas with limited space such as densely developed urban areas.

Minimum BMP Footprint
75 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Monthly Cost: $

Design Considerations
• Water quality volume • Permeability of soil • Distance to groundwater

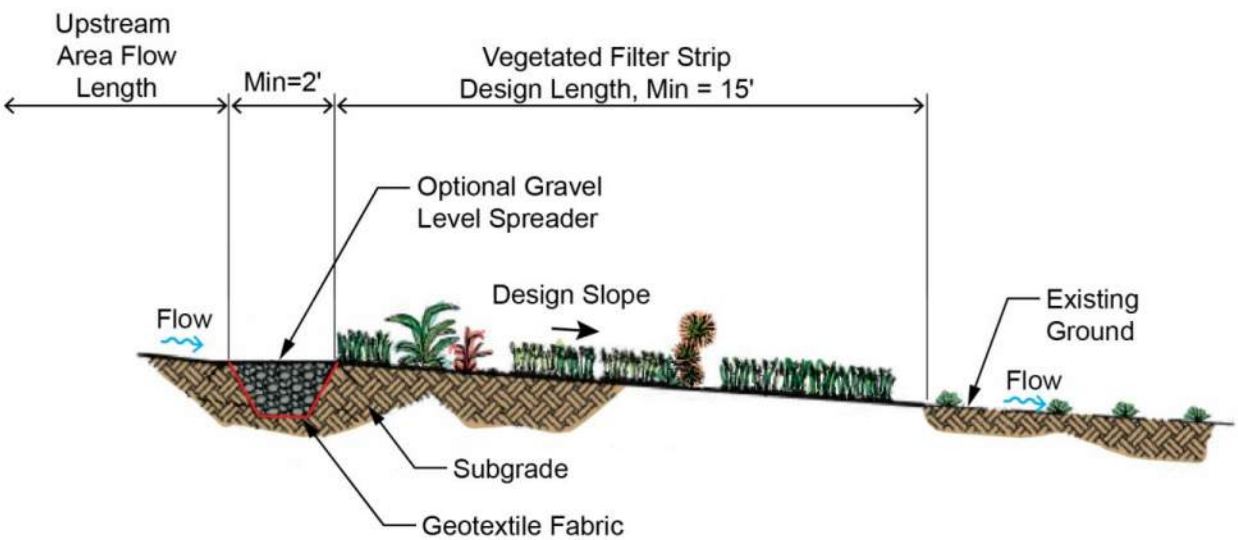
VARIATIONS

Vegetated filter strips can be planted with a wide range of different types of ground cover, including turf or native grasses.

APPLICATIONS

Vegetated filter strips primarily provide pretreatment upstream of infiltration and biofiltration BMPs. Sheet flow must be established across the filter strip to be effective. Sheet flow may be achieved through level spreaders.

Vegetated filter strips are well suited to treat runoff from roofs, driveways, parking lots, and other open impervious areas.



Vegetated Filter Strip Section View (Source: Bowers + Kubota Consulting)

Detention Basin in Mililani, O‘ahu, Hawai‘i (Courtesy of WSP)

DETENTION BASIN

BMP-11

DESCRIPTION

A detention basin is a spacious, shallow reservoir, or excavated pit constructed to temporarily detain stormwater runoff and help prevent downstream flooding. The temporary storage of water allows particles to settle. Typically, a detention basin does not have a permanent pool of water.

ADVANTAGES

- Cost-effective BMP for controlling both stormwater quantity and quality.
- Reduces peak discharge and runoff volume.
- Mitigates downstream flooding.
- Controls channel erosion.
- Provides water quality benefits by reducing the amount of sediment and debris in the receiving water.
- Vegetated basins can enhance the landscape and provide recreational spaces for public enjoyment.

LIMITATIONS

- Not practical for drainage areas less than five acres because scaled-down outlet structures for smaller catchment areas tend to clog.
- Infeasible in locations with a high groundwater table.
- Excavation may disturb archaeological resources.
- May provide limited removal of metals, nutrients, and pathogens.
- Siting is constrained due to lack of available land area.

Minimum BMP Footprint
400 sf

Construction Cost
$$ - $$$

Operations & Maintenance
Frequency: Semi-Annually Cost: $$

Design Considerations

- Interior side slope
- Length to width ratio
- Basin depth
- Time to drain basin
- Basin invert slope
- Outlet size
- Freeboard (Distance from dam crest to max. water surface)

VARIATIONS

The conventional detention basin is the dry extended detention basin, which is designed to drain down over a specified period and remain dry between storm events. These types of basins are typically equipped with an outlet structure or control device to regulate the discharge of water. Other variations of the detention basin include wet ponds, constructed wetlands, and underground detention. Wet ponds have a permanent pool for water quality treatment and can be effective for pollutant removal and peak rate mitigation. Wet ponds also provide aesthetic and wildlife benefits. Constructed wetlands are shallow marsh systems designed to treat stormwater runoff. They are planted with emergent vegetation and can provide significant wildlife benefits. Constructed wetlands are one of the best BMPs for pollutant removal; however, they require a relatively large amount of space. Underground detention systems are often used for sites where space is limited. Underground detention systems can be constructed by excavating a broad area and filling it with uniformly graded aggregate or by using prefabricated underground vaults constructed of materials such as reinforced concrete or high-density polyethylene. Runoff is stored in the vaults or within the void spaces of the aggregate while the vault or aggregate bed is designed with withstand the surface loads such as vehicular traffic. Detention basins work well to provide storm runoff peak rate attenuation but provide minimal water quality treatment when compared to the LID BMPs in this guide. Consequently, detention basins should be used in conjunction with a pretreatment BMP and/or downstream treatment BMP.

APPLICATIONS

Detention basins are often applicable in rural areas as well as in residential, industrial, and commercial developments, provided ample space is available and contaminated runoff or soil is not present. Their implementation may be constrained in densely urbanized areas and certain redevelopment endeavors, primarily due to space constraints. In such cases, alternatives like underground detention or infiltration may be employed. Residential development, industrial development, commercial development, and urban areas can readily use underground systems.

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APPENDIX A FULL BMP FACT SHEETS


Ala Wai Golf Course Infiltration Basin (Courtesy of Bowers + Kubota Consulting)

INFILTRATION BASIN

BMP-1

DESCRIPTION

An infiltration basin is a shallow impoundment, where stormwater runoff is captured, stored, and infiltrated through the basin floor into the soil. The basin is generally vegetated with simple grass cover.

ADVANTAGES

- Cost-effective BMP for controlling both stormwater quantity and quality.
- Reduces peak discharge and runoff volume.
- Mitigates downstream flooding.
- Controls channel erosion.
- Provides water quality benefits by reducing the amount of pollutants in receiving waters.
- Provides groundwater recharge.

LIMITATIONS

- Works best for drainage areas under 5 acres but can go up to 10 acres under the right conditions.
- Infeasible in locations with a high groundwater table.
- Excavation may disturb archaeological resources.
- Basin has a large footprint.

Minimum BMP Footprint
1,000 sf

Construction Cost
$$–$$$

Operations & Maintenance
Frequency: Semi-Annually Cost: $$

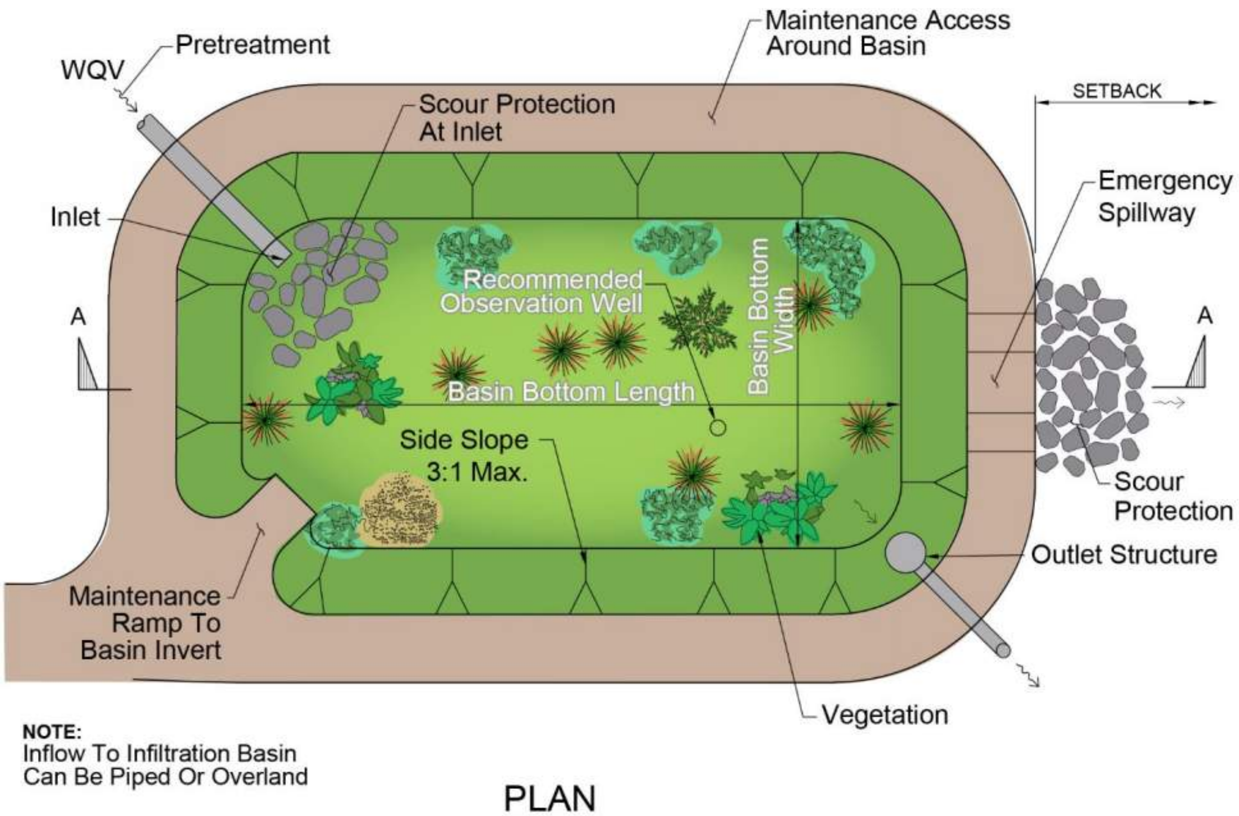
Design Considerations
• Soil infiltration rate • Interior side slope • Length to width ratio • Time to drain basin • Basin invert slope • Water quality volume

VARIATIONS

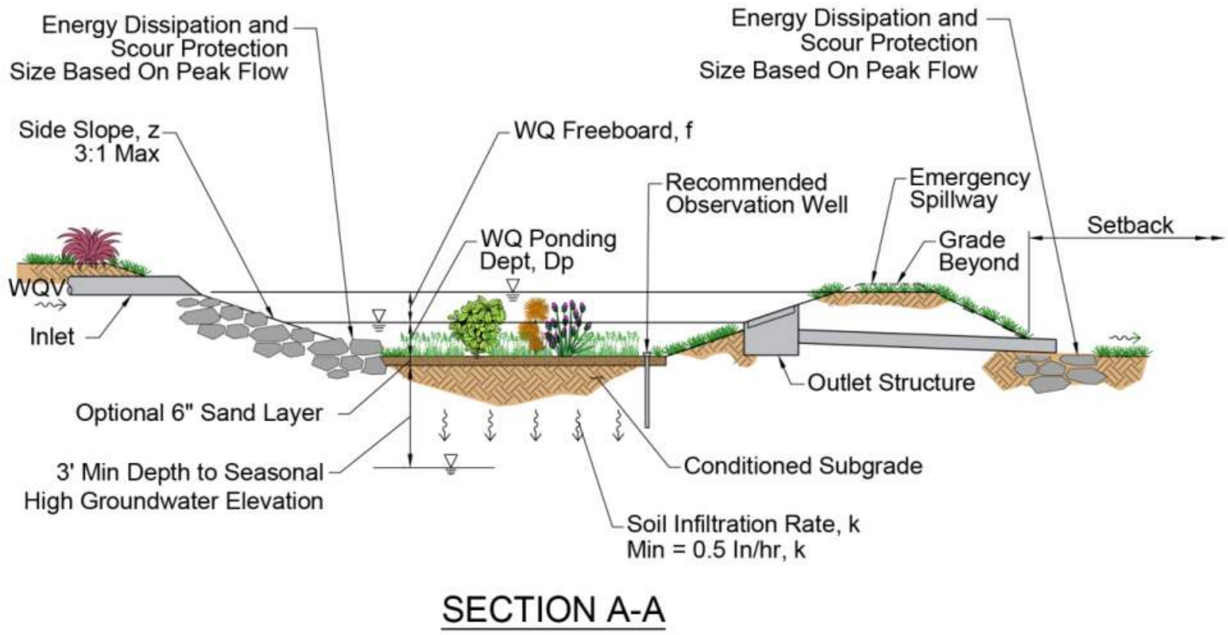
Infiltration basin variations include a subsurface infiltration system and an infiltration berm. A subsurface infiltration system is a rock (or premanufactured material) storage bed beneath surfaces like parking lots, lawns, and playfields, designed for temporary storage and infiltration of stormwater runoff. Infiltration berms are vegetated features aligned with site contours in moderately sloped areas. They are earthen embankments with sloping sides, serving to retain, infiltrate, slow, or redirect stormwater.

APPLICATIONS

Infiltration basins are often applicable in rural areas as well as in residential, industrial, and commercial developments, provided there is ample space. Their implementation may be constrained in densely urbanized areas and certain redevelopment endeavors, primarily due to space constraints.



Source: Bowers + Kubota Consulting



Source: Bowers + Kubota Consulting

SITE CONSIDERATIONS

- Ensure soils on-site are appropriate for infiltration and that the potential for groundwater contamination and long-term maintenance problems are minimal. They should only be located where there is appropriate separation from the groundwater table.
- Avoid constructing infiltration basins on steep slopes, and refrain from altering or modifying slopes significantly to create a basin.
- Maintain the minimum required setbacks from the property line and from private wells or septic systems when siting basins.
- Avoid constructing infiltration basins in or above contaminated soil.

DESIGN GUIDELINES AND CONSIDERATIONS

- Infiltration basins are used for tributary drainage areas less than 10 acres, on land with slopes of less than 20 percent.
- A 6-inch to 12-inch layer of filter material such as coarse sand may be added at the bottom of the infiltration basin to maintain permeability. This layer can capture silt, sediment, and debris that might otherwise clog the upper soil layer below the basin.
- An infiltration basin may not have a defined outlet for releasing runoff from the stormwater quality design storm. Instead, the outflow may occur naturally through the soil matrix. It can be integrated with an extended detention basin to augment runoff storage for both water quality and quantity management.
- Surrounding berms should be compacted earth with a slope no more than 3H:1V.
- Ensure sediment pretreatment structures are designed for easy access and maintenance.
- Inlets discharging into the basins should have erosion protection.

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	60–95%
Total Phosphorus	50–95%
Nitrogen	0–65%
Copper	60–90%
Zinc	65–85%
Bacteria	25–70%
Hydrocarbons	60–95%
Trash/Debris	85-95%

Source: [9]

COST CONSIDERATIONS

Infiltration basins serve as cost-effective stormwater controls due to their minimal infrastructure requirements. The standard construction costs, encompassing contingency and design costs, vary from $55,000 to $85,000 per acre of treated impervious surface. As with many other stormwater controls, economies of scale may lower this unit cost when treating larger areas.

OPERATION AND MAINTENANCE

Activity	Schedule
• Replace pea gravel or topsoil (when clogged)	As needed
• Ensure inlets are clear of debris, including sediment and oil/grease • Stabilize the surrounding area • Mow grass and remove grass clippings of filter strip areas, if applicable • Repair undercut and eroded areas at inflow/outflow structures	Monthly
• Inspect pretreatment devices and diversion structures for debris accumulation and structural integrity; take corrective action as needed	Semiannually
• Aerate the pretreatment basin bottom or de-thatch it, if applicable	Annually
• Scrape the pretreatment bottom to remove accumulated sediment and reseed ground cover, if applicable	Every 5 years
• Perform total rehabilitation of the basin and restore design storage capacity, Excavate the basin bottom to expose clean soil	Upon failure

Source: [13]

SIZING PROCEDURE

1. Determine the Water Quality Volume (WQV)

   $WQV = P \times C \times A_T \times 3630$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. Pretreatment is critical to capture sediment that may otherwise lead to premature failure of the facility. Size the pretreatment forebay assuming a volume equal to 10 percent of the WQV. The forebay volume counts toward the WQV requirement.

   $V_p = 0.1 \times WQV$

3. Calculate the maximum storage depth (d_{max}) of the infiltration basin.

   $$d_{max} = \frac{kt}{12FS}$$

   Where d_{max} = Maximum Storage Depth (ft)
   k = Soil Infiltration Rate from testing (in/hr)
   t = Drawdown Time (hours)
   FS = Infiltration Rate Factor of Safety

   Assume:
   - Maximum drawdown time (t) = 48 hours
   - Minimum factor of safety (FS) = 2 (to account for long-term reduction in infiltration rate due to clogging)

4. Calculate the required bottom surface area of the infiltration basin (A_b). Since the pretreatment forebay is sized for 10 percent of the WQV, the surface is calculated based on the remaining 90 percent of the WQV.

   $A_b = \frac{0.9WQV}{d_{max}}$

   Where A_b = Basin Bottom Surface Area (ft^2)
   WQV = Water Quality Volume (ft^3)
   d_{max} = Maximum Storage Depth from Step 3 (ft)

5. For a rectangular-shaped basin, select a bottom width (w_b) and calculate the resulting bottom length (l_b).

   $l_b = \frac{A_b}{w_b}$

Where l_b = Bottom Length (ft)
A_b = Bottom Surface Area from Step 4 (ft^2)
W_b = Bottom Width (ft)

6. Calculate the total surface area (A_{BMP}) occupied by the BMP (excluding pretreatment area) to ensure adequate space is available.

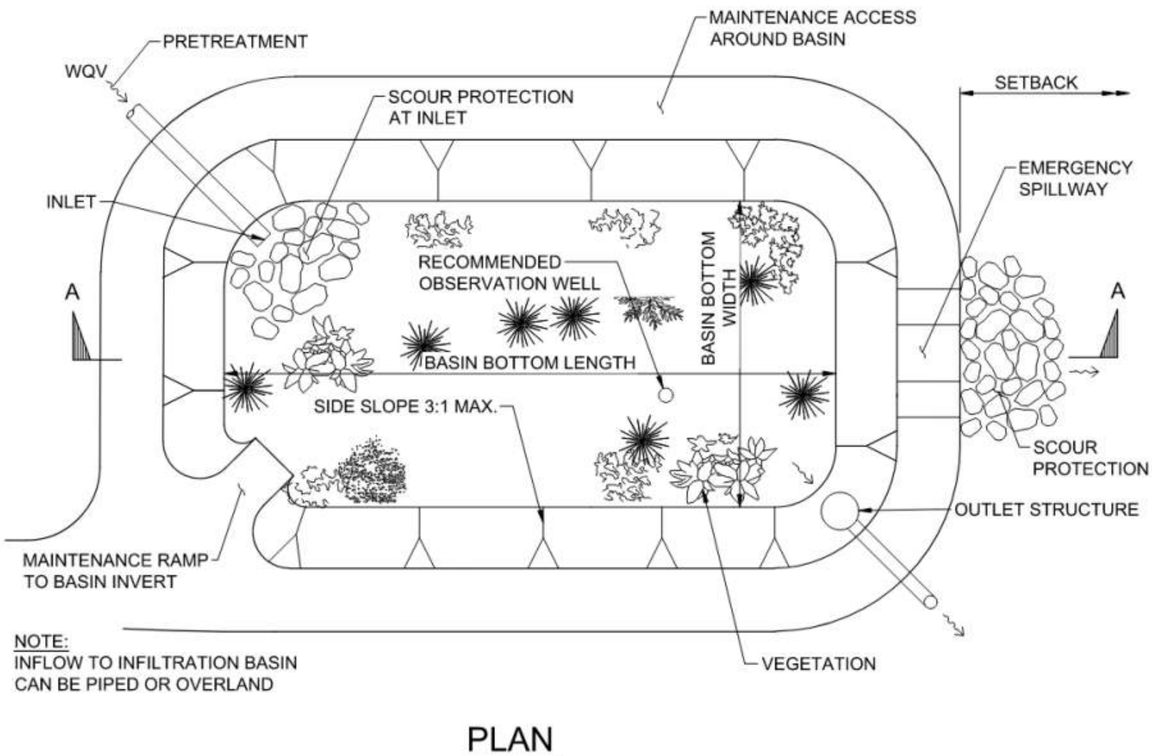
$$A_{BMP} = (w_b + 2zf)\ x\ (l_b + 2zf)$$

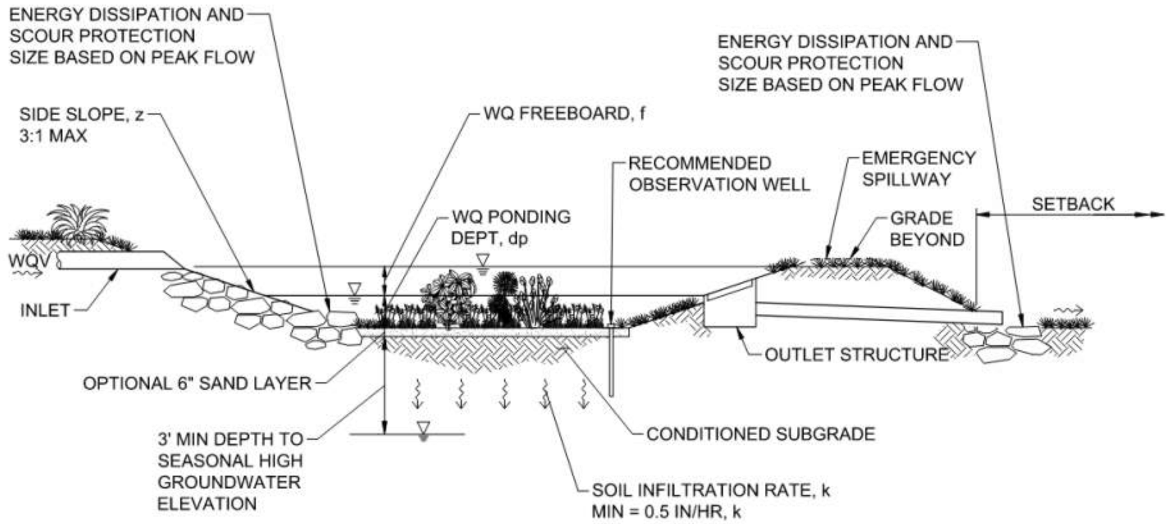
Where A_{BMP} = Total Surface Area, excluding pretreatment (ft^2)
w_b = Bottom Width from Step 5 (ft)
z = Side Slope (length per unit height)
f = Freeboard (ft)
l_b = Bottom Length (ft)

Assume:

- Side slope (z): 3H:1V (typical) and 2H:1V (maximum).
  - Horizontal:Vertical
- Minimum freeboard (f): 1 foot

BMP DETAILS


PRETREATMENT
WQV
MAINTENANCE ACCESS
AROUND BASIN
SETBACK
SCOUR PROTECTION
AT INLET
EMERGENCY
SPILLWAY
INLET
RECOMMENDED
OBSERVATION WELL
BASIN BOTTOM
WIDTH
A
A
BASIN BOTTOM LENGTH
SIDE SLOPE 3:1 MAX.
SCOUR
PROTECTION
OUTLET STRUCTURE
MAINTENANCE RAMP
TO BASIN INVERT
NOTE:
INFLOW TO INFILTRATION BASIN
CAN BE PIPED OR OVERLAND
VEGETATION
PLAN


ENERGY DISSIPATION AND
SCOUR PROTECTION
SIZE BASED ON PEAK FLOW
SIDE SLOPE, z
3:1 MAX
WQ FREEBOARD, f
ENERGY DISSIPATION AND
SCOUR PROTECTION
SIZE BASED ON PEAK FLOW
RECOMMENDED
OBSERVATION WELL
EMERGENCY
SPILLWAY
SETBACK
GRADE
BEYOND
WQ PONDING
DEPT, dp
WQV
INLET
OUTLET STRUCTURE
OPTIONAL 6" SAND LAYER
CONDITIONED SUBGRADE
3' MIN DEPTH TO
SEASONAL HIGH
GROUNDWATER
ELEVATION
SOIL INFILTRATION RATE, k
MIN = 0.5 IN/HR, k

SECTION A-A

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Infiiltration Trench at Punahou School (Courtesy of the City and County of Honolulu)

INFILTRATION TRENCH

BMP-2

DESCRIPTION

An infiltration trench is a rock-filled trench designed for stormwater infiltration and conveyance. Stormwater runoff flows onto the rock and infiltrates through the bottom into the underlying soil. Designs may include an overflow drain, an underdrain, or vegetation.

ADVANTAGES

- Reduces volume of stormwater runoff.
- Reduces peak runoff rate.
- Increases groundwater recharge.
- Linear design makes it suitable for roadway applications.

LIMITATIONS

- Pretreatment recommended upstream to capture sediment loadings to avoid clogging and premature failure.
- The tributary drainage area should be less than five acres.
- Soil infiltration rate should be a minimum of 0.5 inch/hour to provide adequate treatment.
- Should not be used for treatment at industrial sites to avoid groundwater contamination.

Minimum BMP Footprint
80 sf

Construction Cost
$–$$

Operations & Maintenance
Frequency: Monthly Cost:$–$$

Design Considerations

- Utilize pretreatment
- Permeability of soil
- Distance to groundwater
- Install observation wells

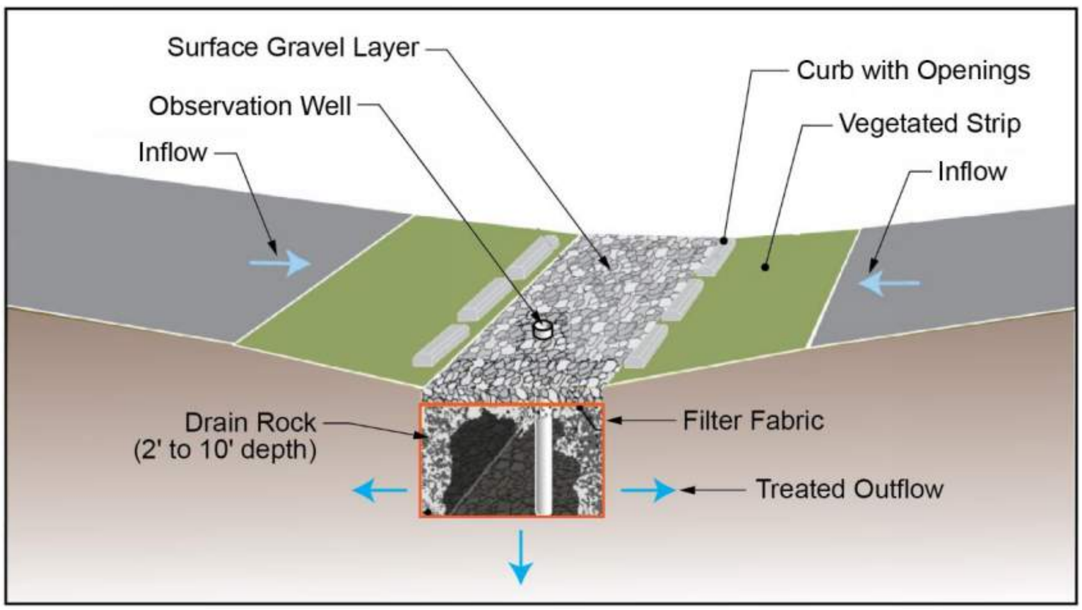
VARIATIONS

Infiltration trenches are linear stormwater BMPs designed for runoff infiltration. Infiltration trenches can be a part of a conveyance system with other pretreatment systems upstream to reduce sediment loading and clogging.

APPLICATIONS

- Urban/commercial areas especially when paired with other stormwater controls.
- Residential
- Retrofit
- Highway/road

See the figure below for a schematic of an infiltration trench. Water flows through vegetated strip towards the gravel layer where it is drained underground.



Source: CalTrans

SITE CONSIDERATIONS

- Verify that site soils are appropriate for infiltration with an infiltration rate of at least 0.5 inch/hr.
- Maintain at least 3 feet of clearance from the bottom of the infiltration trench to the seasonally high groundwater table to avoid groundwater contamination.
- Infiltration trenches should be sited to avoid any risk to groundwater quality and present no threat to subsurface structures such as building foundations.
- Site grading should be relatively level and not exceed greater than 15%.

DESIGN GUIDELINES AND CONSIDERATIONS

- An overflow spillway must be provided in cases when the system clogs or overtops.
- Trench media should be clean, washed material free from clay, silt, and organic material.

- May include a layer of geotextile fabric beneath the stone medium to avoid excessive sediment deposition.
- Infiltration utilizing vegetation should have an adequate soil cover of generally 12–18 inches and must be maintained above the infiltration bed.
- If native soils have poor infiltration rates, an underdrain is recommended to avoid ponding lasting longer than 48 hours. Underdrains are perforated pipes that should have a flow capacity greater than the total planting soil infiltration rate. Cleanouts should be provided to allow inspection and adequate maintenance.
- Vegetative cover must be established over the contributing pervious drainage areas upstream before runoff can be accepted into the infiltration trench.
- Do not allow grass or vegetation to grow within the infiltration trench, unless designed as such.

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	90+%
Total Phosphorus	60%
Nitrogen	60%
Copper	90+%
Zinc	90+%
Bacteria	90+%
Hydrocarbons	90+%

Sources: [2,9]

COST CONSIDERATIONS

Construction costs, including contingency and design costs, typically range from $60,000 to $70,000 per acre of impervious surface treated. Maintenance costs range between 5–10% of the construction costs. The design life is 20–50 years.

OPERATION AND MAINTENANCE

- Regularly remove sediment, trash, and debris from the facility.
- When a reduction in infiltration rate is observed, replace drainage media to remove accumulated sediment and restore infiltration properties.
- Inspect pretreatment devices and/or diversion structures for debris accumulation and structural integrity. Take corrective action as needed.
- Mow and trim surround vegetation.
- Inspect inflow and outflow structures for erosion. Repair as needed.

SIZING PROCEDURE

1. Determine the Water Quality Volume (WQV).

   $$WQV = P \times C \times A_T \times 3630$$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. $C = 0.05 + 0.009I$

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. Pretreatment is critical to capture sediment that may otherwise lead to premature failure of the facility. Size the pretreatment forebay assuming a volume equal to 10 percent of the WQV (DOEE 2020). The forebay volume counts toward the WQV requirement. The forebay volume counts toward the WQV requirement.

   $$Vp = 0.1\,x\,WQV$$

4. Calculate the maximum storage depth (d_{max}) of the infiltration basin.

   $$d_{max} = \frac{kt}{12FS}$$

   Where d_{max} = Maximum Storage Depth (ft)
   k = Soil Infiltration Rate from testing (in/hr)
   t = Drawdown Time (hours)
   FS = Infiltration Rate Factor of Safety

   Assume:
   - Maximum Storage Depth (d_{max}): 2 to 10 ft
   - Maximum drawdown time (t) = 48 hours
   - Minimum factor of safety (FS) = 2 (to account for long-term reduction in infiltration rate due to clogging)

5. Determine the thickness and porosity for the top aggregate layer, rock storage layer, and bottom sand layer. Calculate the total effective storage depth (d_t), which is a function of the depth and porosity of the storage layers, using the following equation:

   $$d_t = d_g n_g + d_r n_r + d_s n_s$$

   Where d_t = Total Effective Storage Depth (ft)
   d_g = Top Aggregate Layer Depth (ft)
   n_g = Top Aggregate Layer Porosity
   d_r = Rock Storage Layer Depth (ft)

n_r = Rock Storage Layer Porosity
d_s = Sand Layer Depth (ft)
n_s = Sand Layer Porosity

Assume the following typical values:

- Aggregate layer porosity (n_g): 0.2 to 0.35
- Rock storage layer depth (d_r): 2 to 10 ft
- Rock storage layer porosity (n_r): 0.3 to 0.4
- Sand layer depth (d_s): 6 to 12 inches to avoid compaction of soil during placement of rock storage layer
- Sand layer porosity (n_s): 0.25 to 0.45

6. Confirm that the total effective storage depth (d_t) is less than the maximum storage depth (d_{max}) calculated in Step 4.

7. Calculate the required surface area of the infiltration trench (A_{BMP}).

$$A_{BMP} = \frac{WQV}{\left(d_t + \frac{kT}{12FS}\right)}$$

Where A_{BMP} = Trench Surface Area (ft^2)
WQV = Water Quality Volume (ft^3)
d_t = Total Effective Water Storage Depth (ft)
k = Soil Infiltration Rate from Step 4 (in/hr)
T = Fill Time (hours)
FS = Infiltration Rate Factor of Safety from Step 4.

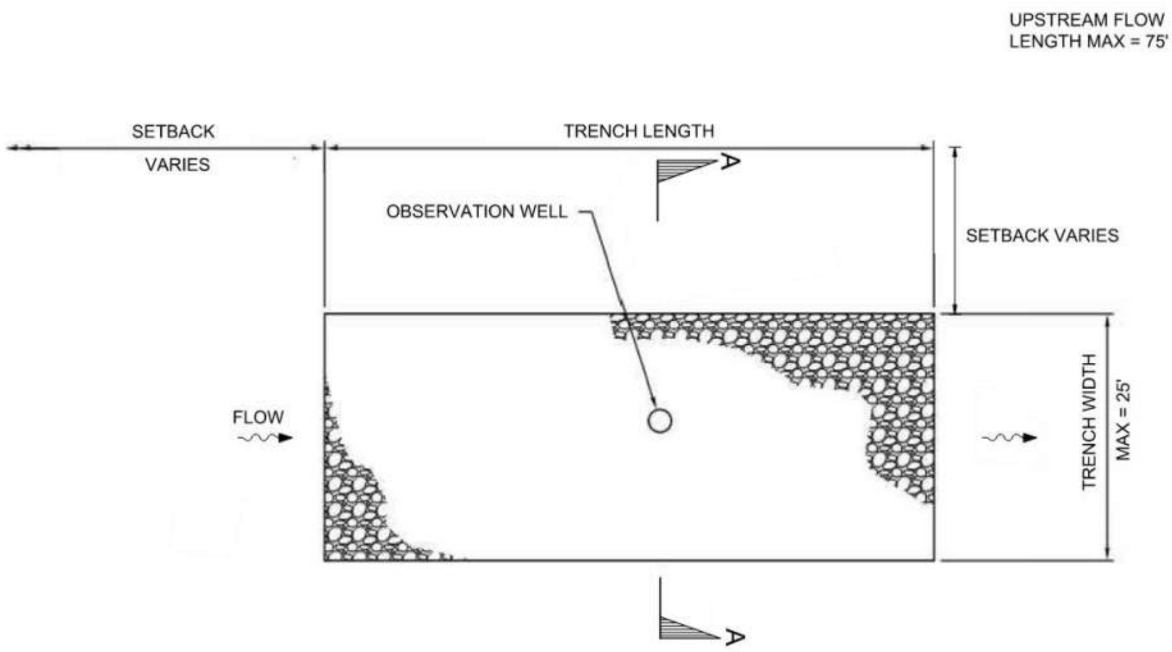
If the required surface area does not fit in the allowable space, adjust the design variables and repeat the calculations as necessary.

8. Based upon the required surface area (A_{BMP}), determine the infiltration trench top width (W) and corresponding top length (L).

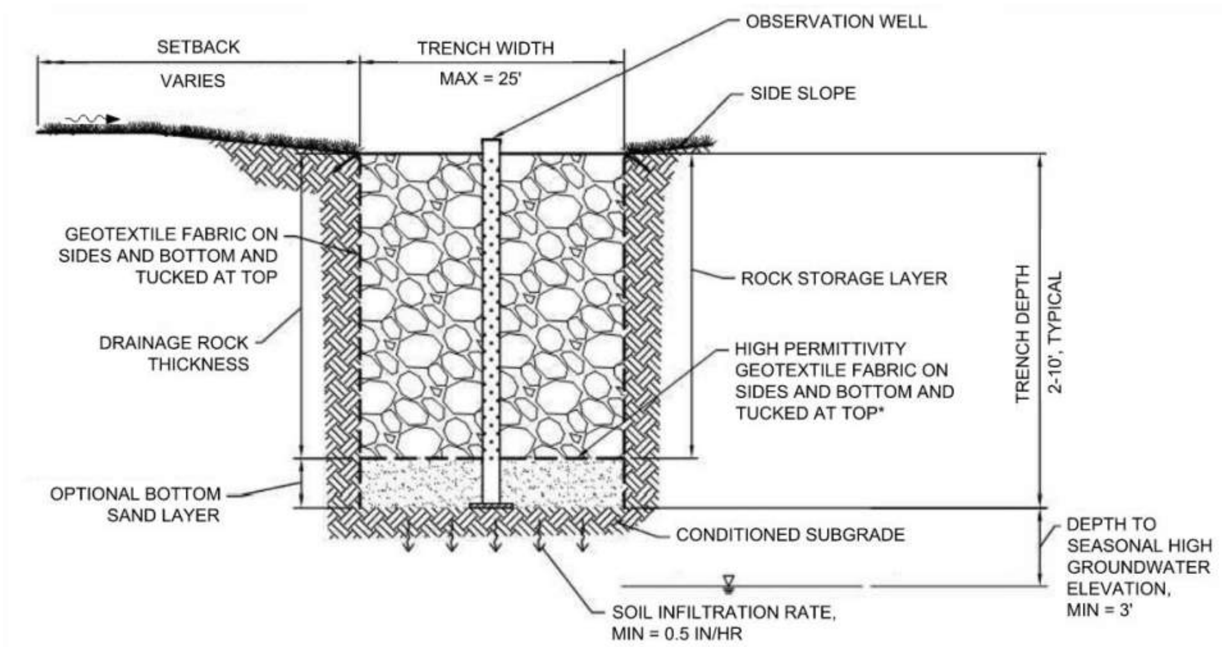
$$L = \frac{A_{BMP}}{W}$$

Where L = Trench Top Length (ft)
A_{BMP} = Trench Surface Area from Step 7 (ft^2)
W = Trench Top Width (ft)

BMP DETAILS



PLAN



*WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC

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Dry Well on Ane Keohokalole Highway, Hawai'i Island (Courtesy of Bowers + Kubota Consulting)

DRY WELL

BMP-3

DESCRIPTION

Dry wells are subsurface storage and infiltration facilities used to capture and temporarily store runoff. A dry well is constructed by excavating a hole in the ground and filling it with open graded aggregate, or a prefabricated perforated storage chamber or pipe segment. Dry wells may be used to aid groundwater recharge and reduce stormwater runoff volume. They are commonly used to accept roof runoff. When designing dry wells, the underlying soil's rate of infiltration and the distance from the dry well bottom to the groundwater table should be taken into consideration.

ADVANTAGES

- Reduces volume of stormwater runoff.
- Reduces peak stormwater runoff rate.
- Improve water quality.
- Visually unobtrusive.

LIMITATIONS

- May not be suitable for roofs with high concentrations of nutrients and other contaminants.
- Not appropriate for soil types C or D or soils with infiltration rates less than 0.5 inch/hour.
- A minimum of 3 feet from the bottom of the dry well to the groundwater table to allow an adequate infiltration rate.

Minimum BMP Footprint
30 sf

Construction Cost
$

Operations & Maintenance
Frequency: Quarterly Cost: $

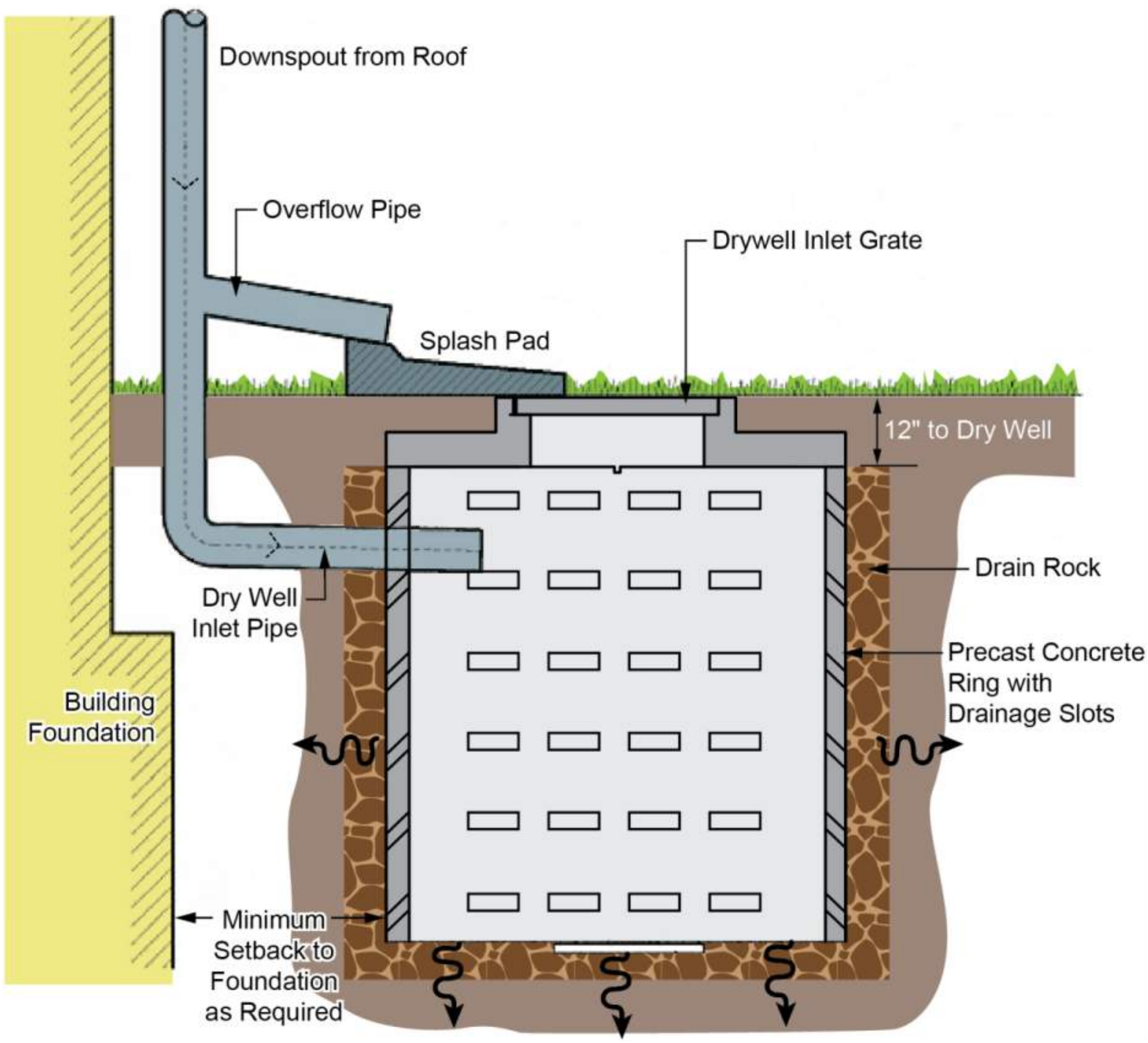
Design Considerations
• Water quality volume • Permeability of soil • Distance to groundwater

VARIATIONS

- Intermediate “Sump” Box—runoff flows through an intermediate box to allow sediments to filter out. Water then flows through a screen into the dry well.
- Prefabricated Dry Well—using prefabricated dry wells in place of aggregate dry wells can increase storage capacity and lower associated costs.

APPLICATIONS

Dry wells are most often used in a residential setting, particularly to capture roof runoff. However, because of their small footprint, dry wells can also be used for commercial areas, ultra urban areas, and retrofits.



Source: American Groundwater Solutions LLC with revisions by Bowers + Kubota Consulting

SITE CONSIDERATIONS

- Dry wells are only feasible when the subsoil is sufficiently permeable to allow for adequate drainage.
- The bottom of the dry well should be a minimum of 3 feet above the groundwater table.
- Locate away from trees or other large vegetation.

DESIGN GUIDELINES AND CONSIDERATIONS

- Stone fill within the dry well must be clean, washed aggregate. Aggregate size should be between 1 inch and 3 inch.
- In areas with high sediment loads, a pretreatment system such as a drain filter should be provided prior to entering the dry well.
- For roof runoff, a roof gutter guard or leaf gutter screen should be used to prevent clogging.
- Dry wells should be designed to include an overflow drain or underdrain to prevent clogging and overtopping.
- Dry wells should be designed to have an observation port for inspection and maintenance. A perforated observation pipe can be inserted vertically into the dry well to monitor drawdown rate.
- Dry wells are typically designed to drain within 48 hours.

EFFECTIVENESS AND POLLUTANT REMOVAL

Effective at capturing and infiltrating the water quality volume. Offers significant pollutant reductions due to minimal to no release of stormwater runoff. Dry wells have high pollutant removal rates for nutrients, sediment, trash, pathogens, pesticides, hydrocarbons, metals, and organic compounds.

COST CONSIDERATIONS

Dry well construction costs are on the low end, when compared to other BMPs. The costs may vary based on the type of installation. One 2003 study estimated the cost to range from approximately $4–$9/cubic foot. This approximation does not account for inflation. Annual maintenance costs typically range from 5–10% of the construction costs. With proper maintenance, a dry well can last up to 30 years.

OPERATION AND MAINTENANCE

- Inspect dry wells after every storm exceeding one inch as well as at least four times a year.
- Remove sediment, debris/trash, and any other waste material from the dry well.
- If the drain downtime of the dry well exceeds 72 hours, drain the dry well via pumping, and clean the perforated piping, if included. If slow drainage persists, the system may need to be replaced.
- Regularly clean out gutters and roof drains to minimize high pollutant loads entering the dry well.
- Replace filter screens that intercept roof runoff as necessary.

SIZING PROCEDURE

1. Determine the Water Quality Volume (WQV) that will need to be treated by the LID BMP.

   $WQV = P \times C \times A_T \times 3630$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. $C = 0.05 + 0.009I$

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. Calculate the maximum storage depth (d_{max}) based upon the soil infiltration rate (k) and the required drawdown time (t):

   $$d_{max} = \frac{kt}{12FS}$$

   Where d_{max} = Maximum Storage Depth (ft)
   k = Soil Infiltration Rate from testing (in/hr)
   t = Drawdown Time (hours)
   FS = Infiltration Rate Factor of Safety

   Assume:
   - Maximum drawdown time (t) = 48 hours
   - Minimum FS = 2 (to account for long-term reduction in infiltration rate due to clogging)

4. Select a design ponding depth (d_p) and determine the thickness and porosity for the planting media and drainage layer. Calculate the total effective storage depth (d_t) following the equation below.

   $d_t = d_p + (l_b n_b)$

   Where d_t = Total Effective Storage Depth (ft)
   d_p = Ponding Depth (ft)
   l_b = Backfill Material Thickness Depth (ft)
   n_b = Backfill Material Porosity

   Assume:
   - Maximum ponding depth (d_p) = 6 inches (typical)
   - Backfill material porosity (n_b) = 0.35 (typical)

5. Confirm that the total effective storage depth (d_t) is less than the maximum storage depth (d_{max}) calculated in Step 3.

6. Calculate the required surface area (A_{BMP}).

$$A_{BMP} = \frac{WQV}{(d_t + \frac{kT}{12FS})}$$

Where A_{BMP} = Box Filter Surface Area (ft^2)
WQV = Water Quality Volume (ft^3)
d_t = Total Effective Storage Depth (ft)
k = Soil Infiltration Rate from Step 3 (in/hr)
T = Fill Time (hours)
FS = Infiltration Rate Factor of Safety from Step 3.

If the required surface area does not fit in the allowable space, adjust the design variables, and repeat the calculations as necessary.

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Left: Residential Rain Garden in Kailua, O'ahu; Right: Rain Garden in Wahikuli Wayside Park, Maui
Photos (Courtesy of Hui o Ko'olaupoko)

BIORETENTION BASIN (RAIN GARDEN)

BMP-4

DESCRIPTION

Rain gardens or bioretention basins are landscaped depressions adapted to provide on-site treatment of stormwater runoff. Rain gardens collect runoff and filter it through a mixture of soil, sand, and/or gravel. The infiltrating stormwater also provides water to the plants in the rain garden. These BMPs function as soil-based and plant-based filtration devices that remove pollutants through physical, biological, and chemical treatment processes.

ADVANTAGES

- Pollutant removal effectiveness is typically high.
- Versatile with broad applicability
- Provides shade and windbreaks.
- Absorbs noise and improves aesthetic vegetated appearance.
- Reduces peak discharge and runoff volume.
- Pretreatment for downstream drainage structures and BMPs.

LIMITATIONS

- In areas with prolonged dry periods, installation of an irrigation system may be required.
- Not recommended for areas with slopes greater than 20% or where tree removal would be required [16].
- Not suitable at locations where the water table is within 3 feet of the bottom of the bioretention facility.
- Potential to create breeding habitat for mosquitoes.

Minimum BMP Footprint
600 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Semi-Annually Cost: $$

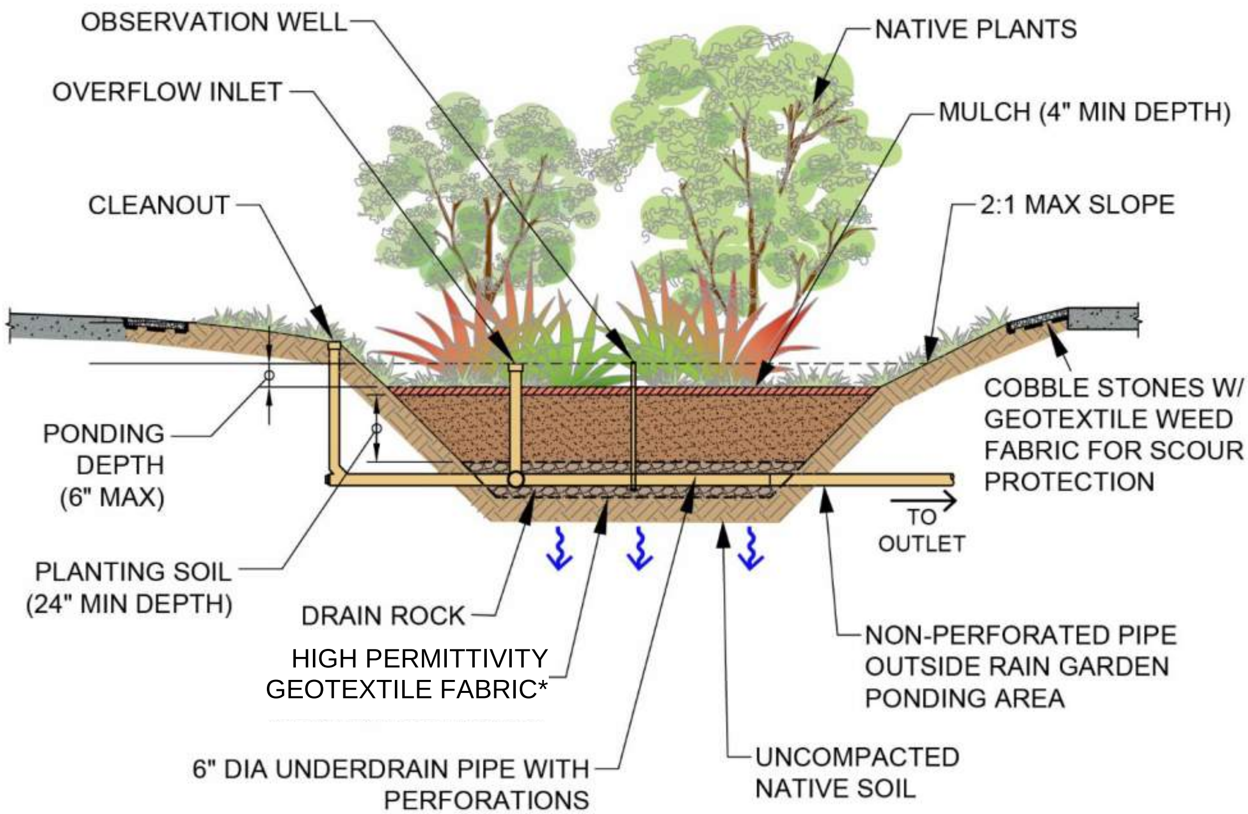
Design Considerations
• Plant selection • Side slope • Soil infiltration rate • Ponding depth • Hydraulic residence time

VARIATIONS

- Subsurface storage/infiltration bed
- Use of an underdrain
- Use of impervious liner
- Designed for either infiltration, infiltration/filtration, or filtration

APPLICATIONS

- Urban areas such as parking lot islands, along roads, at intersections, or other landscaped areas as a retrofit, redevelopment, or new construction.
- Bioretention basins can be tailored to treat hot spots with high pollutant concentrations by adding an impervious liner to the bottom to prevent groundwater or surface water contamination.
- Bioretention basins are suitable for residential areas because it can add beauty to the landscape, resulting in an increase in property value.



*WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC

Source: Bowers + Kubota Consulting

SITE CONSIDERATIONS

- Bottom of bioretention facility must be a minimum of 3 feet above groundwater table.
- Soil groups A or B preferred with a minimum infiltration rate of 0.5 inch/hour.
- Provide landscape and vegetation based on the specific site, soils, and hydrologic conditions.
- Used to treat small drainage areas, typically under one acre, although it can treat up to five acres with design modifications.
- Slope of land should be no steeper than 20%. Land with a gentle slope is ideal as sites that are too flat can be challenging with not enough elevation difference between the inflow and the outflow.

DESIGN CONSIDERATIONS AND GUIDELINES

Plant Selection

Proper plant selection ensures that rain gardens will flourish without the excessive addition of fertilizers and pesticides. Native species should be selected, considering the local climate, expected water depth in the basin, expected tolerances to pollutant loads, ease of maintenance and varying soil moisture. Ground cover, such as grasses or legumes, should be planted after trees and shrubs are in place [3].

See Appendix B for moisture zone maps and suggested native plants.

Design and Sizing Guidelines for Rain Garden

Design Parameter for Rain Garden (Bioretention Basin)	Unit	Value
Mulch Thickness	inches	4–6
Planting Soil Depth	feet	2–4
Drawdown (Drain) Time	hours	48
Maximum Interior Side Slope (length per unit height)		3:1
Maximum Ponding Depth	inches	12
Minimum Depth from basin invert to groundwater table	feet	3
Minimum Freeboard	feet	1.0
Minimum Soil Infiltration Rate	inch/hour	0.5

Source: [3]

An overflow device (e.g., domed riser or spillway) must be included to safely convey runoff from large storm events when the surface and subsurface capacities are exceeded [3].

Observation wells are recommended. They indicate how quickly the basin dewaters following a storm and provide a method of observing how quickly the basin fills up with sediment [3].

Pretreatment is not required; however, in areas with high sediment loadings, pretreatment may be achieved using additional BMPs prior to the bioretention facility. These may include but are not limited to vegetated filter strips or bioswales.

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	15–75%
Total Phosphorus	0–30%
Nitrogen	40–55%
Copper	40–95%
Zinc	40–95%
Bacteria	25–75%
Hydrocarbons	80–95%

Source: [2, 13]

COST CONSIDERATIONS

The cost of rain gardens includes grading, the replacement of fill material with planting soil, and planting vegetation. A 2016 study by the University of New Hampshire Stormwater Center, EPA Region I, and other partners estimated the unit costs for bioretention systems to range from $16 to $45 per cubic foot [18].

Annual operation and maintenance costs for rain gardens are comparable to typical landscaping and irrigation maintenance costs. Using an estimate of 24 annual hours for a small bioretention area and 68 annual hours for a large bioretention area, and the State of Hawaiʻi Wage Rate Schedule [3,15] for a crew of four Landscape and Maintenance Laborers, the annual landscaping and irrigation maintenance cost for a rain garden could range from approximately $3,000 to $9,000.

OPERATION AND MAINTENANCE

Properly designed and installed rain gardens help to reduce the maintenance effort. Appropriately selected plants will aid in reducing fertilizer, pesticide, water, and overall maintenance requirements. Routine maintenance should include a semiannual health evaluation of the vegetation and quarterly inspections that includes: pruning and weeding, removal of large solids, and subsequent removal of any dead or diseased vegetation [5]. Diseased vegetation should be treated using preventative and low-toxic measures to the maximum extent practical [2].

Mulch should be replaced when ponding occurs for more than 48 hours. The entire area may require mulch replacement every 2 to 3 years although spot mulching may be sufficient when there are random void areas.

Rain gardens have the potential to create breeding habitats for mosquitoes and other vectors because of highly organic, often heavily vegetated areas mixed with shallow water. The growth of invasive plant species within bioretention areas, such as water hyacinths or duckweed, which are common wetland plants, can impede water flow and lead to the proliferation of mosquitoes and other nuisance insects. Routine inspections for standing water within the BMP and corrective measures to restore proper infiltration rates are necessary to prevent infestations [2].

Other potential tasks include replacement of dead vegetation, soil pH regulation, erosion repair at inflow points, unclogging the underdrain, repairing overflow structures, and irrigation system maintenance. Depending on pollutant loads, soils may need to be replaced within 5 to 10 years of construction [2]. Inspect the irrigation system periodically to ensure that the right amount of water is being applied and that excessive runoff is not occurring. Check for broken, missing, sunken, misaligned, or tilted sprinkler heads; leaking valves or pipes; clogged nozzles; seal leaks; overspray; pressure problems; a malfunctioning controller; and incorrect spray arc. Minimize excess watering, and repair leaks in the irrigation system as soon as they are observed [3].

SIZING PROCEDURE

1. Determine the Water Quality Volume (WQV) that will need to be treated by the LID BMP.

   $$WQV = P \times C \times A_T \times 3630$$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. $C = 0.05 + 0.009I$

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. Pretreatment is critical to capture sediment that may clog the soil media. Size the pretreatment forebay assuming a volume equal to 10% of the WQV. The forebay's volume counts toward the WQV requirement.

   $$V_P = 0.1 \times WQV$$

   Where V_P = Pretreatment Forebay Volume (ft^3)
   WQV = Water Quality Volume (ft^3)

4. Calculate the maximum storage depth (d_{max}) based upon the soil infiltration rate (k) and the required drawdown time (t).

   $$d_{max} = \frac{kt}{12FS}$$

   Where d_{max} = Maximum Storage Depth (ft)
   k = Soil Infiltration Rate from testing (in/hr)
   t = Drawdown Time (hours)
   FS = Infiltration Rate Factor of Safety

   Assume:
   - Maximum drawdown time (t) = 48 hours

- Minimum FS = 2 (to account for long-term reduction in infiltration rate due to clogging)

5. Select a design ponding depth (d_p) and determine the thickness and porosity for the planting media and drainage layer. Calculate the total effective storage depth (d_t) following the equation below.

$$d_t = d_p + (d_m n_m) + (d_d n_d)$$

Where d_t = Total Effective Storage Depth (ft)
d_p = Ponding Depth (ft)
d_m = Planting Media Depth (ft)
n_m = Planting Media Porosity
d_d = Drainage Layer Depth (ft)
n_d = Drainage Layer Porosity

Assume the following typical values:
- Maximum ponding depth (d_p) = 6 inches
- Planting media depth (d_m) = 2 to 4 feet
- Planting media porosity (n_m) = 0.2 to 0.35
- Drainage layer depth (d_d) = 8 to 12 inches
- Drainage layer porosity = 0.3 to 0.4

6. Confirm that the total effective storage depth (d_t) is less than the maximum storage depth (d_{max}) calculated in Step 4.

7. Calculate the required bottom surface area of the bioretention facility (A_f). Since the pretreatment forebay is sized for 10% of the WQV, the surface is calculated based on the remaining 90% of the WQV.

$$A_b = \frac{0.9 \times WQV}{d_t + \frac{kT}{12FS}}$$

Where A_b = Bottom Surface Area (ft^2)
WQV = Water Quality Volume (ft^3)
d_t = Total Effective Storage Depth (ft)
k = Soil Infiltration Rate from Step 4 (in/hr)
T = Fill Time (hours)
FS = Infiltration Rate Factor of Safety from Step 4

8. For a rectangular-shaped facility, select a bottom width (w_b) and calculate the resulting bottom length (l_b).

$$l_b = \frac{A_b}{w_b}$$

Where l_b = Bottom Length (ft)
A_b = Bottom Surface Area from Step 7 (ft^2)

W_b = Bottom Width (ft)

9. Calculate the total surface area (A_{BMP}) occupied by the BMP (excluding pretreatment area) to ensure adequate space is available.

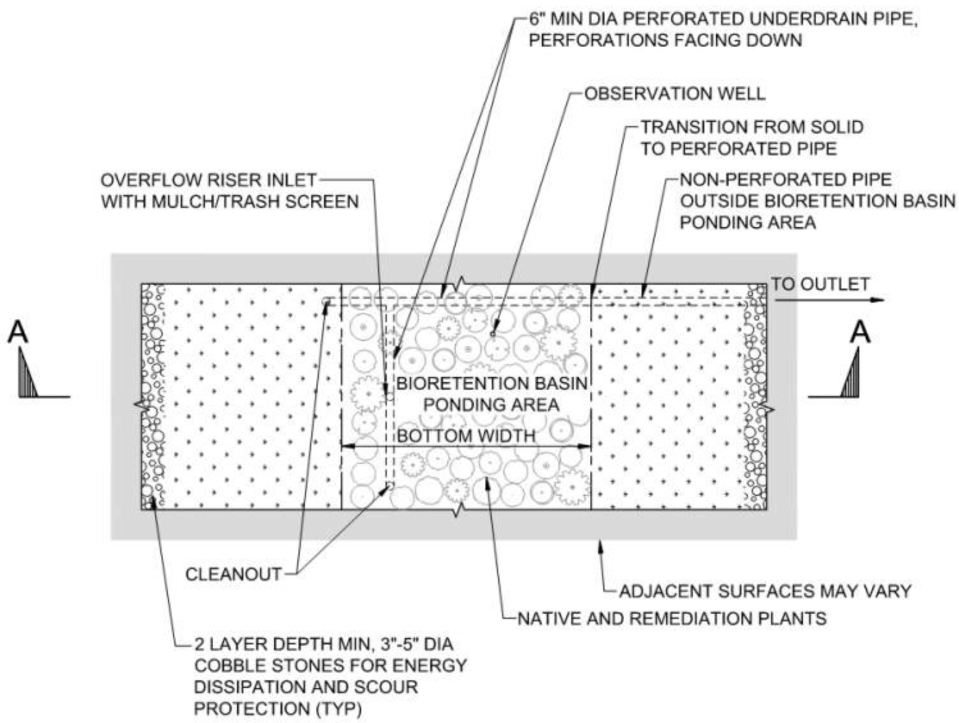
$$A_{BMP} = \left[w_b + 2z\left(d_p + f\right)\right] \times \left[l_b + 2z\left(d_p + f\right)\right]$$

Where A_{BMP} = Total Surface Area, excluding pretreatment (ft^2)
W_b = Bottom Width from Step 8 (ft)
z = Side Slope (length per unit height)
l_b = Bottom Length (ft)
d_p = Design Ponding Depth (ft)
f = Freeboard (ft)

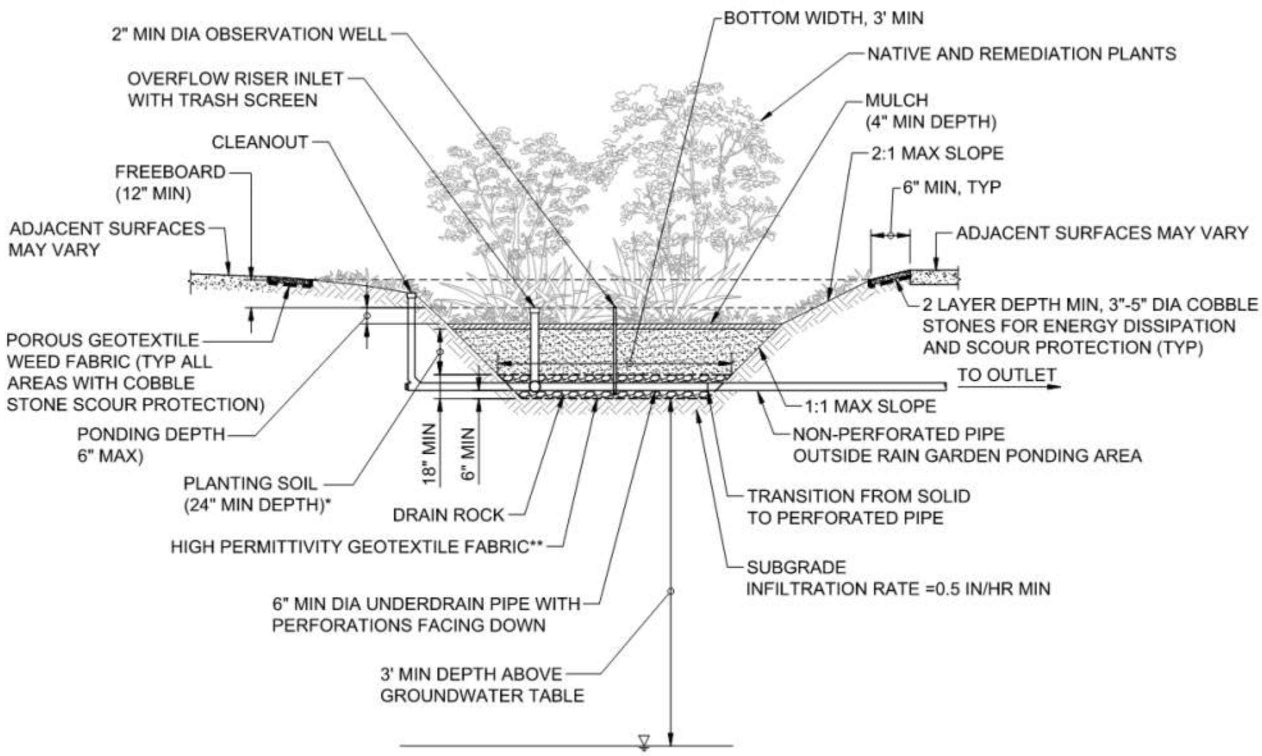
Assume:

- Side slope (z): 3H:1V (typical) and 2H:1V (maximum).
  - Horizontal:Vertical
- Minimum freeboard (f): 1 foot

BMP DETAILS



PLAN



* IF TREES ARE PLANTED IN RAIN GARDEN, MINIMUM PLANTING SOIL DEPTH SHALL BE 36 INCHES OR 1-1/2 TIMES THE ROOT BALL DIAMETER, WHICHEVER IS GREATER

** WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC

SECTION A-A

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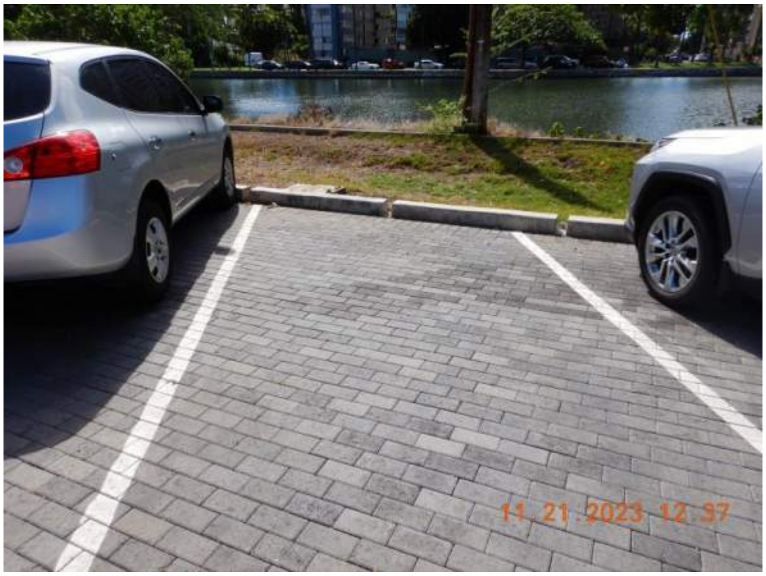


Permeable Pavers at Ala Wai Golf Course, Honolulu, O'ahu,
Courtesy of Bowers + Kubota Consulting

PERMEABLE PAVEMENT

BMP-5

DESCRIPTION

Permeable pavement consists of pavement or interlocking paver blocks designed to allow stormwater infiltration into an underlying aggregate layer until the water infiltrates into the soil matrix. The underground aggregate reservoir layer is designed for surface vehicle load requirements. Permeable pavement can also be referred to as pervious pavement or porous pavement. Permeable pavement is durable with a life span of approximately 20 years, and possibly more with proper maintenance [1].

ADVANTAGES

- Captures surface stormwater runoff volume based on the design storm event.
- Underground infiltration inhibits mosquito breeding.
- Reduces or eliminates space needed for other BMPs.
- Infiltration addresses all pollutants, except litter.
- Microbial growth in aggregates promotes biodegradation of oils and organic materials and adsorption of heavy metals.
- Dual use for pavement structure and stormwater management.

LIMITATIONS

- Low soil permeability will decrease efficiency resulting in higher surface runoff volumes.

Minimum BMP Footprint
600 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Quarterly Cost: $$–$$$

Design Considerations
• Water quality volume • Permeability of soil • Distance to groundwater • Load requirements

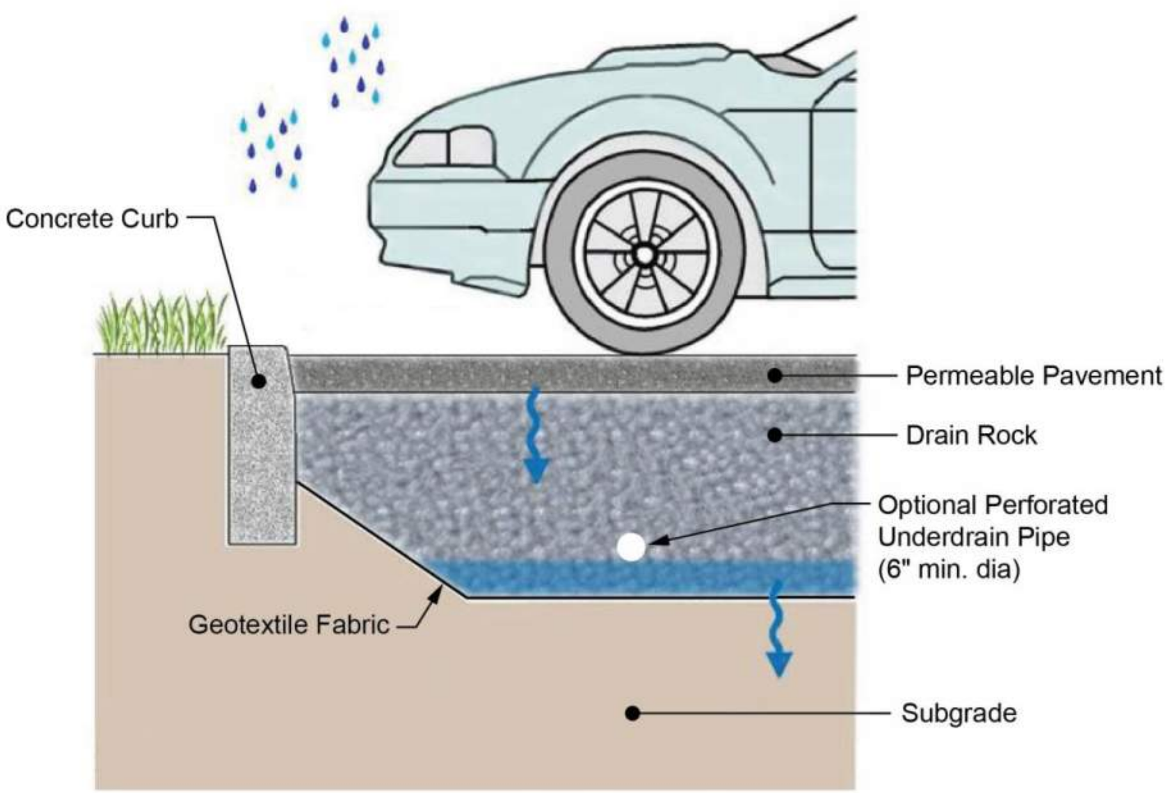
- Higher initial cost than conventional pavement.
- Not applicable for use on highways and high-volume roads due to heavy traffic and sediment loads.
- Not applicable for materials storage areas where silt, sediment, or spillage may occur.

VARIATIONS

Permeable pavement can be used in different variations including the use of interlocking paver blocks, pervious concrete, porous asphalt, or grass pavers. This BMP can also be used with an underdrain system if the native soil within the subgrade has a low infiltration rate.

APPLICATIONS

Applications include low-volume, low-speed areas, such as driveways, parking lots, minor roads and roadway shoulders. Permeable pavement is also applicable for sidewalks, patios, and deck areas. In highly developed areas with little open space, permeable pavement can be applied in retrofit situations when existing conventional pavement is being replaced. Residential properties commonly use permeable pavers due to their customizable options in shape, size, color, and layout. Pavers are also commonly used in walkways, plazas, and parking areas for large-scale projects.



Source: Cahill Associates

SITE CONSIDERATIONS

- Not applicable downstream of landscaped or pervious areas where sediment may lead to premature failure.
- The ratio of the contributing impervious area to pervious concrete should be maximum 1:1.
- The ratio of the contributing impervious area to porous asphalt or permeable pavers should be maximum 3:1.
- Products may need to be cut to fit into retrofit areas.

Considerations when designing permeable pavement systems include knowing the site's characteristics such as the native soil group and infiltration rate, depth to the groundwater table, available contiguous space, and design storm rainfall. The design criteria include a maximum depth of 3 feet for the reservoir layer, a drain time of 48 hours, a minimum depth of 3 feet from the reservoir invert to the groundwater table, and a minimum soil infiltration rate of 0.5 inch/hour. This information and guidelines to designing a permeable pavement system can also be found in the Sizing Procedure below.

For parking lot application, the subgrade should have less than 2% slope in any direction to enable even distribution and infiltration. For applications with subgrade slopes greater than 2%, incorporate subsurface check dams or underdrains to minimize flow conveyance beneath the pavement layer.

DESIGN GUIDELINES AND CONSIDERATIONS

The pavement and reservoir layer should be designed to support the anticipated vehicle load. The designer should consult with the licensed geotechnical engineer performing the field investigation to establish design criteria of the pavement system.

Perforated underdrain pipes should be elevated above the bottom of the underlying base to protect against sediment buildup in the pipe and allow water to infiltrate. Pipes should lay along the base layer with minimal slope to provide uniform distribution of water. These pipes may provide additional storage volume.

The design shall also incorporate an overflow system to convey runoff downstream or to other stormwater runoff BMPs during storm events that exceed the design capacity.

Coordinate with the manufacturer to select the appropriate paver model. Select paver colors that will be available for long time frames and consider long lead times.

Pretreatment is not required if the permeable pavement does not receive runoff containing fine sediments. Fine sediment will lead to premature clogging of the permeable pavement. If the system does receive runoff from other surfaces, pretreatment is necessary to prevent premature failure and may be achieved with the use of gravel filter strips, vegetated buffer strips, or vegetated swales. Pavement locations should avoid areas with tress that produce a lot of leaves and branches to prevent clogging.

Additional design details on specific pavement systems are provided by the National Asphalt Pavement Association, the National Ready-Mix Concrete Association, the Interlocking Concrete Pavement Institute, American Concrete Institute, and the American Association of State Highway and Transportation Officials [3].

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	82–95+%
Total Phosphorus	60–65%
Nitrogen	80–85%
Copper	95–99%
Zinc	95–99%
Bacteria	90+%
Hydrocarbons	80–90+%

Sources: [2,5,7,11]

COST CONSIDERATIONS

Porous asphalt is generally 15% to 25% higher in cost than standard asphalt. Pervious concrete is generally more expensive than porous asphalt. Estimated capital cost for permeable asphalt and concrete range from $4 to $25 per square foot. Permeable pavers vary in cost depending on the type and manufacturer. Annual maintenance cost ranges from $1,200 to $2,000 for vacuum sweeping.

OPERATION AND MAINTENANCE

Permeable pavement will require regular vacuum sweeping or hosing down (minimum every three months or as recommended by the manufacturer) to keep the surface from clogging. Maintenance frequency needs may vary depending on the traffic volume at the site. The frequency of maintenance will increase when regenerative air sweepers, such as Elgin Crosswind sweepers, are used. Regenerative air sweepers can maintain the infiltration rate of permeable pavement, but true vacuum sweepers will be needed to restore infiltration. The use of leaf blowers to clear the pavement surface is helpful at extending maintenance intervals. Deep cleaning using pressure washers should only be used when infiltration is noticeably reduced. Inspect for signs of pavement failure and repair any surface deformations or broken pavers. Replenish aggregate in joints or grids as needed.

SIZING PROCEDURE

1. Determine the Water Quality Volume (WQV) that will need to be treated by the LID BMP.

   $$WQV = P \times C \times A_T \times 3630$$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)

C = Volumetric Runoff Coefficient
A_T = Treatment Area (acres)
3630 = Conversion Factor

2. $C = 0.05 + 0.009I$

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. Calculate the maximum storage depth (d_{max}) based upon the soil infiltration rate (k) and the required drawdown time (t).

   $$d_{max} = \frac{kt}{12FS}$$

   Where d_{max} = Maximum Storage Depth (ft)
   k = Soil Infiltration Rate from testing (in/hr)
   t = Drawdown Time (hours)
   FS = Infiltration Rate Factor of Safety

   Assume:
   - Maximum drawdown time (t) = 48 hours
   - Minimum FS = 2 (to account for long-term reduction in infiltration rate due to clogging)

4. Select a design ponding depth (d_p) and determine the thickness and porosity for the planting media and drainage layer. Calculate the total effective storage depth (d_t) following the equation below.

   $$d_t = (d_{pave} n_{pave}) + (d_r n_r)$$

   Where d_t = Total Effective Storage Depth (ft)
   d_{pave} = Pavement Course Depth (ft)
   n_{pave} = Pavement Course Porosity
   d_r = Rock Storage Layer Depth (ft)
   n_r = Rock Storage Layer Porosity

   Assume:
   - Porous asphalt porosity (n_{pave}) = 0.16 to 0.25 (typical)
   - Pervious concrete porosity (n_{pave}) = 0.15 to 0.35 (typical)
   - Rock storage layer porosity = 0.3 to 0.4 (typical)

5. Confirm that the total effective storage depth (d_t) is less than the maximum storage depth (d_{max}) calculated in Step 4.
6. Calculate the required surface area of the permeable pavement (A_{BMP}).

$$A_{BMP} = \frac{WQV}{d_t + \frac{kT}{12FS}}$$

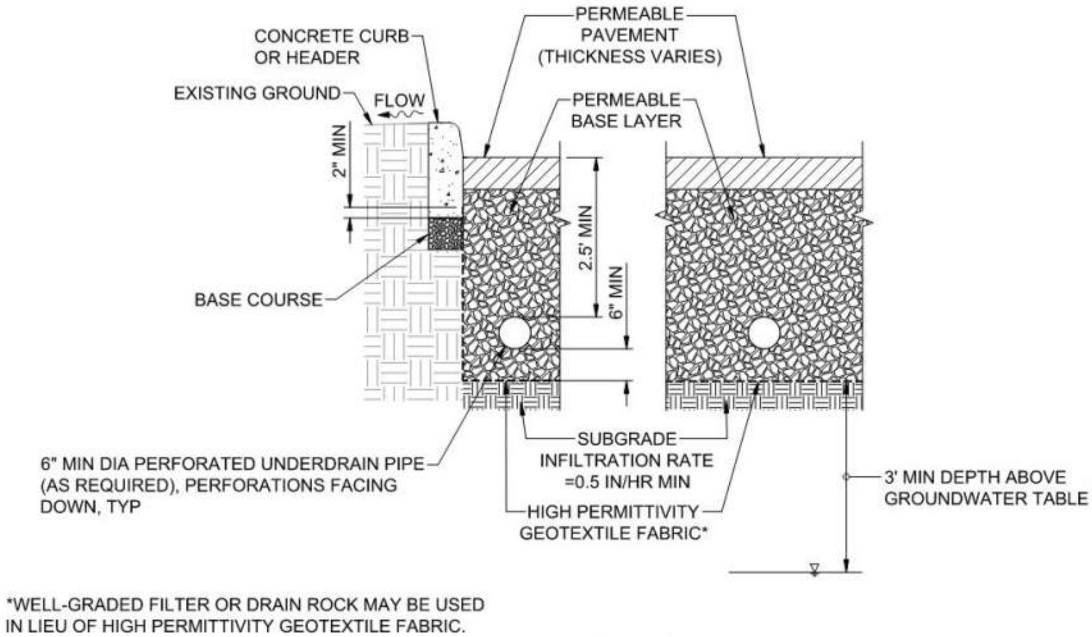
Where A_{BMP} = Total Surface Area (ft^2)
WQV = Water Quality Volume (ft^3)
d_t = Total Effective Storage Depth from Step 4 (ft)
k = Soil Infiltration Rate from Step 3 (in/hr)
T = Fill Time (hours)
FS = Infiltration Rate Factor of Safety from Step 3

7. Based upon the allowable space, determine the permeable pavement width (W) and corresponding length (L).

$$L = \frac{A_{BMP}}{W}$$

Where L = Pavement Length (ft)
A_{BMP} = Trench Surface Area from Step 6 (ft^2)
W = Pavement Width (ft)

BMP DETAILS



SECTION

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Left: Cistern at a residence. Right: Rain barrel at a residence. (Courtesy of Honolulu Board of Water Supply)

RAINWATER HARVESTING

BMP-6

DESCRIPTION

Rainwater harvesting is the capture and temporary storage of roof runoff in rain barrels or cisterns for non-potable outdoor purposes like irrigation and washing vehicles. Rain barrels, which are often aboveground plastic tanks, capture smaller runoff volumes. Cisterns, with greater capacity and pressurized distribution, can be aboveground or underground.

ADVANTAGES

- Recycles roof stormwater runoff for non-potable water uses.
- Provides runoff volume and pollutant reduction.
- Reduced water demands and cost for landscape irrigation.
- Wide applicability.

LIMITATIONS

- Periodic maintenance and cleaning to ensure effective stormwater storage while reducing algae growth and limiting mosquito breeding.
- If captured water is not used as anticipated or excessive rainfall occurs, the extra water collected must be managed to prevent overtopping and erosion of areas below the rain barrel or cistern.
- Improper or infrequent use, such as the rain barrel or cistern not being emptied between storm events, may result in unintended discharges.

Minimum BMP Footprint
Varies

Construction Cost
$

Operations & Maintenance
Frequency: Semi-Annually Cost: $

Design Considerations

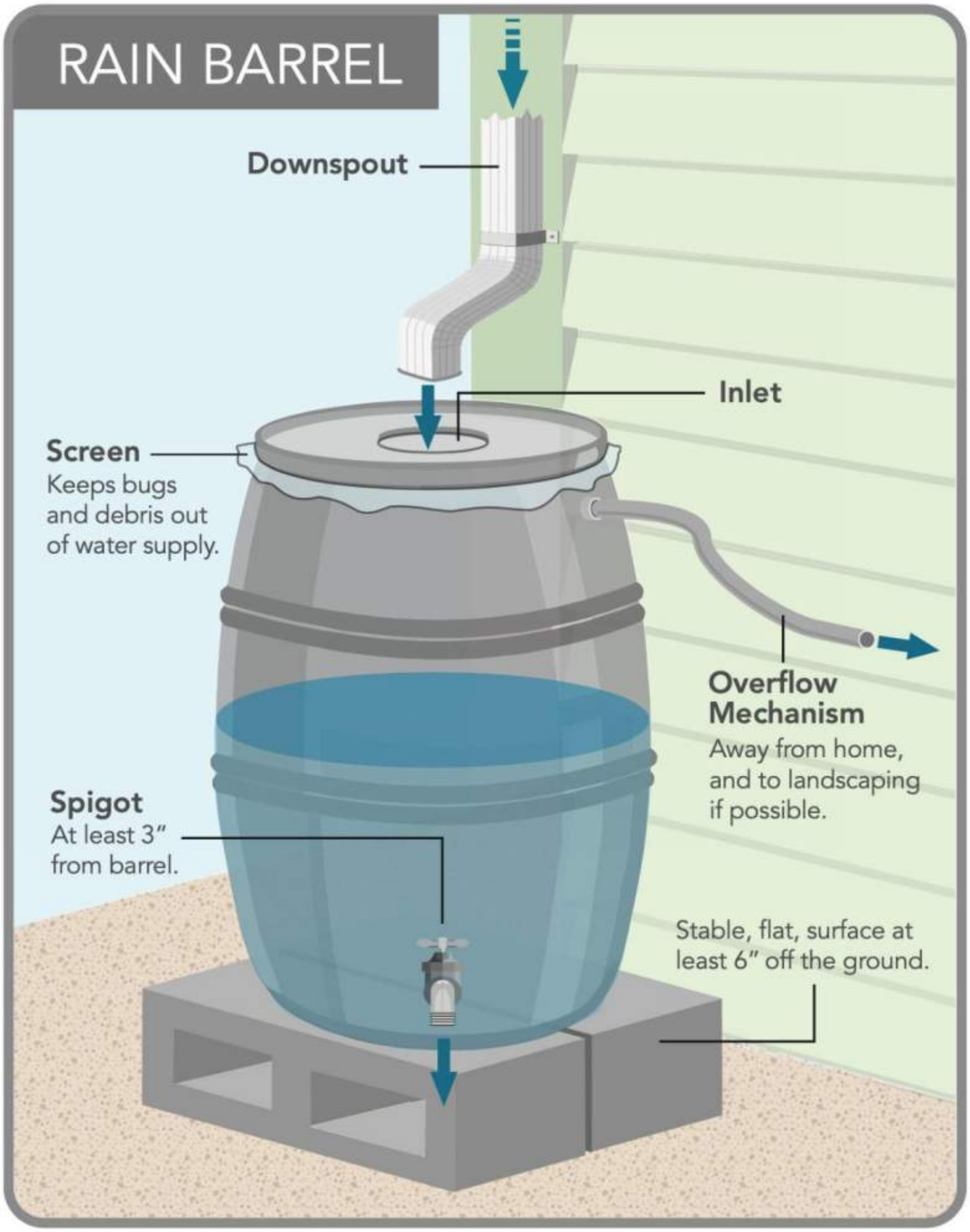
- Location
- Storage capacity
- Structural support
- Evaporation Rate
- Rainfall

VARIATIONS

- Rain barrels
  - Typically, rooftop downspouts link to rain barrels, gathering and storing water for future use. These barrels are prevalent in households, where water is repurposed for garden irrigation. They also find application in smaller-scale commercial and institutional settings.
- Cisterns
  - A cistern is a storage tank with greater capacity compared to a rain barrel. Typically, cisterns reuse stormwater for irrigation. Cisterns are available in various materials (fiberglass, concrete, etc.) and can be installed aboveground or underground. Sizes range from 200 to 10,000 gallons and larger.
- Vertical Storage Tank
  - A vertical storage tank is a large-scale structure designed to store large amounts stormwater. These tanks are the largest among stormwater capture and reuse containers, and their application depends on drainage area and water demand. Vertical storage tanks are most suitable for extensive irrigation or fire suppression and should be planned by a licensed expert. They are typically used at commercial, educational, or institutional facilities with substantial water requirements.
- Underground Storage Systems (using manufactured modular products)
  - Stormwater runoff can be stored underground using structural plastic units beneath pavements and landscaped areas. These modular units offer significant storage capacity in a compact space and do not require additional structural support. Implementing an underground storage system is ideal for institutional or commercial applications. These systems are more intricate than other types of stormwater storage systems, necessitating professional engineering design and requiring pumps supply irrigation systems.

APPLICATIONS

Harvesting/Reuse is applicable to many types of projects. The only caveat is that there must be a roof or area with which nearby to capture the stormwater. Rain barrels are mostly used in residential areas. Rainwater collected through rainwater harvesting can substitute potable water for purposes like irrigation, mechanical systems, or toilet flushing, primarily in rural areas.



Source: City of Palo Alto Stormwater Program

SITE CONSIDERATIONS

- Soils N/A
- Slope—Relatively flat
- Potential hotspots—Yes with treatment
- Maximum drainage area—N/A

DESIGN GUIDELINES AND CONSIDERATIONS

- Locate rain barrels and cisterns where it will be most useful or needed. Rain barrels and cisterns may be installed aboveground or underground but should be elevated higher than the landscape to promote gravity flow [4]. In areas where the tank is to be buried partially below the water table, special design features must be incorporated to keep the tank secured [2].
- Tanks should capture at least 80% of the average annual runoff volume and meet 80% of the annual overall demand [2]. Tanks shall be sized to drain the tank in 48 hours after rainfall [2].
- Use local pan evaporation and rainfall data [2].
- Use opaque materials to minimize algae growth in the rain barrel or cistern.
- Tanks shall be vector proof, childproof, and have tight-fitting covers to prevent mosquitoes from breeding [2].
- Overflow pipes and rainwater inlet pipes should be the same size.
- Any rain barrel, cistern, or rainwater collection pipe shall not be directly connected to any drinking water pipe system. Keep rainwater systems separate from drinking water piping [3].
- The foundation for the tanks must support the weight of the rain barrel or cistern and its stored water and be secured [1]. Straps can be used to prevent a rain barrel or cistern from tipping.

EFFECTIVENESS AND POLLUTANT REMOVAL

Rain barrels and cisterns capture roof runoff that may contain sediment, nutrients, and small amounts of metals. Cisterns alone may remove settleable and floatable material if the accumulated material is monitored and regularly removed. Cisterns cannot remove soluble material, thus providing limited pollutant reduction [5].

COST CONSIDERATIONS

The total cost of the system includes the rain barrel or cistern, spigots, overflow connector pipes, straps, and installation labor. The estimated unit cost range for rain barrels is $70 to $300 [7]. The Honolulu Board of Water Supply offers a $40 rebate for residential rain barrel catchment systems. The estimated unit cost range for cisterns is $300 to $10,000 [6]. The estimated annual maintenance cost of a cistern ranges from $1,650 to $2,650 [2]. The annual maintenance cost of a rain barrel is expected to be minimal (less than $1,000, inclusive of system component repairs or replacement, cleaning of screens and gutters, and prevention of algae growth in the barrel with chlorine tablets [8, 9, 12]).

OPERATION AND MAINTENANCE

- Conduct inspections of cisterns and barrels every 6 months.
- Take note of any exterior and interior structural damage (e.g., concrete, manhole lids, screens, etc.).
- Thoroughly clean and inspect inlets, filters, outlets, and overflow pipes for potential blockages and sediment buildup.
- Remove leaves and debris from gutters and drainage paths upstream of the cistern or rain barrel.
- Trim back overhanging trees and vegetation above the roof drainage area as needed.
- Inspect and test pumping systems and apply lubrication to all valves.
- Monitor mosquitoes and implement measures to prevent breeding, such as adjusting screens or introducing larvicide pellets (for non-potable use only).
- For proprietary systems, follow any additional maintenance procedures as per the manufacturer's recommendations.

SIZING PROCEDURE

Sizing a rainwater harvesting system is an iterative process and sizing calculations may need to be done multiple times to determine the appropriate cistern volume.

1. For the project site, determine the corresponding Monthly Rainfall Rate (R) in inches using NOAA rainfall data or other sources.

2. Determine the Monthly Pan Evaporation Rate (Epan) by using Reference 14 or other sources.

3. Calculate the Volumetric Runoff Coefficient using the following equation developed by the EPA for smaller storms in urban areas:

   $$C = 0.05 + 0.009I$$

   Where C = Volumetric Runoff Coefficient
   R = Monthly Rainfall Rate from Step 1 (in)

4. Calculate the tributary drainage area (A_d) of the cistern.

5. Determine the flow entering the cistern each month assuming the entire runoff volume will be stored for reuse based on the following equation:

   $$Q = 3630RCA_d$$

   Where Q = Monthly Runoff Volume (ft^3)
   R = Monthly Rainfall Rate from Step 1 (in)
   C = Volumetric Runoff Coefficient from Step 3
   A_d = Tributary Drainage Area from Step 4 (ac)

6. Calculate the monthly water demand based on identified reuse applications which may include irrigation or other industrial uses.

i) Calculate the design evaporation rate (E_o) associated with irrigation:

$$E_o = E_{pan} \times K_p \times K_l$$

Where E_o = Design Evaporation Rate (in)
R = Monthly Pan Evaporation Rate from Step 2 (in)
K_p = Pan Evaporation Coefficient
K_l = Landscape Coefficient

Assume:

- Pan evaporation coefficient (K_p): 0.8 for Hawaiian climate
- Landscape coefficient (K_l): 0.6 (average)

ii) Subtract the flow entering system (rainfall) from the flow existing system via irrigation and other demands (total reuse) to determine the monthly total demand (D_T).

$$D_T = D_{IRR} + D_R$$

$$\rightarrow D_T = \left[\frac{E_o - R}{e}\right] \times A_i \times 3630 + D_R$$

Where D_T = Monthly Total Demand (ft^3)
D_{IRR} = Monthly Irrigation Demand (ft^3)
D_R = Monthly Other Demand (ft^3)
E_o = Design Evaporation Rate from Step 6i (in)
R = Monthly Rainfall Rate from Step 1 (in)
E = System Efficiency
A_i = Irrigated Area (acres)

Assume:

- System efficiency factor (e): 0.9 to account for water loss due to leakage, splash, etc.

Perform a monthly water balance analysis starting with January and ending with December using the difference between the monthly rainfall (Q) and the monthly demands (D_T) from Steps 5 and 6.

The storage volume at the beginning of the month (V_b) is the same as the storage volume at the end of the previous month (V_e). For the first month of the analysis (January), V_b is set to 0.

If Q exceeds D_T for a given month, the difference is added to the storage volume at the beginning of the next month (V_b), and the storage volume at the end of the month (V_e) is computed.

$$V_e = V_b + Q - D_T$$

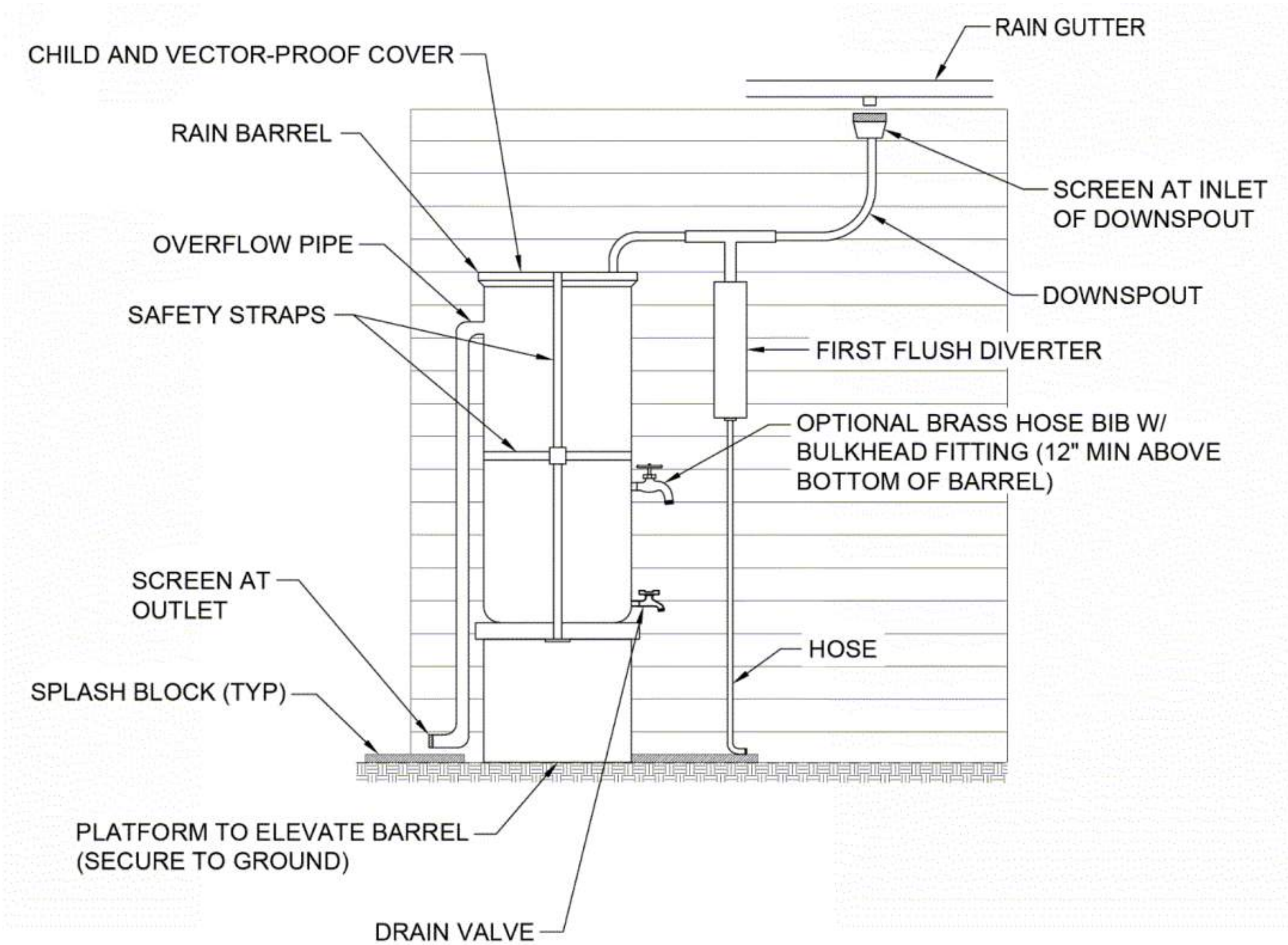
Where V_e = Storage Volume at the end of the month (ft^3)
V_b = Storage Volume at the beginning of the month (ft^3)

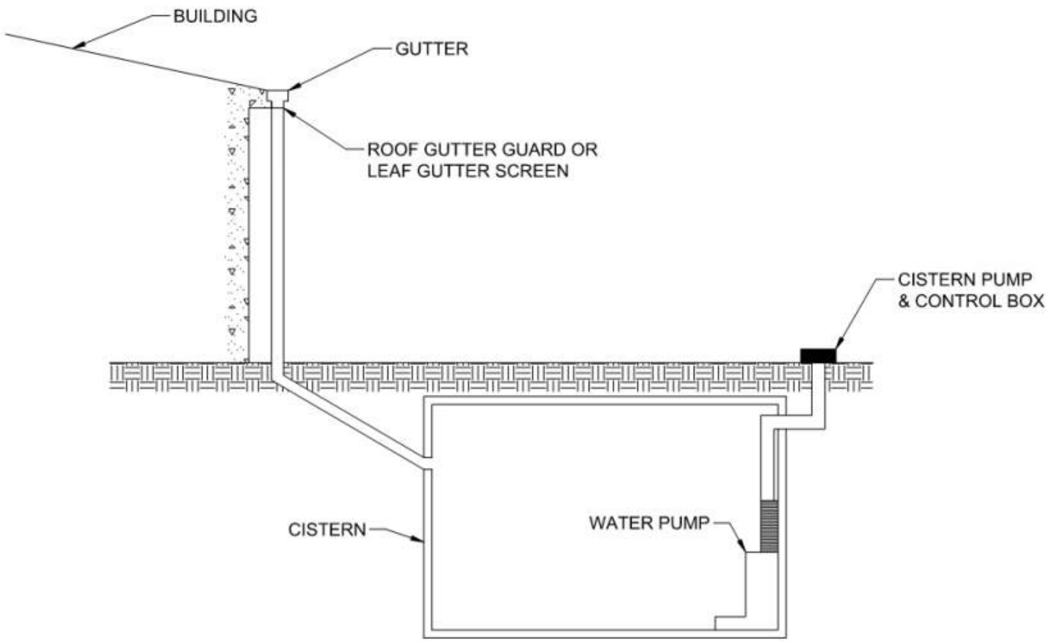
Q = Monthly Runoff Demand (ft^3)
D_T = Monthly Total Demand (ft^3)

If D_T exceeds Q for a given month, the difference is subtracted from the storage volume at the beginning of the month (V_b), and the storage volume at the end of the month (V_e) is computed. The process is continued for the remaining months until December. If the computed storage volume at the end of the month is negative, a value of 0 is shown for V_e.

iii) Size the cistern volume to be greater than the highest value of (V_e) over the course of the entire year. Include any freeboard requirements or additional volume required as a factor of safety. If the cistern is designed to have a volume less than the maximum V_e due to cost or space constraints, the system needs to also incorporate a bypass system or other means to manage the excess stormwater flows.

BMP DETAILS


RAIN GUTTER
CHILD AND VECTOR-PROOF COVER
RAIN BARREL
SCREEN AT INLET OF DOWNSPOUT
OVERFLOW PIPE
DOWNSPOUT
SAFETY STRAPS
FIRST FLUSH DIVERTER
OPTIONAL BRASS HOSE BIB W/ BULKHEAD FITTING (12" MIN ABOVE BOTTOM OF BARREL)
SCREEN AT OUTLET
HOSE
SPLASH BLOCK (TYP)
PLATFORM TO ELEVATE BARREL (SECURE TO GROUND)
DRAIN VALVE



THIS DETAIL SHOWS AN UNDERGROUND CISTERN. ABOVEGROUND CISTERNS WILL BE SIMILAR TO THAT OF RAIN BARRELS. CISTERNS TEND TO HAVE A MUCH LARGER VOLUME THAN THAT OF RAIN BARRELS.

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Left: Turtle Bay (Courtesy of Sea Grant); Right: Frank Fasi Municipal Building Parking Structure (Courtesy of CCH-DFM)

GREEN ROOFS

BMP-7

DESCRIPTION

Green roofs are an eco-friendly alternative to standard roofs, effectively reducing stormwater runoff and offering various environmental and aesthetic advantages. By utilizing innovative design strategies, they make productive use of spaces typically unused for stormwater management. Unlike traditional roofing materials, green roofs absorb, store, and naturally disperse stormwater, also acting as thermal regulators for the building.

ADVANTAGES

- Effective stormwater management and energy conservation.
- Alleviation of the urban heat island effect.
- Prolonged lifespan of roofing materials.
- Enhanced visual appeal for living and working environments.

LIMITATIONS

- Cost (intensive systems).
- Careful design and construction required.
- Maintenance requirements until plants are established.
- Difficult to keep plants alive with green roof soil shallower than 4 inches.

BMP Footprint Size
350 sf

Construction Cost
$$ - $$$

Operations & Maintenance
Frequency: Quarterly Cost: $$

Design Considerations

- Location
- Storage capacity
- Structural support
- Evaporation Rate
- Rainfall

VARIATIONS

- Depending on the plant material and planned usage for the roof area, vegetated roofs can be categorized as systems that are intensive, semi-intensive, or extensive. Intensive systems allow for more variety but are expensive and require more maintenance. Intensive systems require the deepest soil and can accommodate many types of plantings, including large shrubs and trees. Semi-intensive systems also require a deeper soil layer and form a transition from extensive to intensive greening. Semi-intensive systems require moderate maintenance and occasional irrigation depending on the location. A typical growing medium depth for a semi-intensive green roof is 6 to 10 inches.
- Among green roof systems, extensive vegetated roofs are the most popular. Extensive green roofs excel in reducing stormwater runoff and are cost-effective compared to other options. Extensive systems have three variations of assemblies that can be considered in design.
    - Single media assemblies find common use in pitched roof applications and in situations where a lightweight installation is needed. These systems typically feature drought-resistant plants and employ coarse engineered media with excellent permeability.
    - Dual media assemblies employ two distinct types of non-soil growth media. In this setup, a fine-grained media with some organic content is layered atop a base of course, lightweight aggregate. This design omits a geocomposite drain. The aim of this design is to enhance drought resistance. These assemblies are usually 4 to 6 inches thick.
    - Dual media with synthetic retention/detention layer systems incorporate non-permeable plastic panels with cup-like depressions on the top surface (essentially, a modified geocomposite drain sheet). These panels are filled with coarse lightweight aggregate. The cups capture and hold water while also creating an air pocket at the base of the assembly.

APPLICATIONS

Green roofs are not commonly used for residential structures. They are suitable for various types of buildings including commercial and industrial buildings. They are suitable in ultra urban environments, where available space is at a premium. Green roofs can be installed either during initial construction or added as a retrofit.

SITE CONSIDERATIONS

The capacity of a green roof to retain stormwater depends on factors like its size, the depth and composition of the growing medium, slope and plant types. It's essential that green roofs are easily accessible, and property owners should be aware of the maintenance needed to keep them effective.

DESIGN GUIDELINES AND CONSIDERATIONS

- Building capacity should accommodate the weight of green roof materials under saturated conditions.
- Green roof components, or layers, can vary based on specific types and uses. Typically, they include (from top to bottom): a vegetation layer, engineered planting media, filter mat, drainage layer, and moisture barrier.
- The drainage layer below the growth media should be designed to convey the design storm without backing water up into the growing media. The drainage layer should convey flow to an outlet or overflow system such as a traditional rooftop drainage system with inlets set slightly above the elevation of the vegetated roof surface.
- Vegetation selection should align with local climate conditions with an emphasis on low-maintenance plants.
- Construction teams have the option to build green roofs incrementally, or they can opt for pre-assembled systems. Some suppliers even offer modular trays containing all necessary components.
- Suitable roof substructures can include wooden construction, metal sheeting and reinforced concrete decks. The foundation for the vegetated roof should be a waterproof roof structure with adequate load-bearing capacity.
- Maximum pitch on green roofs is around 10 degrees.
- The minimum depth of soil media is two inches and the minimum drainage layer is two inches.
- Safety measures against wind uplift must be considered during design.
- The building must include adequate and readily available roof access for delivery of construction materials and for routine maintenance.

EFFECTIVENESS AND POLLUTANT REMOVAL

Green roofs are effective in mitigating stormwater impacts. They can significantly lower peak flows during storms, decrease total stormwater discharge, and reduce the release of certain pollutants compared to conventional roofs. Research findings suggest that green roofs can retain at least 80 percent of stormwater in small events, with variable rates for larger events. They can reduce total stormwater volume and peak flows by 30 to 90 percent, particularly in smaller rain events before saturation.

COST CONSIDERATIONS

The construction cost of vegetated roofs varies greatly, depending on factors such as:

- Height of the building
- Accessibility to the structure by large equipment such as cranes and trailers
- Depth and complexity of the assembly
- Remoteness of the project from sources of material supply
- Size of the project

While the initial installation of green roofs tends to be more expensive than conventional roofs, they can be cost-effective in the long-term. The life span of a green roof is typically comparable to, if not superior to, that of a conventional roof. For instance, an extensive green roof can last for approximately 25 years, potentially higher than the life span of a conventional roof. While green roof materials are relatively inexpensive, ranging from $1 to $3 per square foot, installation is labor-intensive and often requires a crane, which can add $4,000 to $5,000 per day. Total green roof costs are often cited as $15 to $35 per square foot, with the cost per square foot decreasing as the size increases. However, expenses can reach as high as $60 per square foot. Maintenance costs are initially higher for vegetation establishment; but after the first 5 years, they typically range from $0.10 to $1.00 per square foot per year.

OPERATION AND MAINTENANCE

- Irrigation should be applied as needed during plant establishment and drought periods.
- During the initial plant establishment phase, consider three to four visits for basic weeding, fertilization, and infill planting.
- Adjust the soluble nitrogen content of the soil to a range of one to five parts per million, based on soil test results.
- Once plants are established, regular maintenance is vital. This includes biannual removal of weeds and unwanted plants across the entire roof. For grass and herb vegetation, clear organic buildup annually.

SIZING PROCEDURE

1. Determine the Water Quality Volume (WQV)

   $$WQV = P \times C \times AT \times 3630$$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. $$C = 0.05 + 0.009I$$

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. Select initial values for the soil media thickness (l_m), drainage layer thickness (l_d), and allowable ponding depth (d_p).

4. Calculate the total effective storage depth based on instantaneous storage capacity using the void space in the soil media and drainage layer, and the allowable ponding:

   $$d_t = \frac{d_p + l_m n_m + l_d n_d}{12}$$

   Where d_t = Total Effective Water Storage Depth (ft)
   d_p = Ponding Depth (in)
   l_m = Planting Media Thickness Depth (in)
   n_m = Planting Media Porosity
   l_d = Drainage Layer Thickness (in)
   n_d = Drainage Layer Porosity

5. Calculate area required (A_{BMP}) based on the instantaneous storage capacity:

   $$A_{BMP} = \frac{WQV}{d_t}$$

Where A_{BMP} = BMP Area (ft^2)
WQV = WQV from step 1 (ft^3)
d_t = Total Effective Water Storage Depth from Step 4 (ft)

If the calculated area does not fit in the available space, either reduce the tributary area and/or increase one or more of the design depths (ponding, soil media, drainage layer), and repeat the calculations.

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Kuono Marketplace, Kahala, O'ahu (Courtesy of Bowers + Kubota Consulting)

TREE AND PLANTER BOX FILTERS BMP-8

DESCRIPTION

Tree and planter box filters, also known as vegetated biofilters, are stormwater treatment devices filled with engineered soil media, and are typically located in a sidewalk, parking lot, or median. Runoff flows from adjacent impervious areas into the device and infiltrates through the soil media before being directed back into the drainage system. Pollutant removal is accomplished by filtration from the soil media and by evapotranspiration and phytoremediation from the vegetation.

ADVANTAGES

- Pollutant removal effectiveness is typically high.
- Provides an aesthetic vegetated appearance.
- Standardized design and layout.
- Ease of construction and maintenance.
- Pretreatment for downstream structures and BMPs.

LIMITATIONS

- In areas with prolonged dry periods, installation of an irrigation system may be required.
- Not applicable downstream of landscaped or pervious areas where heavy sediment loadings may lead to premature failure.
- Width of sidewalk or right-of-way may limit tree box size.
- Areas with high density of underground utilities may limit use of trees and planter box filters.
- Tree roots may damage sidewalks.

Minimum BMP Footprint
16 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Annually Cost: $

Design Considerations

- Bioretention area and depth
- Bioretention media
- Ponding depth
- Underground drain system
- Vegetation
- Water quality volume

VARIATIONS

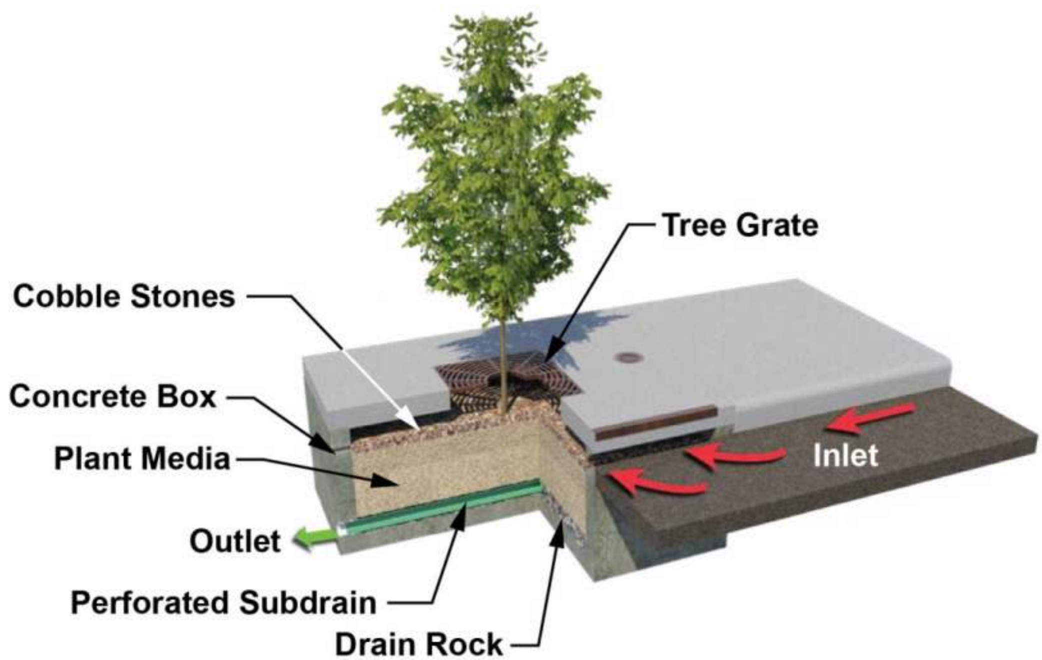
Tree and planter box BMPs have several variations that include contained, infiltration, or flow-through systems. The contained systems are generally traditional planters that capture rainwater and have weep holes to drain the excess water from the planter. This type of planter box can be installed to retrofit an existing urban streetscape or large area of pavement such as at an entryway to a building.

The second variation is an infiltration system designed to filter stormwater runoff through the planter's soil, capturing pollutants in the process, and then infiltrating into the native soil beneath the planter. Typically, these planters are constructed to be level with the surrounding paved surfaces. The planter is sized to accept runoff and temporarily store the water in a reservoir on top of the soil. This variation does not have an underdrain system.

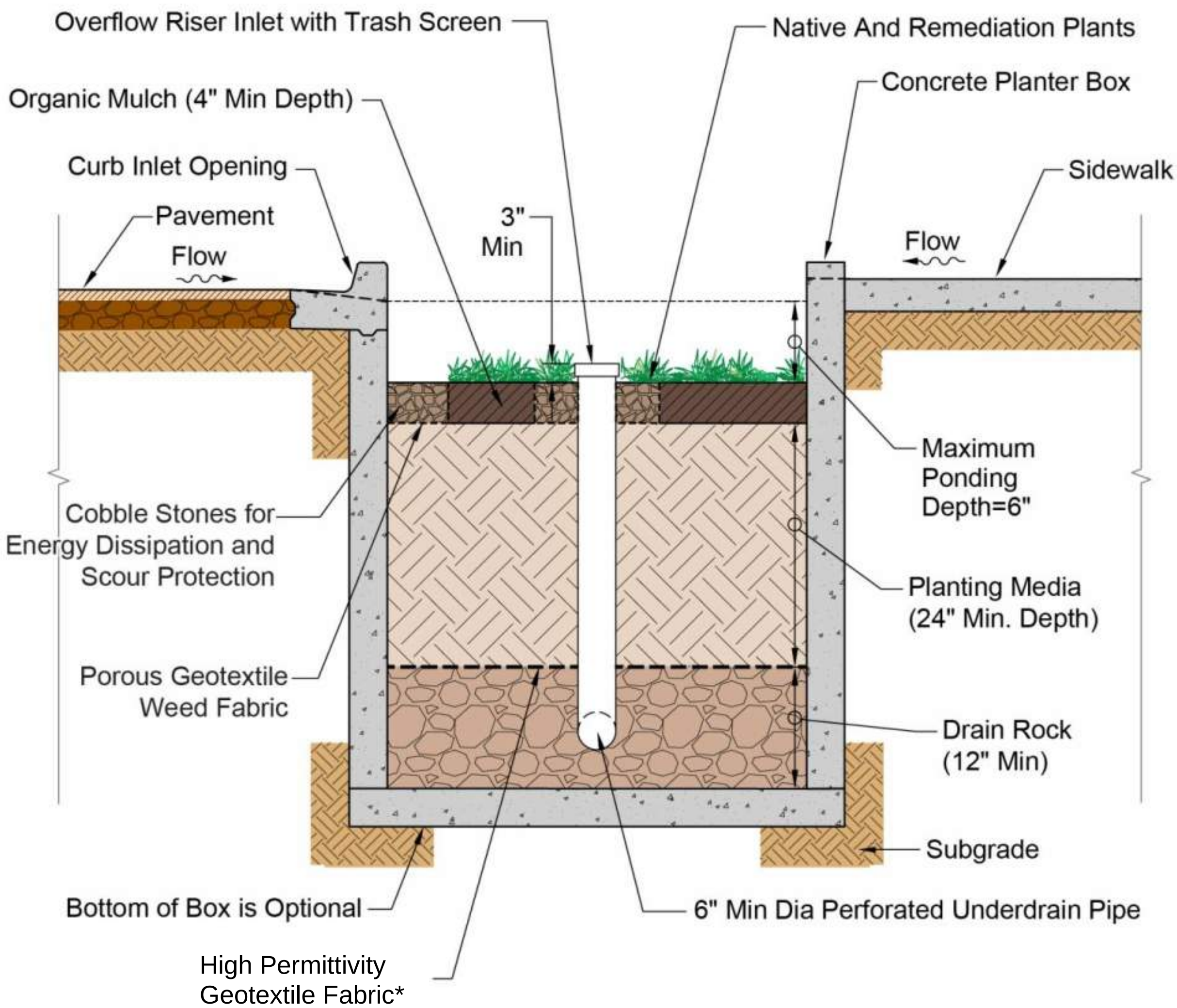
The third variation is a flow-through box system. This variation is completely contained with an impervious bottom and drains to the stormwater system. Pollutant reduction is achieved as the water filters through the soil media. Flow control is achieved by temporarily ponding runoff above the soil and in a gravel layer below it. Once the stormwater has filtered through the soil, the stormwater exits through a perforated underdrain system that flows to the downstream drainage system.

APPLICATIONS

Planter and tree box filters are typically applied in urban areas. They can handle high pollutant loadings. They have a relatively small footprint and can accommodate vertical elevation drops along its edges. Often tree box filters are used in series to treat the entire water quality volume. Areas that work well with a box filter system include sidewalks, urban streetscapes, and residential, commercial, and light industrial buildings.



Tree Box Filter (Source: Contech)



*Well-graded filter or drain rock may be used in lieu of high permittivity geotextile fabric

Planter Box Filter Section View (Source: Bowers + Kubota Consulting)

SITE CONSIDERATIONS

The footprint requirements for proprietary tree box filters vary by manufacturer. Tree box filters can range from a minimum footprint of 4′x4′ to a maximum footprint of 9′x17′. The footprint must be equivalent to roughly 5% of its contributing impervious drainage area. The box filter should maintain a clearance of at least 3 feet above the seasonally high groundwater table to avoid groundwater contamination.

DESIGN GUIDELINES AND CONSIDERATIONS

At sites where pretreatment is not required, automatic retractable screens may still be used to keep large solids out of the tree box filter.

All tree box filters must be able to safely bypass flows more than the stormwater quality design storm to downstream drainage systems when the surface and subsurface capacities of the tree box filter are exceeded. If a mulch layer is used on the surface of the planting bed, consideration should be given to problems caused by flotation during storm events. A cleanout pipe should be connected at the end of all underdrain pipe runs [4].

The entrance or inflow must be designed to avoid erosion within the planter box. Various options, such as gravel, splash blocks, perforated pipes, and erosion control mats, can be considered as options.

If utilizing an underdrain system, the underdrain pipe must be a minimum diameter of 4 inches and should be perforated PVC Schedule 40 pipe or equivalent corrugated high-density polyethylene (HDPE) pipe encased in a layer of #57 washed stone, 8–12 inches thick. The underdrain system must be connected to an overflow drain to allow overflow to enter the downstream drainage system.

Vegetation must accommodate adequate sight distance at intersections.

Plant Selection
The designer should work with the manufacturer or landscape architect to select native plant species.

The following native Hawaiian trees are highly salt and wind tolerant.

Scientific Name	Common Name	Height (inches)
Calophyllum inophyllum	kamani	40
Cordia subcordata	kou	20
Hibiscus tiliaceus	hau	30
Myoporum sandwicense	naio	15-20
Pandanus odoratissimus	pandanus, hala	15
Thespesia populnea	milo	30

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	80–90+%
Total Phosphorus	50–80%
Nitrogen	20–65%
Copper	40–55%
Zinc	50–80%
Bacteria	90+%
Hydrocarbons	80–90%

Sources: [1, 8, 12, 13]

COST CONSIDERATIONS

The estimated capital cost of one tree box filter ranges from about $15,000 to $50,000. Mulch and media replacement ranges from $400 to $800 per year per tree box filter. A study that was part of the San Diego Stormwater Urban Mitigation Plan in 2012 indicated that annual maintenance costs ranged from $2,367 to $3,781 for flow-through planter box filters.

OPERATION AND MAINTENANCE

Maintenance consists of the removal of litter, replacement of mulch, and pruning of trees on an annual basis or per the manufacturer's recommendations. Routine maintenance should include a semiannual health evaluation of the trees and quarterly inspections that includes: pruning and weeding, removal of large solids and subsequent removal of any dead or diseased vegetation [5]. Diseased vegetation should be treated using preventative and low-toxic measures to the maximum extent practical [3]. Inspect the irrigation system periodically to ensure that the right amount of water is being applied and that excessive runoff is not occurring. Check for broken, missing, sunken, misaligned, or tilted sprinkler heads; leaking valves or pipes; clogged nozzles; seal leaks; overspray; pressure problems; a malfunctioning controller; and incorrect spray arc. Minimize excess watering, and repair leaks in the irrigation system as soon as they are observed [4].

SIZING PROCEDURE

1. Determine the Water Quality Volume (WQV) that will need to be treated by the LID BMP.

   $$WQV = P \times C \times A_T \times 3630$$

   Where WQV = Water Quality Volume (ft)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. $C = 0.05 + 0.009I$

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. If an open-bottom structure is used, calculate the maximum storage depth (d_{max}) based upon the underlying soil infiltration rate (k) and the required drawdown time (t). Otherwise, if a closed-bottom structure is used, continue to Step 4.

   $$d_{max} = \frac{kt}{12FS}$$

   Where d_{max} = Maximum Storage Depth (ft)
   k = Soil Infiltration Rate from testing (in/hr)
   t = Drawdown Time (hours)
   FS = Infiltration Rate Factor of Safety

Assume:
- Maximum drawdown time (t) = 48 hours (a shorter period may be used for high-pedestrian traffic areas where ponding may be a nuisance)
- Minimum FS = 2 (to account for long-term reduction in infiltration rate due to clogging)

4. Select a design ponding depth (d_p) and determine the thickness and porosity for the engineered soil media. Calculate the total effective storage depth (d_t) following the equation below.

$$d_t = d_p + (d_s n_s) + (d_d n_d)$$

Where d_t = Total Effective Storage Depth (ft)
d_p = Ponding Depth (ft)
d_s = Engineered Soil Media Depth (ft)
n_s = Engineered Soil Media Porosity
d_d = Drainage Layer Depth (ft)
n_d = Drainage Layer Porosity

Assume the following typical values:
- Maximum ponding depth (d_p) = 6 inches
- Engineered soil media porosity (n_m) = 0.25
- Drainage layer porosity = 0.3 to 0.4

5. Confirm that the total effective storage depth (d_t) is less than the maximum storage depth (d_{max}) calculated in Step 3.

6. Calculate the required surface area (A_{BMP}) of the box filter.

$$A_{BMP} = \frac{WQV}{(d_t + \frac{kT}{12FS})}$$

Where A_{BMP} = Box Filter Surface Area (ft^2)
WQV = Water Quality Volume (ft^3)
d_t = Total Effective Storage Depth (ft)
k = Soil Infiltration Rate from Step 3 (in/hr)
T = Fill Time (hours)
FS = Infiltration Rate Factor of Safety from Step 3.

If the required surface area does not fit in the allowable space, adjust the design variables, and repeat the calculations as necessary.

7. Based upon the required surface area (A_{BMP}), determine the top width (W) and corresponding top length (L) of the box filter.

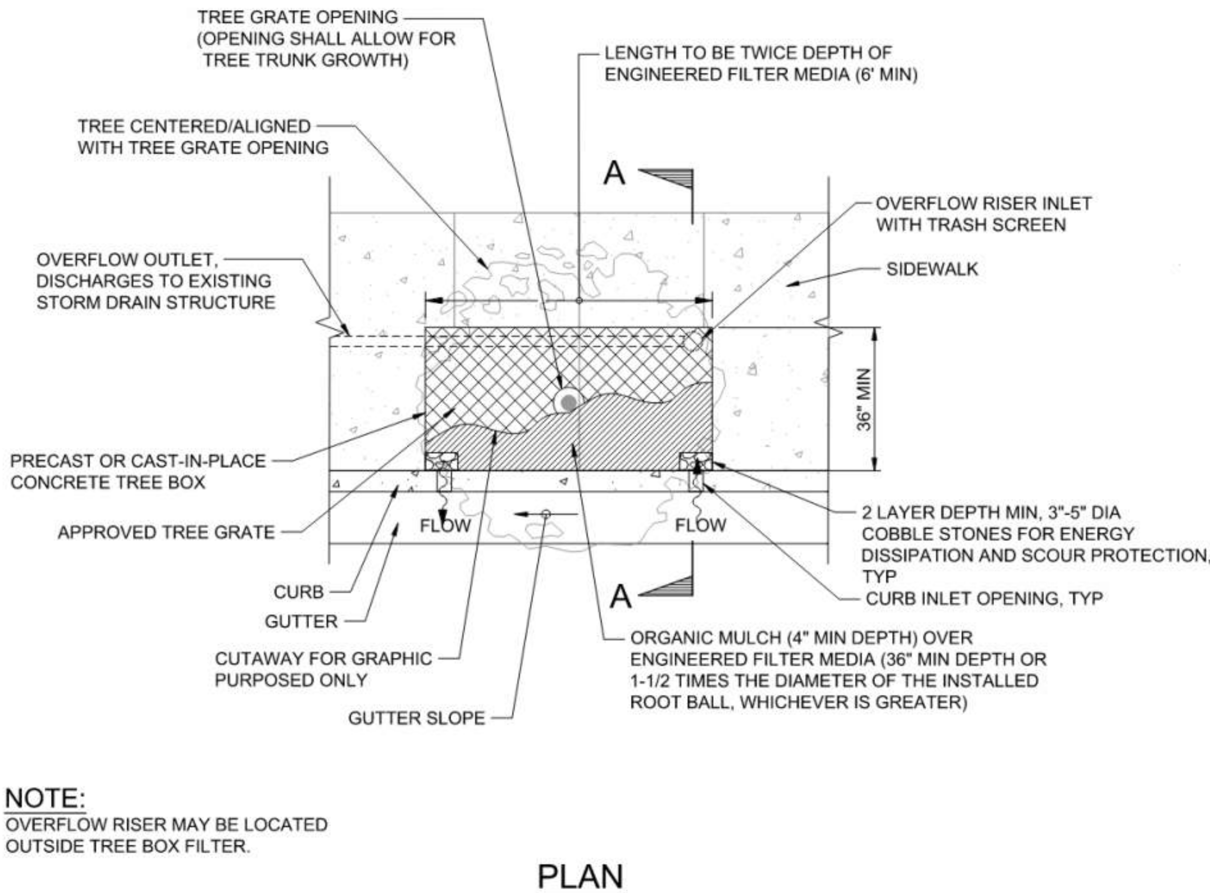
$$L = \frac{A_{BMP}}{W}$$

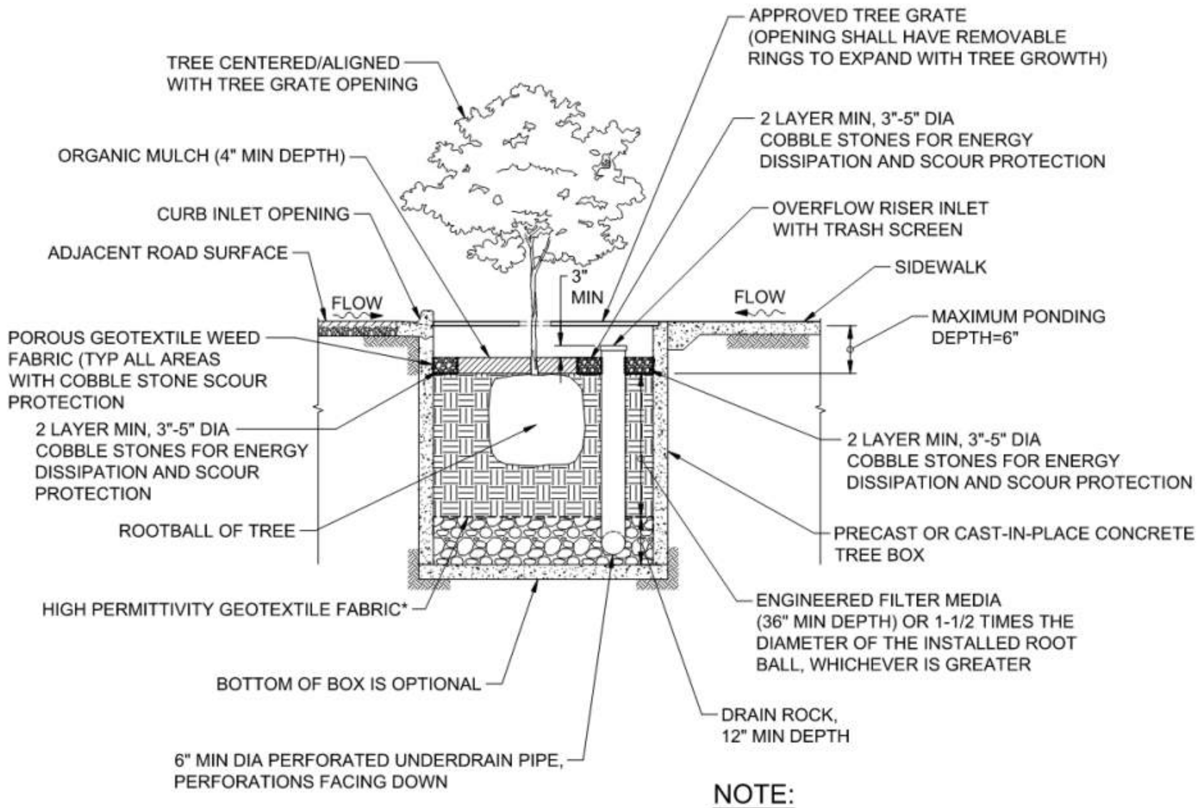
Where L = Top Length (ft)

A_{BMP} = Box Filter Surface Area from Step 6 (ft^2)
W = Top Width (ft)

8. Design a bypass system to convey peak flows more than the WQV to adjacent downstream BMP devices or drainage structures. Evaluate resulting gutter spread and impact upon surface street or parking lot flooding, where applicable.

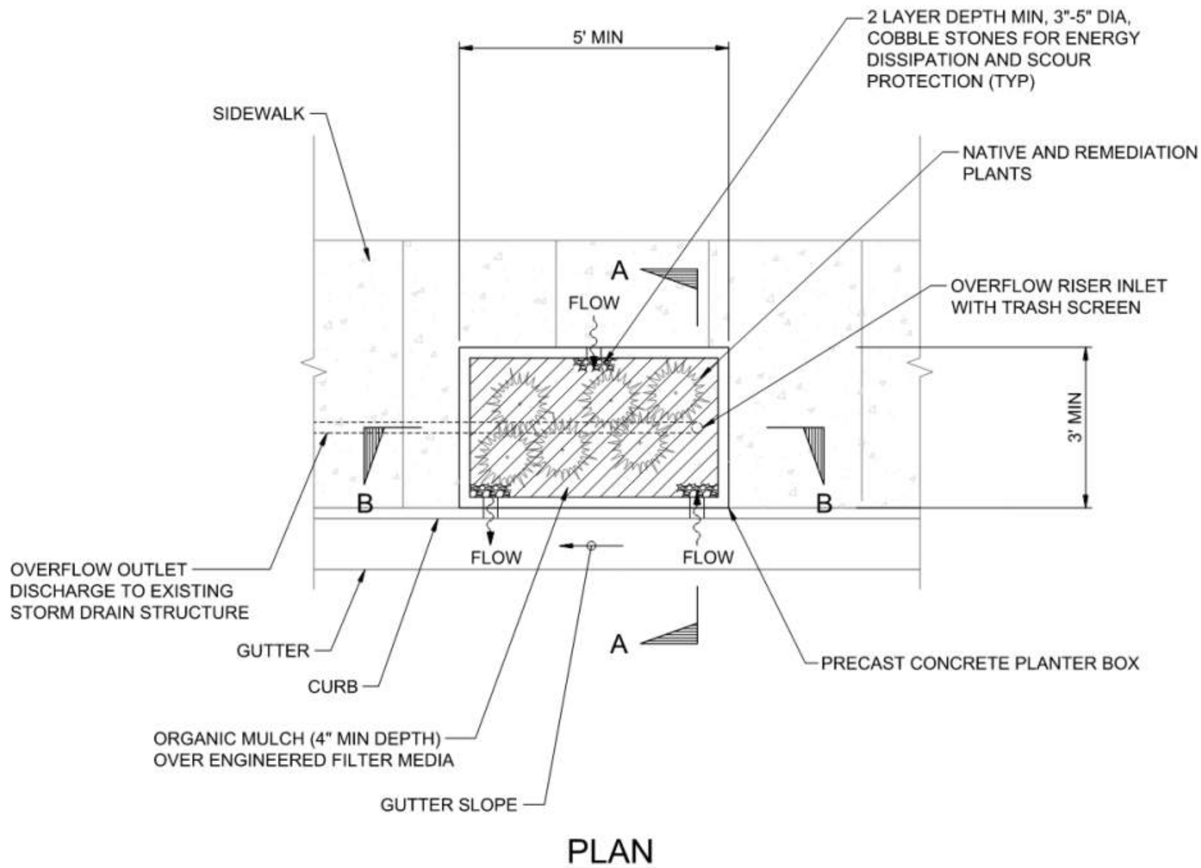
BMP DETAILS


TREE GRATE OPENING (OPENING SHALL ALLOW FOR TREE TRUNK GROWTH)
LENGTH TO BE TWICE DEPTH OF ENGINEERED FILTER MEDIA (6' MIN)
TREE CENTERED/ALIGNED WITH TREE GRATE OPENING
A
OVERFLOW RISER INLET WITH TRASH SCREEN
OVERFLOW OUTLET, DISCHARGES TO EXISTING STORM DRAIN STRUCTURE
SIDEWALK
36" MIN
PRECAST OR CAST-IN-PLACE CONCRETE TREE BOX
APPROVED TREE GRATE
FLOW
FLOW
2 LAYER DEPTH MIN, 3"-5" DIA COBBLE STONES FOR ENERGY DISSIPATION AND SCOUR PROTECTION, TYP
CURB INLET OPENING, TYP
A
CURB
GUTTER
CUTAWAY FOR GRAPHIC PURPOSED ONLY
ORGANIC MULCH (4" MIN DEPTH) OVER ENGINEERED FILTER MEDIA (36" MIN DEPTH OR 1-1/2 TIMES THE DIAMETER OF THE INSTALLED ROOT BALL, WHICHEVER IS GREATER)
GUTTER SLOPE
NOTE:
OVERFLOW RISER MAY BE LOCATED OUTSIDE TREE BOX FILTER.
PLAN

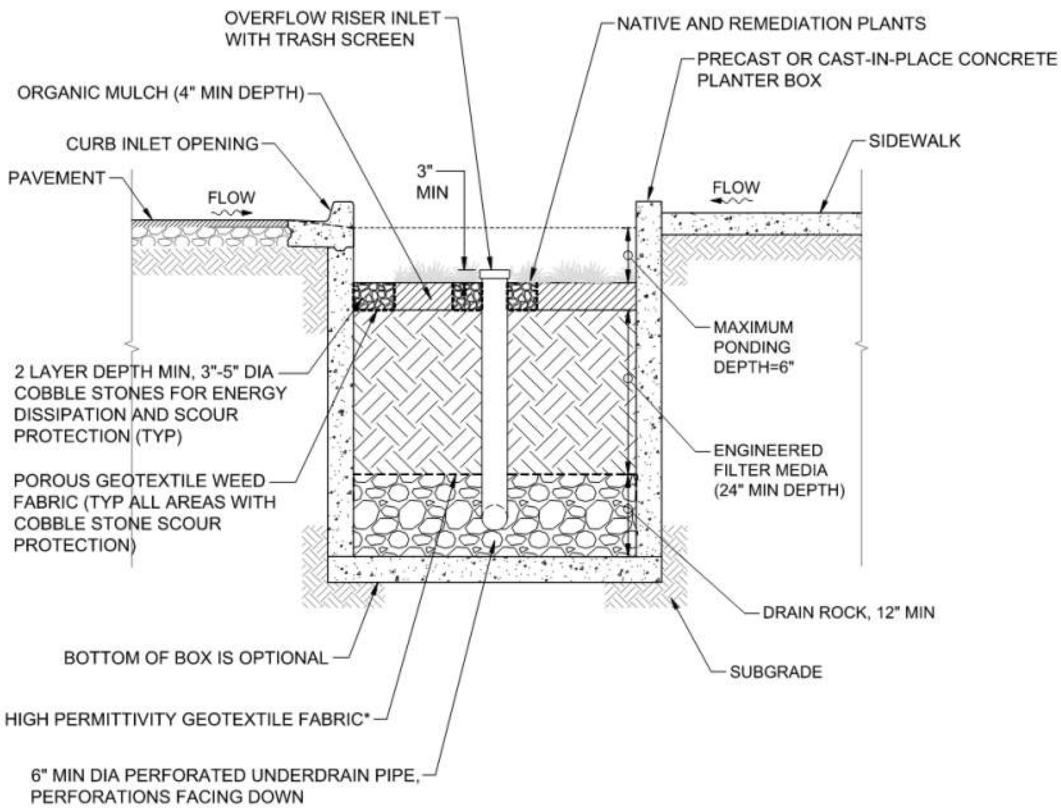


SECTION A-A

NOTE:
OVERFLOW RISER MAY BE LOCATED OUTSIDE TREE BOX FILTER.
*WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC.

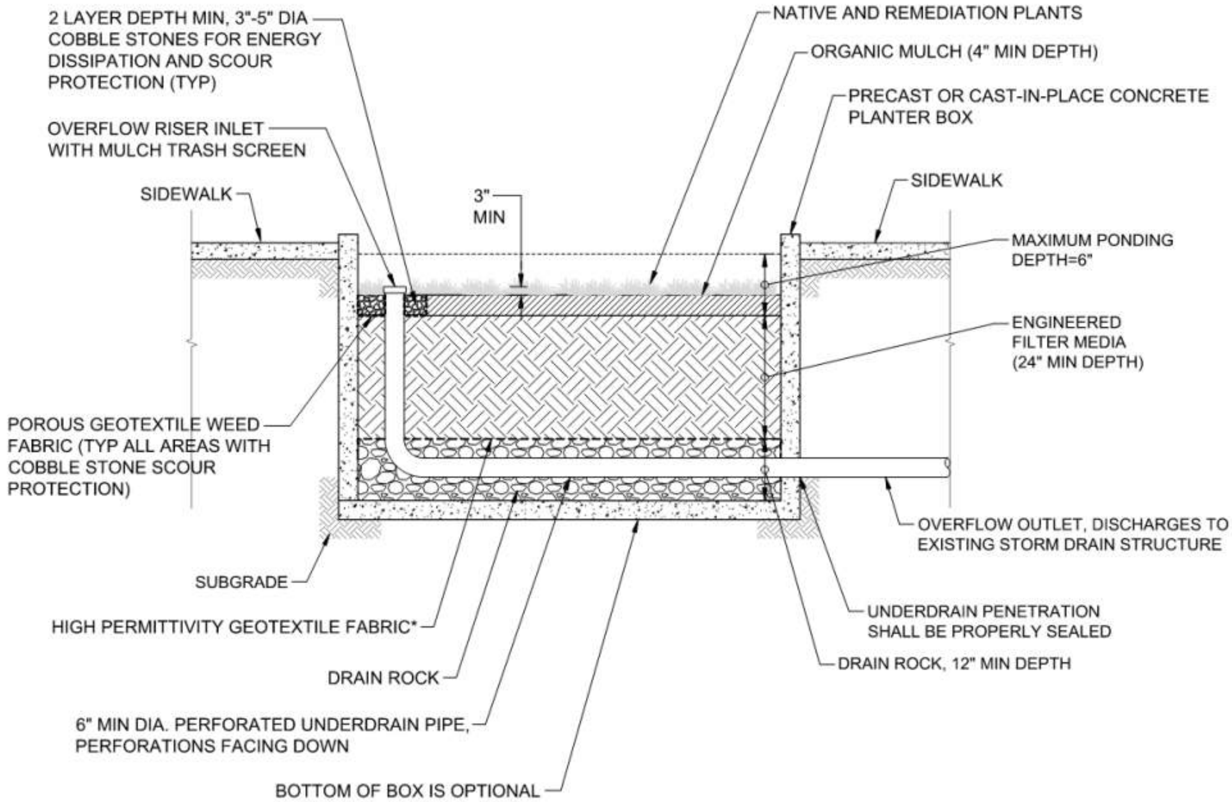


NOTE: OVERFLOW RISER MAY BE LOCATED OUTSIDE PLANTER BOX.



NOTE: *WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC.

SECTION A-A



NOTE: *WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC.

SECTION B-B

REFERENCES

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2. Caltrans. 2010. *Treatment BMP Technology Report*. CTSW-RT-09-239.06. Sacramento: Division of Environmental Analysis.

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Bioswale adjacent to Kumuhao Street, Waimanalo, Oʻahu (Courtesy of the City and County of Honolulu)

BIOSWALES

BMP-9

DESCRIPTION

Swales are shallow, vegetated open channels or drainage pathways designed for conveyance of the design storm flow. Swales effectively reduce the speed of runoff, promote infiltration within the soil and planting media, and filter pollutants as water moves through the BMP. Swale variations include the vegetated swale and the enhanced swale.

ADVANTAGES

- Effectively promotes removal of various stormwater pollutants.
- May be incorporated into different landscape settings such as yards, road shoulders, rights-of-way, and provides treatment to roof downspout discharges.
- Enhanced swales can achieve flood control and groundwater recharge.
- Swales provide an inexpensive option for roads and highways compared to a typical curb and gutter, while reducing maintenance costs.

LIMITATIONS

- During dry periods, irrigation may be required to maintain vegetation.
- Hotspot areas are not suitable for swales as excessive oils and grease may reduce efficacy of pollutant removal rates.
- If heavy sediment loading is anticipated, a BMP for pretreatment is recommended.
- If clogged, swale systems may require reconstruction.
- Limited applications where space is a concern.

Minimum BMP Footprint
1000 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Monthly Cost: $ - $$

Design Considerations

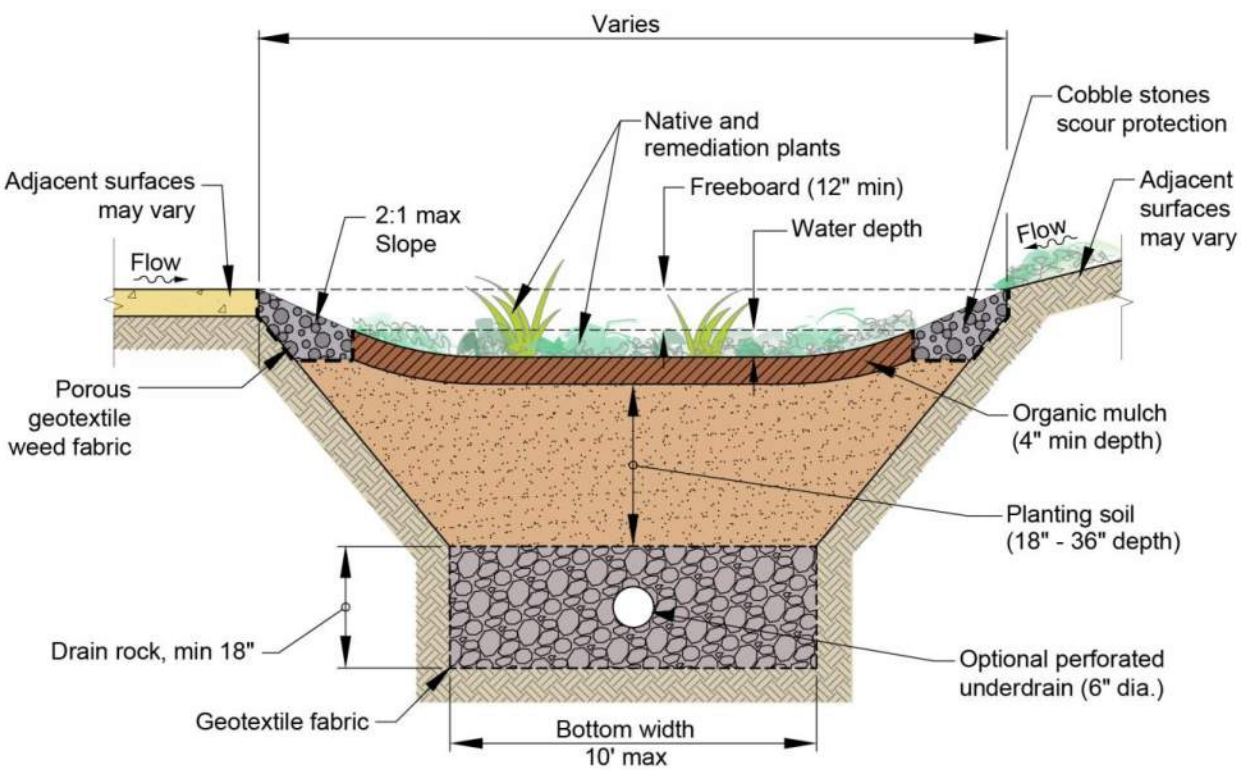
- Water quality volume
- Permeability of soil
- Distance to groundwater
- Load requirements

VARIATIONS

Variations include a vegetated swale or an enhanced swale. A vegetated swale typically has runoff entering one side of the swale and exiting at the other end of the swale. Vegetated swals are designed to reduce runoff velocities to allow pollutants to be removed via sedimentation, adsorption, and infiltration through the soil. A vegetated swale does not have engineered planting media or an underdrain system. An enhanced swale is similar to a vegetated swale but differs by featuring a permeable planting media and underdrain system beneath the swale to allow for capture and treatment of the water quality volume. Enhanced swales promote groundwater recharge while reducing runoff volume that enters the storm drainage system.

APPLICATIONS

- Residential—Swales can be used for side and backyard areas to minimize runoff volume and slow runoff flow.
- Commercial/Industrial—swales can provide drainage around the site and slow discharge from other BMPs that drain to the swale.
- Highway/Road—vegetated swales can provide an excellent alternative to curb and gutter systems but vehicle and pedestrian safety must be considered during design of the swales.



Bioswale Section View (Source: Bowers + Kubota Consulting)

SITE CONSIDERATIONS

- Enhanced Swale
  - An enhanced swale requires a footprint equivalent to roughly 8%–40% of its contributing impervious drainage area.
  - Enhanced swales require a bottom width of roughly 2–8 feet.
  - Check dams are only required if the longitudinal slope is greater than 2% but must be less than 5%.
  - Requires minimum of 3 feet from bottom of swale to seasonally high water table.
- Vegetated Swale
  - A vegetated swale requires a footprint equivalent to roughly 2%–4% of its contributing impervious drainage area.
  - The flow velocity must not exceed 1 foot/second.
  - Vegetated swales must not have a bottom width greater than 10 feet.
  - Requires minimum of 2 feet from the bottom of the swale to seasonally high water table.

DESIGN GUIDELINES AND CONSIDERATIONS

- Enhanced Swale
  - Landscape design should specify proper grass species based on specific site, climate, soils, and hydrologic conditions. Vegetation should be chosen to only require maintenance no more than semiannually.
  - The underdrain diameter must be a minimum of 6 inches and must be placed at a minimum slope of 0.5%.
- Vegetated Swale
  - Check dams may be used to achieve velocity requirements; decrease runoff volume, rate, and velocity; and promote filtration and settling of nutrients and other pollutants.
  - Dense turf grass is recommended to promote sedimentation, filtration, and nutrient uptake to limit erosion and maintain reduced flow velocities.
  - Does not require pretreatment.

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	83-92%
Total Phosphorus	29-80%
Nitrogen	39-89%
Copper	46%
Metals	88-90%
Zinc	63%
Oil/Grease	75%

Sources: [7,8]

COST CONSIDERATIONS

Costs will vary between the different variations of swales; however, an estimated construction cost of vegetated swales is roughly between $0.85 to $2.30 per cubic foot of storage capacity, or between $25,000–$50,000 per acre of impervious surface treated. Operation and maintenance costs are roughly 3% of construction costs between $500–$1,500 per acre of impervious surface treated. A 2012 Study by the San Diego Stormwater Urban Mitigation Plan estimated that annual maintenance costs for a vegetated swale ranged from $1,476 to $2,623.

OPERATION AND MAINTENANCE

Maintenance primarily involves litter control and maintaining vegetation and plant cover. Other maintenance activities include the following:

- Inspect areas for clogging; clean as necessary.
- Remove accumulated trash and debris.
- Inspect and correct erosion problems.
- Remove sediment buildup from the bottom of the swale if accumulation reaches 25% of the original design volume.
- Mow grass to maintain a height of 3–4 inches.

SIZING PROCEDURE

Enhanced Swale

1. Determine the Water Quality Volume (WQV) that will need to be treated by the LID BMP.

   $$WQV = P \, x \, C \, x \, AT \, x \, 3630$$

   Where WQV = Water Quality Volume (ft^3)
   P = Design Storm Runoff Depth (1 inch)
   C = Volumetric Runoff Coefficient
   A_T = Treatment Area (acres)
   3630 = Conversion Factor

2. C = 0.05 + 0.009I

   Where C = Volumetric Runoff Coefficient
   I = Percent of Impervious Cover

3. Pretreatment is critical to capture sediment that may clog the soil media. Size the pretreatment forebay assuming a volume equal to 10% of the WQV. The forebay's volume counts toward the WQV requirement.

   $$VP = 0.1 \, x \, WQV$$

   Where V_P = Pretreatment Forebay Volume (ft^3)
   WQV = Water Quality Volume (ft^3)

4. Select a design ponding depth (d_p) and determine the thickness and porosity for the planting media and drainage layer. Calculate the total effective storage depth (d_t) following the equation below.

$$d_t = d_p + (d_m n_m) + (d_d n_d)$$

Where d_t = Total Effective Storage Depth (ft)
d_p = Ponding Depth (ft)
d_m = Planting Media Depth (ft)
n_m = Planting Media Porosity
d_d = Drainage Layer Depth (ft)
n_d = Drainage Layer Porosity

Assume:
- Total effective storage depth (d_t) is based on the storage capacity using the void space in the planting media and drainage layer and the ponding depth.
- Maximum ponding depth (d_p) if check dams are used: 1 foot.
- Average ponding depth: 0.5 feet (half of maximum ponding depth).
- Planting media depth (d_m) = 1.5 to 3 feet (typical)
- Planting media porosity (n_m) = 0.2 to 0.35 (typical)
- Drainage layer depth (d_d) = 8 to 12 inches (typical)
- Drainage layer porosity = 0.3 to 0.4 (typical)

5. Calculate the required bottom surface area of the bioretention facility (A_f). Since the pretreatment forebay is sized for 10% of the WQV, the surface is calculated based on the remaining 90% of the WQV.

$$A_b = \frac{0.9 \times WQV}{d_t}$$

Where A_b = Swale Bottom Area (ft^2)
WQV = Water Quality Volume (ft^3)
d_t = Total Effective Storage Depth (ft) from Step 4.

6. Calculate the total area required (A_{BMP}) to ensure adequate space is available.

$$A_{BMP} = \left[b + 2z\left(\frac{d_p}{12} + f\right)\right] \times \frac{A_b}{b}$$

Where A_{BMP} = Total Surface Area (ft^2)
b = Bottom Width (ft)
z = Swale Side Slope (length per unit height)
A_b = Swale Bottom Area from Step 5 (ft^2)
d_p = Design Ponding Depth from Step 4 (in)
f = Freeboard (ft)

Assume:
- Swale side slope (z): 3H:1V (typical) and 2H:1V (maximum).
  - Horizontal:Vertical
- Minimum freeboard (f): 1 foot

- Minimum bottom width (b): 2 feet to ensure adequate surface area for filtration and to facilitate mowing during maintenance.
- Maximum bottom width (b): 10 feet to reduce land disturbance area.

Vegetated Swale

1. Determine the Water Quality Flow Rate (WQFR).

$$WQFR = C \times i \times A_T$$

Where WQFR = Water Quality Flow Rate (cfs)
C = Runoff Coefficient (from Table below)
i = Rainfall Intensity (in/hr) = 0.4 in/hr
A_T = Treatment Area (acres)

Type of Surface or Condition	Runoff Coefficient (C)
Concrete pavement	0.80
Asphalt pavement	0.70
Gravel roadways or shoulders	0.50
Pervious concrete	0.10 – 0.60
Porous asphalt	0.10 – 0.55
Grass	0.10
Grid pavements with grass or aggregate	0.10

2. Assuming a trapezoidal swale, determine initial dimensions based on Manning's equation.

$$A \times R^{2/3} = \frac{WQFR \times n}{1.49 \times s^{1/2}}$$

Where A = Cross Sectional Area (ft^2)
R = Hydraulic Radius (ft)
WQFR = Water Quality Flow Rate (cfs)
n = Manning's roughness coefficient
s = Longitudinal Slope (ft/ft)

Assume:
- Manning's roughness coefficient (n): 0.15 for medium grass, 0.25 for dense grass, and 0.35 for very dense Bermuda-type grass.
- Longitudinal slope (s): 2 to 6%

3. Use the following equations to calculate the cross-sectional area (A) and hydraulic radius (R) and solve for the bottom width (b)which will be the only remaining unknown variable.

$$A = (b + zy) \times y$$

$$R = \frac{(b + zy) \times y}{b + 2y\sqrt{1 + z^2}}$$

Where b = Bottom Width (ft)
z = Swale Side Slope (length per unit height)
y = Depth of Flow (ft)

Assume:

- Minimum bottom width (b): 2 feet to ensure adequate surface area for filtration and to facilitate mowing during maintenance.
- Maximum bottom width (b): 10 feet to reduce land disturbance area.
- Swale side slope (z): 3H:1V (typical) and 2H:1V (maximum).
- Depth of flow (y): 4 inches (0.33 feet) for swales that are mowed infrequently.

If the calculated bottom width falls outside of this range, decrease the tributary area and/or adjust one or more swale dimensions and repeat the calculations.

4. Calculate the design flow rate (Q) based on the resulting bottom width (b) and assumed swale dimensions from Step 2 and 3 using Manning's equation.

$$Q = \frac{1.49}{n} \times A \times R^{2/3} \times s^{1/2}$$

5. Determine the design flow velocity (V) using the flow continuity equation.

$$V = \frac{Q}{A}$$

Where V = Design Flow Velocity (ft/s)
Q = Design Flow Rate (cfs)
A = Cross-Sectional Area (ft^2)

Assume:

- Maximum design flow velocity (V): 1 ft/s at WQFR.

6. Calculate the swale length (L) based on the following equation.

$$L = 60 \times VT$$

Where L = Swale Length (ft)
V = Design Flow Velocity from Step 5 (ft/s)
T = Hydraulic Residence Time (min)

Assume:

- Hydraulic residence time (T): 9 minutes
- Minimum swale length (L): 100 ft

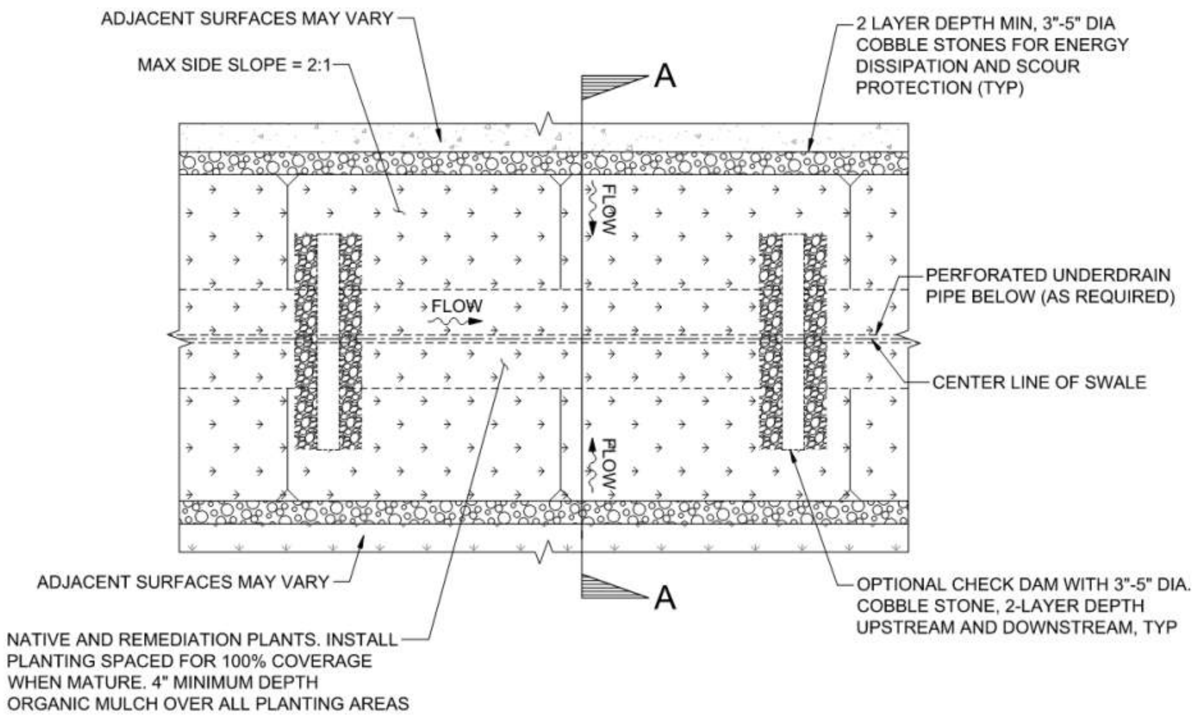
Adjust the swale dimensions as needed to achieve the recommended minimum swale length (L). If necessary, the bottom width (b) may be increased as long as the hydraulic residence time (T) remains greater than 9 minutes.

7. Calculate the total area required (A_{BMP}) to ensure adequate space is available.

$$A_{BMP} = \left[b + 2z\left(\frac{y}{12} + f\right)\right] \times L$$

Where A_{BMP} = Total Surface Area (ft^2)
b = Bottom Width (ft)
z = Swale Side Slope (length per unit height)
y = Depth of Flow from Step 3 (inches)
f = Freeboard (ft)
L = Swale Length from Step 6 (ft)

BMP DETAILS



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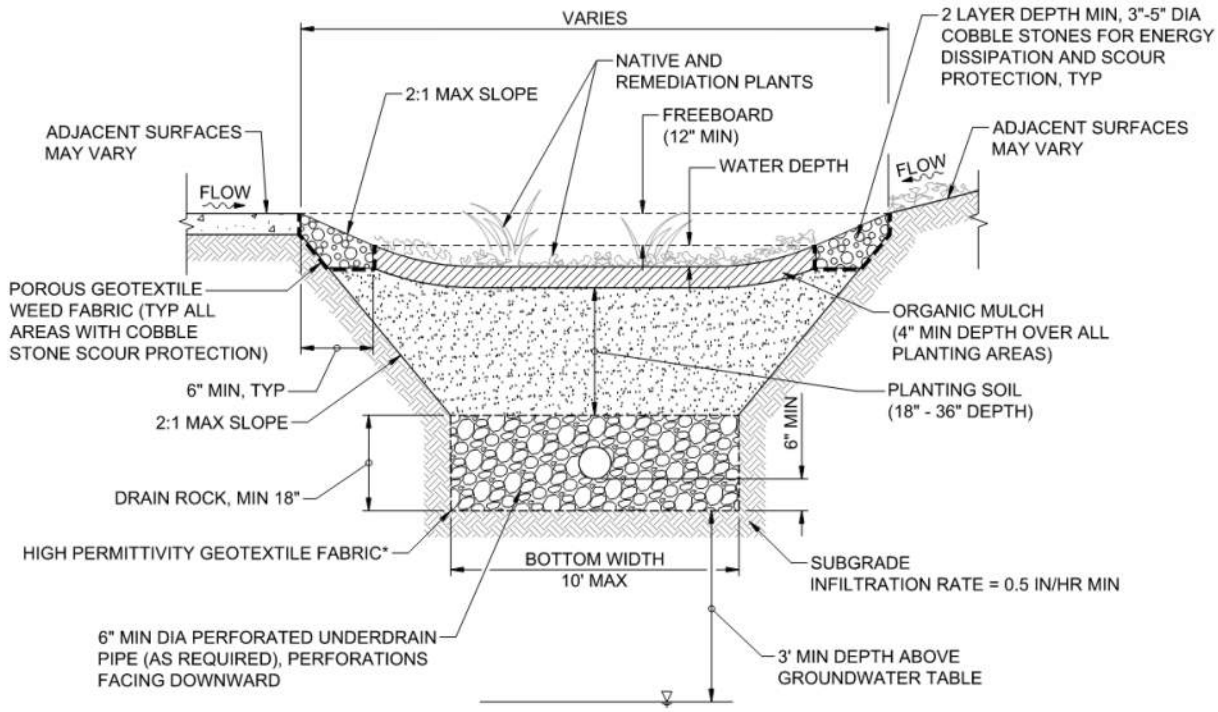

NOTE: OPTIONAL CHECK DAMS WITH COBBLE STONE SCOUR PROTECTION NOT SHOWN

*WELL-GRADED FILTER OR DRAIN ROCK MAY BE USED IN LIEU OF HIGH PERMITTIVITY GEOTEXTILE FABRIC

SECTION A-A

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Courtesy of State of Hawaiʻi Department of Transportation

VEGETATED FILTER STRIP

BMP-10

DESCRIPTION

A vegetated filter strip, sometimes referred to as a vegetated buffer strip, is a well-maintained strip of vegetation located adjacent and typically parallel to roadways or other impervious areas. They are typically vegetated with turf or native grasses and function by reducing the velocities of stormwater runoff and filtering out sediment and other pollutants via sedimentation. These strips rely on sheet flow across them, often achieved with level spreaders. Vegetated filter strips are commonly designed as pretreatment BMPs to treat runoff from impervious surfaces before reaching other BMPs such as a vegetated swale or bioretention basin.

ADVANTAGES

- Ability to filter and infiltrate stormwater runoff.
- Provides wildlife habitat while limiting cost and improving aesthetics.
- Promotes natural hydrologic balance and maintains groundwater recharge while reducing sediment load.
- Relatively easy to install and requires low maintenance.
- Effective at removing certain chemicals or heavy metals.

LIMITATIONS

- Not intended for treatment of concentrated flows.
- May be better suited in treatment trains for comprehensive stormwater management.
- Not suitable for high velocity runoff or areas with steep slopes, which may lead to erosion or damage of filter strip.
- Filter strips are not recommended in areas with limited space such as densely developed urban areas.

Minimum BMP Footprint
75 sf

Construction Cost
$$

Operations & Maintenance
Frequency: Monthly Cost: $

Design Considerations
• Water quality volume • Permeability of soil • Distance to groundwater

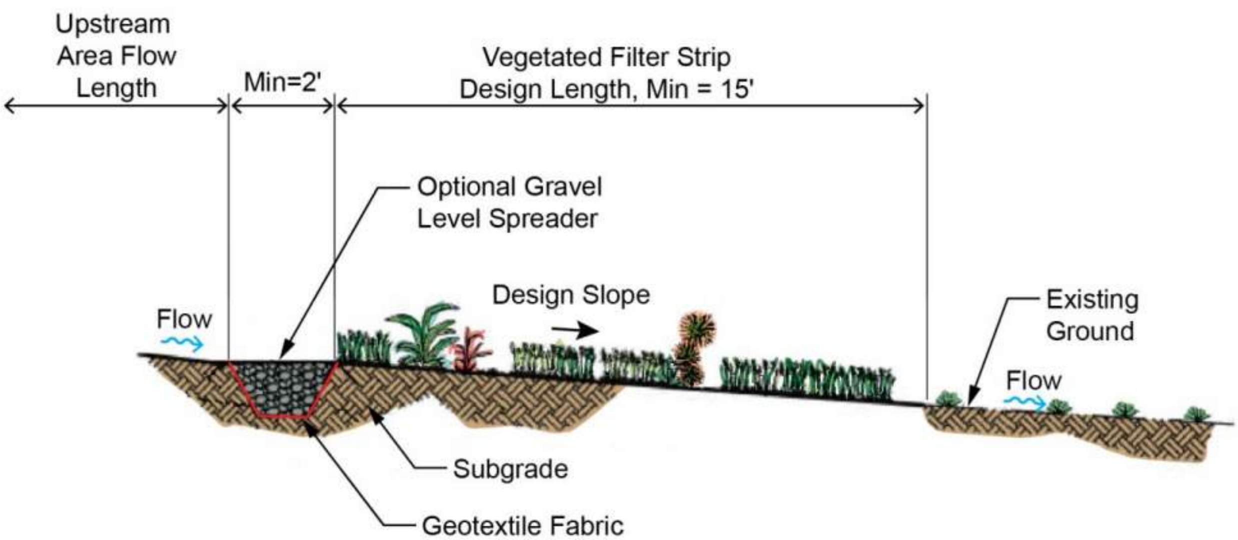
VARIATIONS

Vegetated filter strips can be planted with a wide range of different types of ground cover, including turf or native grasses.

APPLICATIONS

Vegetated filter strips primarily provide pretreatment upstream of infiltration and biofiltration BMPs. Sheet flow must be established across the filter strip to be effective. Sheet flow may be achieved through level spreaders.

Vegetated filter strips are well suited to treat runoff from roofs, driveways, parking lots, and other open impervious areas.



Vegetated Filter Strip Section View (Source: Bowers + Kubota Consulting)

SITE CONSIDERATIONS

Vegetated filter strips require a footprint equivalent to and no less than 0.4% of its contributing impervious drainage area. The maximum upstream area flow length must be 75 feet, and the minimum length is 15 feet.

The lateral slope (perpendicular to flow) must not exceed 2%, and the longitudinal slope (in the direction of flow) should range between 1% and 15%.

Vegetated filter strips may be used in potential hot spots (i.e., areas that may contain contaminated soil or groundwater) but must be planned with special design considerations to avoid spreading the contamination.

DESIGN GUIDELINES AND CONSIDERATIONS

Dense grass, preferably native grass, should be chosen based on compatibility with climate conditions, soils, and topography including its ability to tolerate urban stresses from pollutants and ponding fluctuations.

Filter strips must be protected with temporary erosion control BMPs until vegetation has been stabilized. Avoid using fertilizers that have the potential to enter receiving waters.

Berms and/or curbs can be installed along the sides of the strip, parallel to the direction of flow, to prohibit runoff from laterally bypassing the strip.

A level spreader should be provided at the upper edge of the strip to evenly distribute the runoff across the width of the filter strip. Level spreader options include a gravel trench, porous pavement strips, slotted curbing, or concrete headers. The top of the level spreader should be approximately one inch below the pavement surface.

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	86%
Total Phosphorus	66%
Nitrogen	56%

Sources: [7]

COST CONSIDERATIONS

Filter strip construction costs may range from little to no cost (assuming the area was to be grassed regardless of use as treatment) to $50,000 per acre depending on enhanced vegetation and design variations. Annual maintenance costs range from $130 to $1,800 per acre of the filter strip. Maintenance costs may be on the lower end if maintenance needs are already part of the site's existing landscape maintenance routine.

OPERATION AND MAINTENANCE

- Monitoring of recently planted vegetation to ensure that the strip is vegetated properly. Maintain a minimum of 90% grass coverage to ensure continued effectiveness.
- Repair eroded areas or scour holes caused by high flow velocities or channelization.
- Regular mowing, trimming, and watering as applicable. Grass height has little impact on pollutant removal. Mowing is only required for safety and aesthetics or to suppress weeds or woody vegetation.
- Regular inspection of the vegetation for damage.
- Removal of accumulated sediment and debris at the toe, the berm, and the strip itself. Monitoring sediment accumlation is important to ensure that sheet flow is consistent and that no preferential flow paths develop.
- Adjust or replace level spreader if flows are not evenly distributed over the entire width of filter strip.
- Remove trash and debris as required to prevent clogging downstream BMPs and facilities.

SIZING PROCEDURE

1. Determine the Water Quality Flow Rate (WQFR).

   $$WQFR = C \times i \times A_T$$

   Where WQFR = Water Quality Flow Rate (cfs)
   C = Runoff Coefficient (from Table below)
   i = Rainfall Intensity (in/hr) = 0.4 in/hr
   A_T = Treatment Area (acres)

Type of Surface or Condition	Runoff Coefficient (C)
Concrete pavement	0.80
Asphalt pavement	0.70
Gravel roadways or shoulders	0.50
Pervious concrete	0.10–0.60
Porous asphalt	0.10–0.55
Grass	0.10
Grid pavements with grass or aggregate	0.10

2. Determine the filter strip width (w), which is typically equal to the width of the adjacent impervious surface contributing flow to the filter strip. If the width of the filter strip (w) is less than the adjacent impervious surface, provide a transition to direct the runoff evenly across the filter strip width.

3. Determine the longitudinal slope (s) based upon the proposed site conditions.

4. Compute the design flow depth (y) based upon the width (w) and longitudinal slope (s) of the filter strip using a simplified form of Manning's Equation, as follows.

   $$y = \left[\frac{WQFR \times n}{1.49 \times w \times \sqrt{s}}\right]^{0.6}$$

   Where y = Depth of Flow (ft)
   WQFR = Water Quality Flow Rate (cfs)
   n = Manning's roughness coefficient
   w = Width perpendicular to direction of flow (ft)
   s = Longitudinal Slope parallel to direction of flow (ft/ft)

   Assume:
   - Manning's roughness coefficient (n): 0.15 for medium grass, 0.25 for dense grass, and 0.35 for very dense Bermuda-type grass.
   - Maximum depth of flow (y): 1 inch.

If the depth of flow (y) exceeds the maximum depth allowed, reduce the tributary drainage area of the impervious surface and/or increase the filter width (w) or longitudinal slope (s) and recalculate.

5. Calculate the design flow velocity (V) across the filter strip based on the following equation.

$$V = \frac{WQFR}{wy}$$

Where V = Design Flow Velocity (ft/s)
WQFR – Water Quality Flow Rate (cfs)
w = Design Width (ft)
y = Depth of Flow (ft)

Assume:
- Maximum design flow velocity (V): 1 ft/s

If the design flow velocity (V) is greater than 1 ft/s, redesign the filter strip by adjusting one or more design parameters and recalculate. A velocity greater than 1 ft/s will flatten grass, thereby reducing filtration.

6. Calculate the filter strip length (L) based on the following equation:

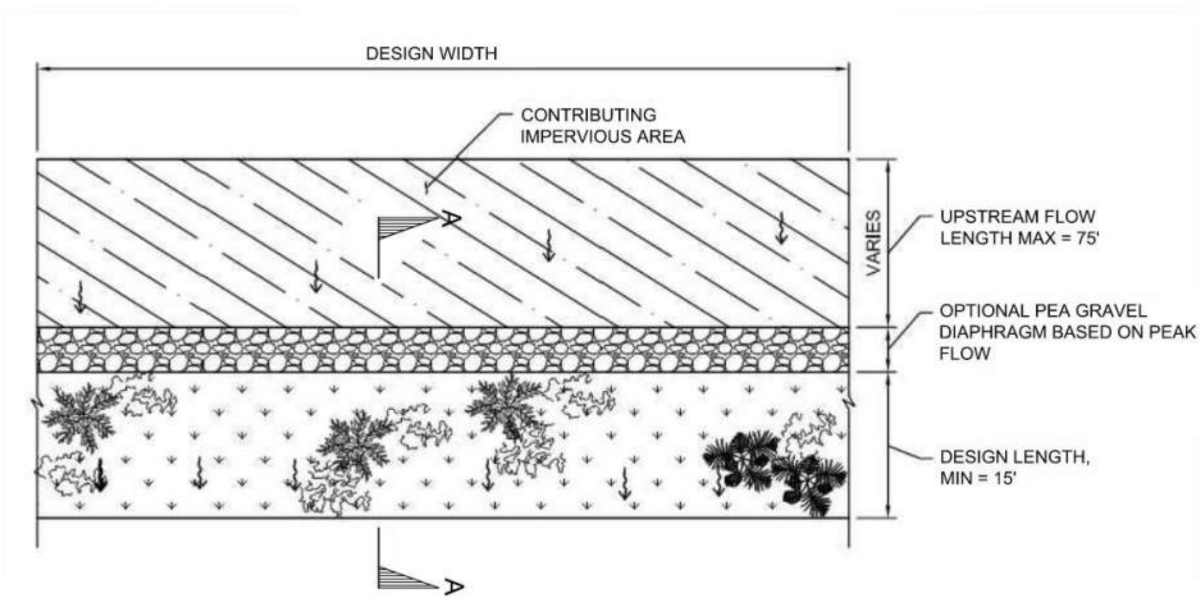
$$L = 60 \times VT$$

Where L = Design Length (L)
V = Design Flow Velocity from Step 5 (ft/s)
T = Hydraulic Residence Time (min)

Assume:
- Hydraulic residence time (T): 9 minutes
- Minimum length (L): 15 feet to provide filtration and contact time
- Maximum length (L): 100 feet

Ensure that the proposed site can accommodate the required filter strip length (L); otherwise, redesign the filter strip or explore other LID BMP options.

BMP DETAILS



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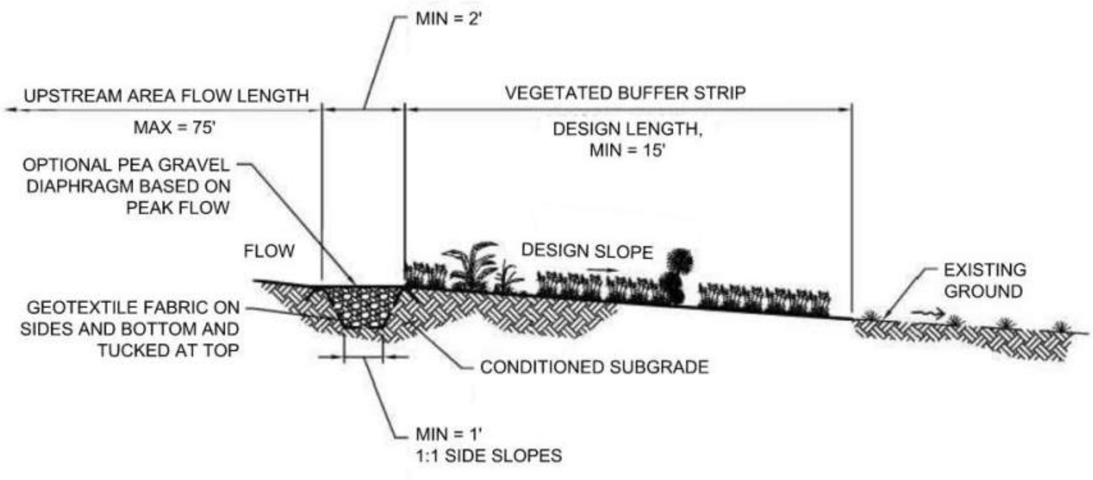
MIN = 2'
UPSTREAM AREA FLOW LENGTH
MAX = 75'
VEGETATED BUFFER STRIP
DESIGN LENGTH,
MIN = 15'
OPTIONAL PEA GRAVEL
DIAPHRAGM BASED ON
PEAK FLOW
FLOW
DESIGN SLOPE
EXISTING
GROUND
GEOTEXTILE FABRIC ON
SIDES AND BOTTOM AND
TUCKED AT TOP
CONDITIONED SUBGRADE
MIN = 1'
1:1 SIDE SLOPES

SECTION A-A

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Detention Basin in Mililani, Oʻahu, Hawaiʻi (Courtesy of WSP)

DETENTION BASIN

BMP-11

DESCRIPTION

A detention basin is a spacious, shallow reservoir, or excavated pit constructed to temporarily detain stormwater runoff and help prevent downstream flooding. The temporary storage of water allows particles to settle. Typically, a detention basin does not have a permanent pool of water.

ADVANTAGES

- Cost-effective BMP for controlling both stormwater quantity and quality.
- Reduces peak discharge and runoff volume.
- Mitigates downstream flooding.
- Controls channel erosion.
- Provides water quality benefits by reducing the amount of sediment and debris in the receiving water.
- Vegetated basins can enhance the landscape and provide recreational spaces for public enjoyment.
-

LIMITATIONS

- Not practical for drainage areas less than five acres because scaled-down outlet structures for smaller catchment areas tend to clog.
- Infeasible in locations with a high groundwater table.
- Excavation may disturb archaeological resources.
- May provide limited removal of metals, nutrients, and pathogens.
- Siting is constrained due to lack of available land area.

Minimum BMP Footprint
400 sf

Construction Cost
$$ - $$$

Operations & Maintenance
Frequency: Semi-Annually Cost: $$

Design Considerations

- Interior side slope
- Length to width ratio
- Basin depth
- Time to drain basin
- Basin invert slope
- Outlet size
- Freeboard (Distance from dam crest to max. water surface)

VARIATIONS

The conventional detention basin is the dry extended detention basin, which is designed to drain down over a specified period and remain dry between storm events. These types of basins are typically equipped with an outlet structure or control device to regulate the discharge of water. Other variations of the detention basin include wet ponds, constructed wetlands, and underground detention. Wet ponds have a permanent pool for water quality treatment and can be effective for pollutant removal and peak rate mitigation. Wet ponds also provide aesthetic and wildlife benefits. Constructed wetlands are shallow marsh systems designed to treat stormwater runoff. They are planted with emergent vegetation and can provide significant wildlife benefits. Constructed wetlands are one of the best BMPs for pollutant removal; however, they require a relatively large amount of space. Underground detention systems are often used for sites where space is limited. Underground detention systems can be constructed by excavating a broad area and filling it with uniformly graded aggregate or by using prefabricated underground vaults constructed of materials such as reinforced concrete or high-density polyethylene. Runoff is stored in the vaults or within the void spaces of the aggregate while the vault or aggregate bed is designed with withstand the surface loads such as vehicular traffic. Detention basins work well to provide storm runoff peak rate attenuation but provide minimal water quality treatment when compared to the LID BMPs in this guide. Consequently, detention basins should be used in conjunction with a pretreatment BMP and/or downstream treatment BMP.

APPLICATIONS

Detention basins are often applicable in rural areas as well as in residential, industrial, and commercial developments, provided ample space is available and contaminated runoff or soil is not present. Their implementation may be constrained in densely urbanized areas and certain redevelopment endeavors, primarily due to space constraints. In such cases, alternatives like underground detention or infiltration may be employed. Residential development, industrial development, commercial development, and urban areas can readily use underground systems.

SITE CONSIDERATIONS

- Position basins downhill from disturbed or developed areas on the site. Ensure that the basins capture as much site runoff as practicable, particularly from impervious surfaces like roads, parking lots, and buildings and when other BMPs will not be used.
- Avoid constructing basins on steep slopes, and refrain from altering or modifying slopes significantly to create a basin.
- Do not exacerbate runoff potential by removing trees to install a basin.

DESIGN GUIDELINES AND CONSIDERATIONS

- Detention basins are commonly used for drainage areas ranging from five to 50 acres, on land with slopes of less than 20 percent.
- Design detention basins to alleviate peak runoff rates for rainfall events ranging from one-year to 100-year occurrences.
- Incorporate an emergency outlet or spillway capable of handling the 100-year peak design flow.
- Ensure that detention basins can treat the runoff volume generated by the water quality design storm, unless supplementary upstream BMPs are in place.

- The lowest point in a detention basin should sit at least three feet above the seasonal high water table. If high water table conditions are expected, consider designing a wet pond or constructed wetland.
- Keep maximum water depth of the basins under eight feet.
- Distance from the basin inlet to the outlet should be maximized.
- Address mosquito control.
- Ensure that the side slopes are sufficiently shallow so that pedestrians can walk out of the basin easily.
- Consider fencing or other protective measures to ensure that pedestrians do not inadvertently enter the basin, unless the basin has been designed to serve the dual purposes of stormwater management and recreation.
- Consider signage to warn pedestrians about entering the detention basin.

EFFECTIVENESS AND POLLUTANT REMOVAL

Pollutant	Pollutant Removal Rates
Total Suspended Solids	20–70%
Total Phosphorus	15–25%
Nitrogen	5–30%
Copper	20–40%
Zinc	0–60%
Bacteria	25–50%
Hydrocarbons	40–80%
Trash/Debris	65–85%

Source: [13]

COST CONSIDERATIONS

In one recent study, the University of New Hampshire (UNH) Stormwater Center worked in collaboration with EPA Region I and other partners to estimate the cost of stormwater BMPs [10]. The approximate cost for a dry detention basin would be approximately $7–$21 per cubic foot.

Annual routine operation and maintenance costs (O&M) generally range from 5 to 10 percent of the total construction cost [5]. A 2012 study produced by the County of San Diego estimated the annual O&M cost for a dry detention basin with grass/vegetated lining ranged from $2,433 for a small basin to $4,724 for a large basin corresponding to 25.8 and 53.0 annual maintenance hours, respectively [5].

The costs referenced above are expected to be higher in Hawaiʻi.

OPERATION AND MAINTENANCE

Detention facilities need a maintenance plan, and privately owned ones should have legal safeguards like an easement or deed restriction to prevent neglect or removal. For underground detention systems, regular sediment and debris removal are vital maintenance activities. Maintenance includes inspecting and cleaning all catch basins, inlets, and pretreatment devices upstream of the underground detention basin at least twice a year. The underground detention basin and its outlet should be inspected annually and cleaned when necessary.

A maintenance plan for the basin should be established, encompassing the following tasks:

- All basin structures should be inspected for clogging and excessive debris and sediment accumulation at least four times per year and after every storm greater than one inch of rain. Structures that should be inspected include basin bottoms, trash racks, outlet structures, riprap or gabion structures, and inlets.
- Sediment should be removed from the forebay before it occupies 50 percent of the forebay, typically every 3 to 10 years. Sediment removal should be conducted when the basin is completely dry.
- Wet ponds and constructed wetlands should be drained prior to sediment removal. Sediment should be disposed of properly. Once sediment is removed, disturbed areas need to be immediately stabilized and revegetated. Proper disposal of removed material depends on the nature of the drainage area and the intent and function of the system.
- Mowing and/or trimming of vegetation should be performed as necessary to sustain the system, but all detritus must be removed from the basin. The embankment should be mowed 1–2 times per year to prevent the establishment of woody vegetation.
- Inspections should assess the vegetation, erosion, flow channelization, bank stability, inlet and outlet conditions, embankment, and sediment and debris accumulation.
- Vegetated areas should be inspected annually for unwanted growth of invasive species.
- Vegetative cover should be maintained at a minimum of 85 percent.

SIZING PROCEDURE

1. Compute the pre-project (i.e., undeveloped) and post-project (i.e., developed) weighted runoff coefficients.

$$C_c = (\sum_{i=1}^{n} C_i A_i)\ /A_t$$

Where C_c = Composite Weighted Runoff Coefficient
$C_{1,2,..n}$ = Runoff Coefficient for each Land Use Cover Type
$A_{1,2,..n}$ = Drainage Area to each Land Use Cover Type (acres)
A_t = Total Drainage Area (acres)

Type of Surface or Condition	Runoff Coefficient (C)
Roofs	0.90
Concrete	0.80
Stone, brick, or concrete pavers with mortared joints and bedding	0.80
Asphalt	0.70
Stone, brick, or concrete pavers with sand joints and bedding	0.70
Pervious concrete	0.10
Porous asphalt	0.10
Permeable interlocking concrete pavement	0.10
Grid pavements with grass or aggregate surface	0.10
Crushed aggregate	0.10
Grass	0.10
Grass over Porous Plastic	0.05
Gravel over Porous Plastic	0.05

2. Compute the peak inflow rate using the Rational Method:

   $$q_i = C_a i A$$

   Where q_i = Peak Inflow Rate into Basin (ft^3)
   C_a = Post-Project Weighted Runoff Coefficient
   i = Peak Rainfall Intenisty (in/hr)
   A = Drainage Area (acres)

3. Compute the peak outflow rate using the pre-project runoff coefficient, which effectively forces the detention basin to maintain pre-project discharge rates:

   $$q_o = C_b i A$$

   Where q_o = Peak Inflow Rate leaving Basin (ft^3)
   C_b = Pre-project Weighted Runoff Coefficient
   i = Peak Rainfall Intensity (in/hr)
   A = Drainage Area (acres)

4. Calculate the estimated basin storage volume:

   $$s = 3{,}630 \times PA\left[1 - \left(\frac{q_o}{q_i}\right)\right]$$

   Where s = Storage Volume in the Basin (ft^3)

P = Design Storm Runoff Depth (in)
A = Drainage Area (acres)
q_o = Peak Outflow Rate from Step 3 (ft^3)
q_i = Peak Inflow Rate from Step 2 (ft^3)

5. Select initial values for the detention basin total width (w_t), total length (l_t), and depth (d) based on space availability, topography, and existing drainage facilities. Also select values for the interior side slopes (z) and required freeboard (f). Calculate the basin invert width and invert length:

$$w_b = w_t - 2z(d + f)$$

$$l_b = l_t - 2z(d + f)$$

Where w_b = Basin Bottom Width (ft)
l_b = Basin Bottom Length (ft)
w_t = Basin Total Width (ft)
l_t = Basin Total Length (ft)
z = Basic Interior Side Slope (length per unit height)
d = Depth of Flow for Storage Volume (ft)
f = Freeboard (ft)

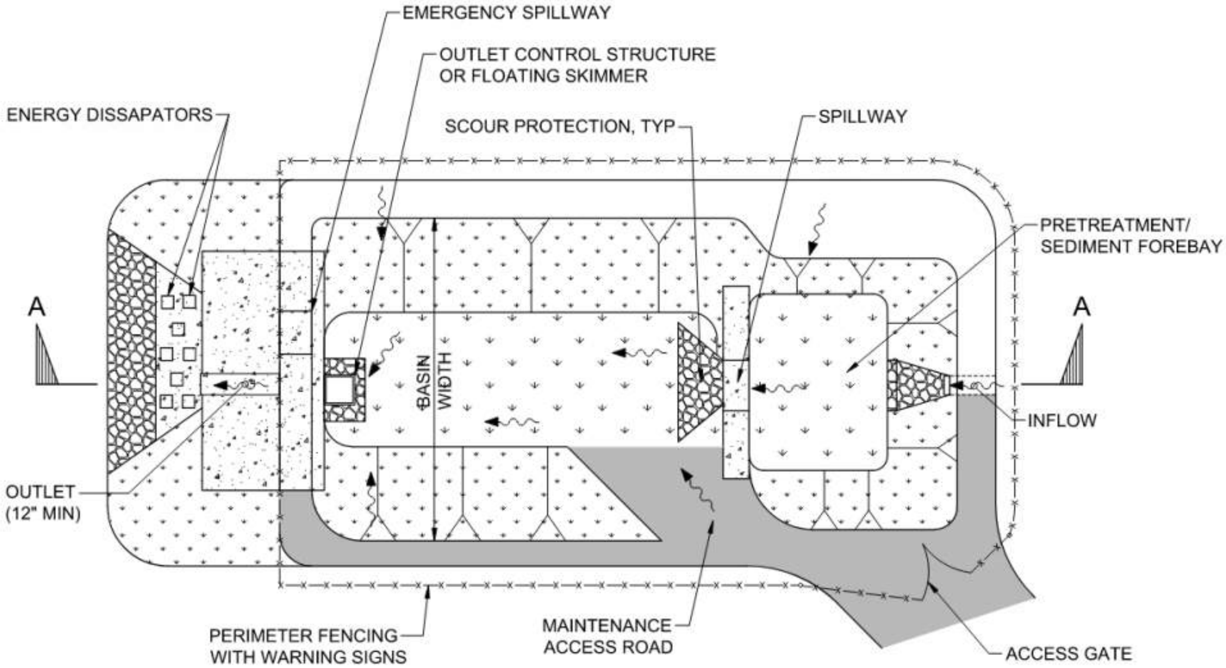
6. Calculate the resulting storage volume using the prismoidal formula for trapezoidal basins:

$$V = w_b l_b d + (w_b + l_b) z d^2 + 4z^2 d^3/3$$

Where V = Volume of Trapezoidal Basin (ft^3)
w_b = Basin Bottom Width from Step 5 (ft)
l_b = Basin Bottom Length from Step 5 (ft)
d = Depth of Flow for Storage Volume form Step 5 (ft)
z = Basin Interior Side Slope from Step 5

Compare the calculated volume (V) to the required volume (s) from Step 4. If the calculated volume is greater than or equal to the required volume, the selected dimensions (w_t and l_t) and depth (d) are adequate for preliminary design. If the calculated volume is less than the required volume, increase one or both dimensions and/or the depth (d) and repeat Steps 5 and 6. If the footprint area and depth are set to maximum allowable values based on site characteristics and the calculated volume is still less than the required volume, reduce the drainage area (A) and repeat Steps 2 through 6.

BMP DETAILS



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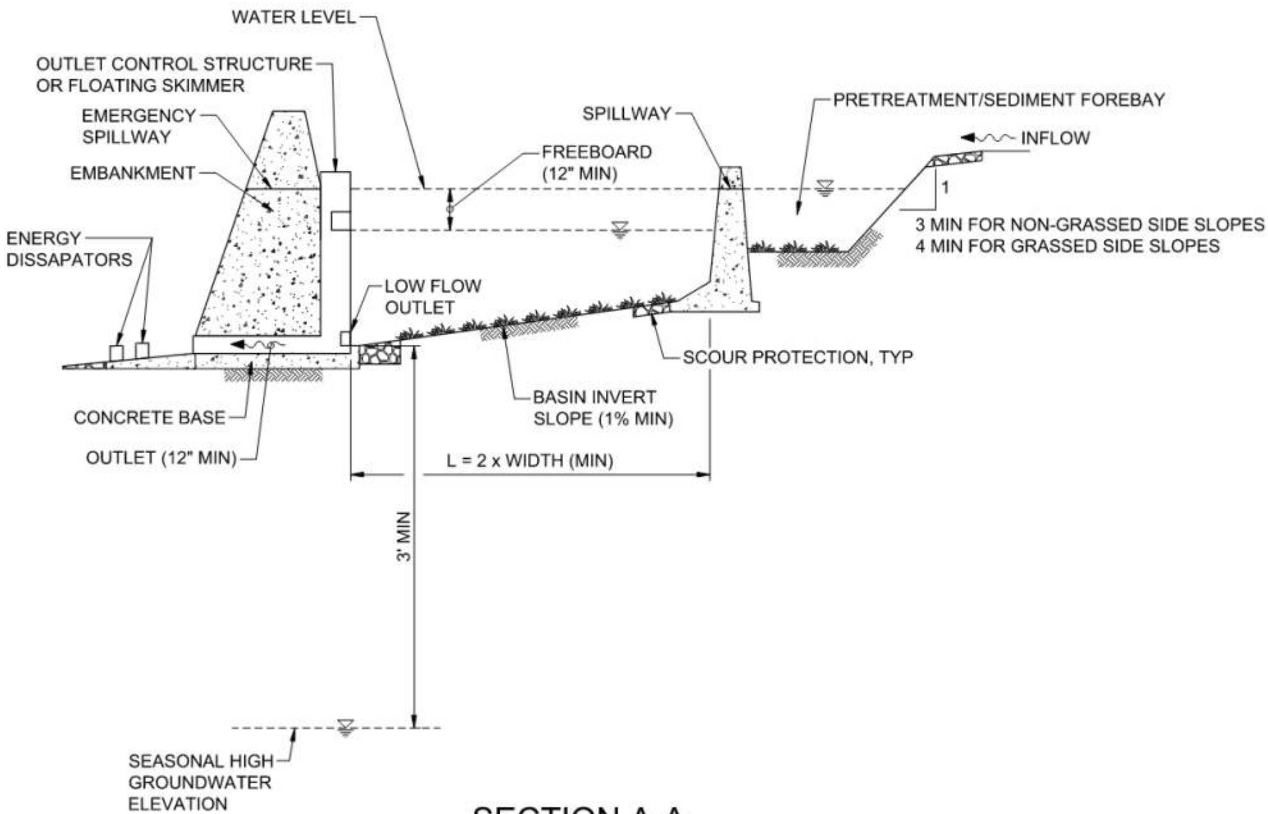
WATER LEVEL
OUTLET CONTROL STRUCTURE
OR FLOATING SKIMMER
EMERGENCY
SPILLWAY
EMBANKMENT
ENERGY
DISSAPATORS
SPILLWAY
FREEBOARD
(12" MIN)
PRETREATMENT/SEDIMENT FOREBAY
INFLOW
1
3 MIN FOR NON-GRASSED SIDE SLOPES
4 MIN FOR GRASSED SIDE SLOPES
LOW FLOW
OUTLET
SCOUR PROTECTION, TYP
CONCRETE BASE
BASIN INVERT
SLOPE (1% MIN)
OUTLET (12" MIN)
L = 2 x WIDTH (MIN)
3' MIN
SEASONAL HIGH
GROUNDWATER
ELEVATION

SECTION A-A

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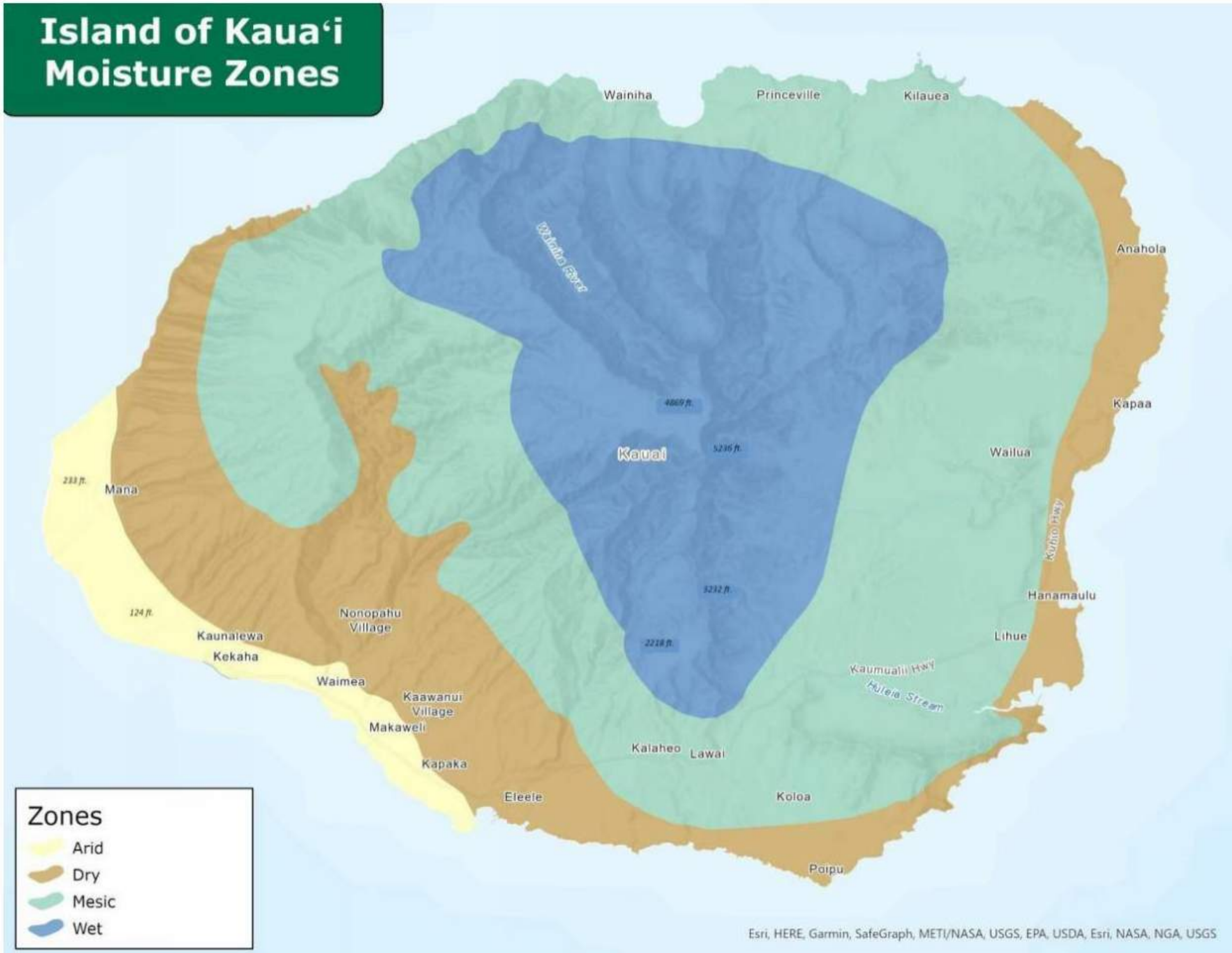
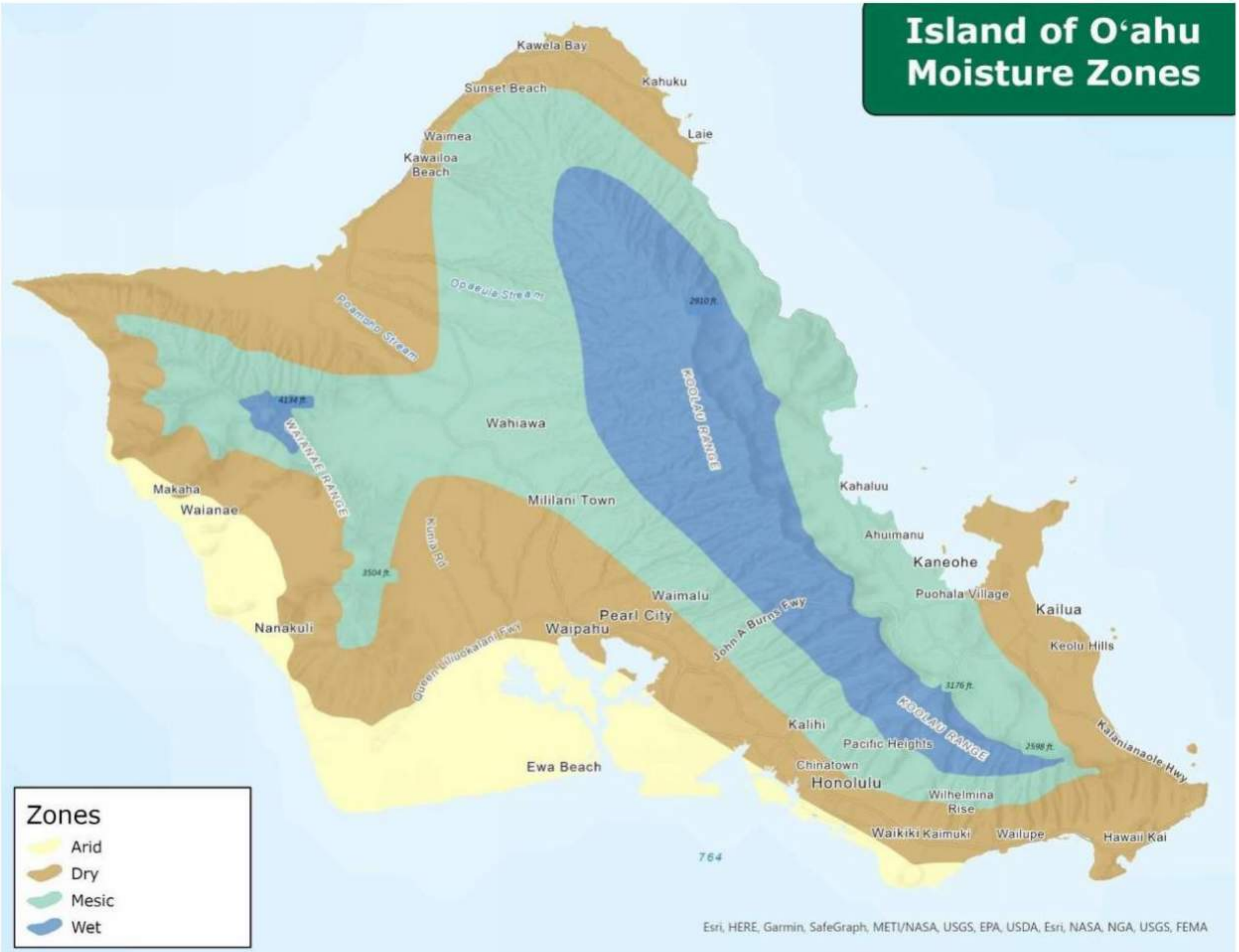
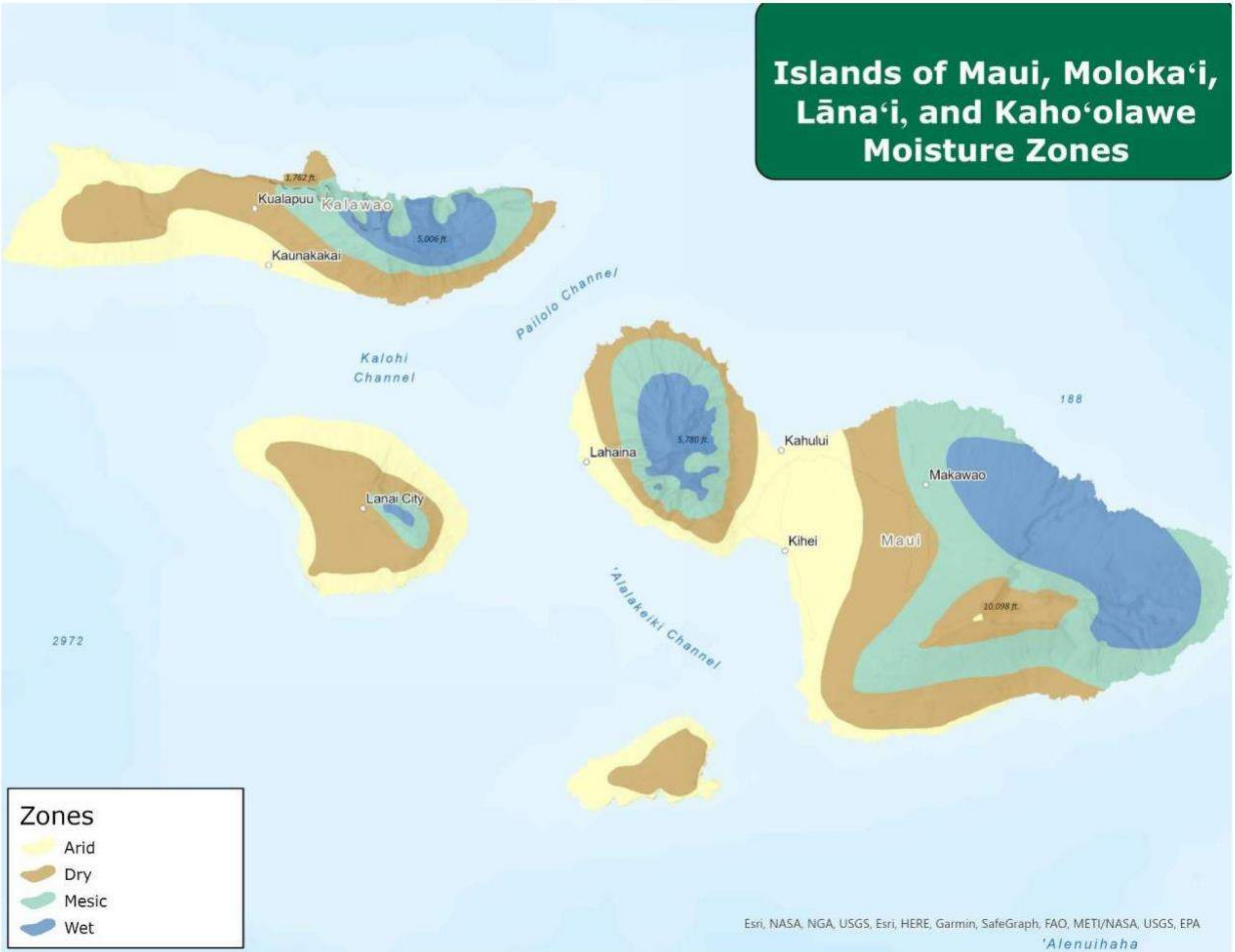
APPENDIX B MOISTURE ZONES AND PLANT LISTS

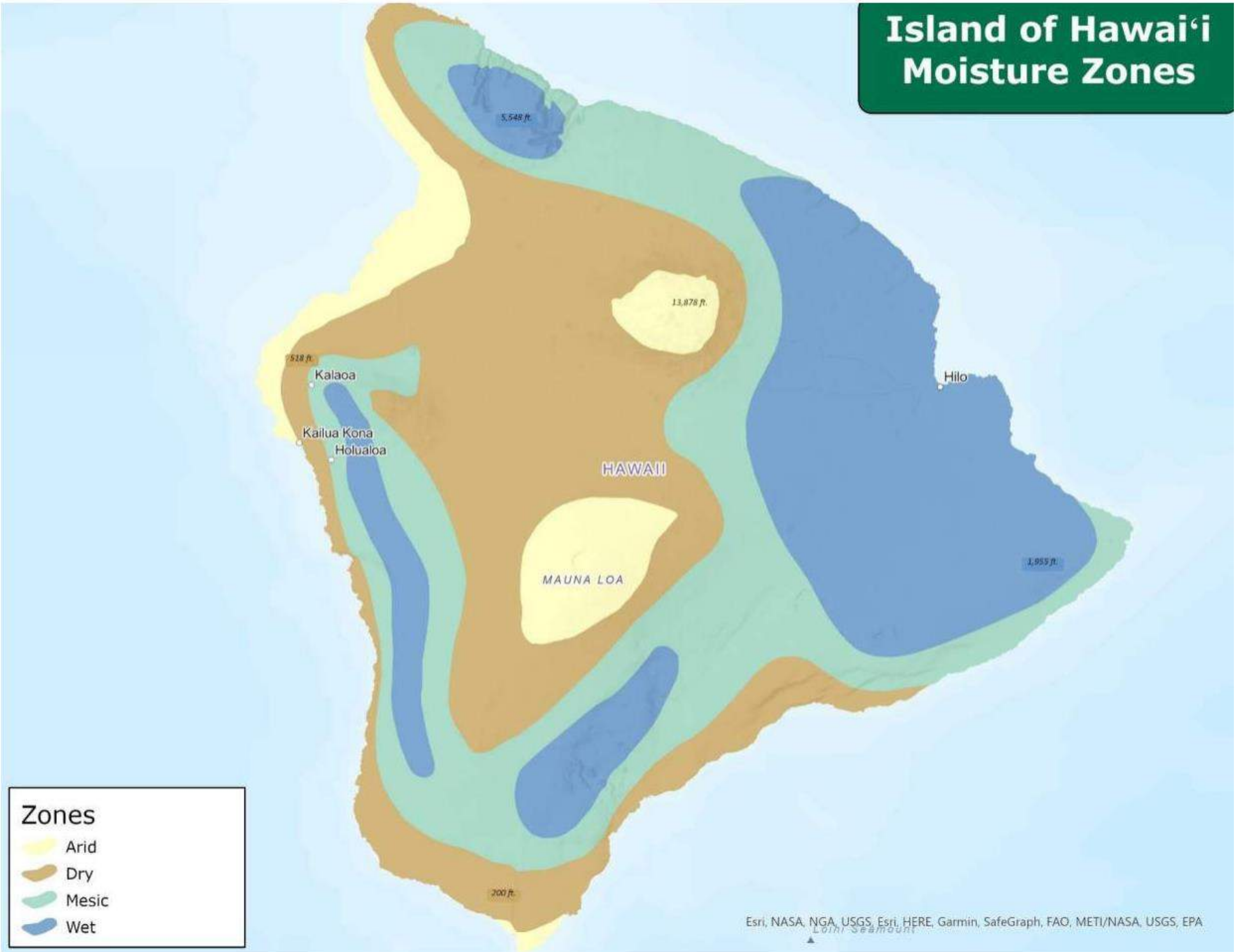
MOISTURE ZONES



Island of Kauaʻi
Moisture Zones
Wainiha
Princeville
Kilauea
Anahola
Kapaa
Wailua
Kuhio Hwy
Hanamaulu
Lihue
Kaumualii Hwy
Huleia Stream
4869 ft.
5236 ft.
Kauai
3232 ft.
2218 ft.
233 ft.
Mana
124 ft.
Kaunalewa
Kekaha
Nonopahu Village
Waimea
Kaawanui Village
Makaweli
Kapaka
Eleele
Kalaheo
Lawai
Koloa
Poipu
Zones
Arid
Dry
Mesic
Wet
Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, EPA, USDA, Esri, NASA, NGA, USGS


Island of O'ahu
Moisture Zones
Kawela Bay
Kahuku
Sunset Beach
Waimea
Laie
Kawailoa Beach
Opaeula Stream
Poamoho Stream
2910 ft.
KOOLAU RANGE
4134 ft.
WAIANAE RANGE
Wahiawa
Makaha
Waianae
Kunia Rd
Mililani Town
Kahaluu
Ahuimanu
Kaneohe
3504 ft.
Waimalu
Puohala Village
Kailua
Pearl City
Nanakuli
Queen Liliuokalani Fwy
Waipahu
John A Burns Fwy
Keolu Hills
3176 ft.
KOOLAU RANGE
Kalihi
Pacific Heights
2598 ft.
Kalanianaole Hwy
Ewa Beach
Chinatown
Honolulu
Wilhelmina Rise
Waikiki
Kaimuki
Wailupe
Hawaii Kai
764
Zones
Arid
Dry
Mesic
Wet
Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, EPA, USDA, Esri, NASA, NGA, USGS, FEMA


Islands of Maui, Moloka'i, Lāna'i, and Kaho'olawe Moisture Zones
1,762 ft.
Kualapuu
Kalawao
5,006 ft.
Kaunakakai
Pailolo Channel
Kalohi Channel
188
Kahului
5,780 ft.
Lahaina
Makawao
Lanai City
Kihei
Maui
'Alalakeiki Channel
10,098 ft.
2972
Zones
Arid
Dry
Mesic
Wet
Esri, NASA, NGA, USGS, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA
'Alenuihaha


Island of Hawai'i
Moisture Zones
5,548 ft.
13,878 ft.
518 ft.
Kalaoa
Kailua Kona
Holualoa
Hilo
HAWAII
MAUNA LOA
1,955 ft.
200 ft.
Zones
Arid
Dry
Mesic
Wet
Esri, NASA, NGA, USGS, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA

WET AND DRY CLIMATE PLANTS

‘A‘ali‘i H
Dodonaea viscosa

‘Āhinahina H
Artemisia mauiensis

‘Akoko H
Euphorbia celastroides

‘Āweoweo H
Chenopodium oahuensis

Hinahina ewa H
Achyranthes splendens

‘Ihi L
Portulaca villosa

‘Ilima H
Sida fallax

Kāwelu M
Eragrostis Variabilis

Kulu‘ī H
Nototrichium humile sandwicense

Maiapilo H
Capparis sandwichiana

Naio papa H
Myoporum sandwicenses

‘Ohai M
Sesbania Tomentosa

‘Ōhelo kai M
Lycium sandwicense

Pā‘ūohi‘iaka L
Jacquemontia ovalifolia

Pōhinahina H
Vitex rotundifolia

Pōhuehue L
Ipomea pes-caprae

‘Ūlei H
Osteomeles anthyllidifolia

DRY CLIMATE PLANTS

L Plants under 12″ height
M Plants between 12″ - 36″ height
H Plants over 36″ height

ʻAhuʻawa M
Cyperus javanicus

ʻĀkia H
Wikstroemia uva-ursi

ʻĀkulikuli L
Sesuvium portulacastrum

Carex M
Carex wahuensis

ʻIlieʻe H
Plumbago zeylanica

Kokiʻo keʻokeʻo H
Hibiscus arnottianus

Koʻokoʻolau H
Bidens menziesii

Kupukupu M
Nephrolepis cordifolia