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SERIES

LATIS

VEGETATED SWALES



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Vegetated Swales

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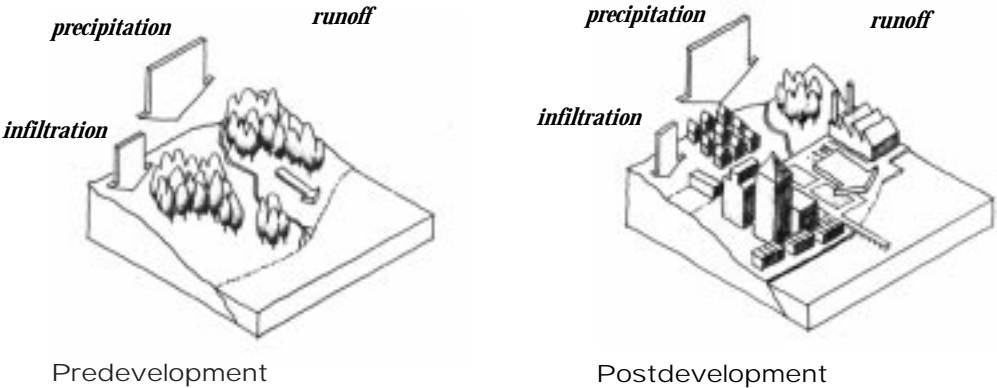
Self-Study Exam

The Hydrologic Cycle

In its natural condition, soil is covered with a complex matrix of mulch and roots that allow rainwater to infiltrate slowly into the soil. Because most rainstorms are not large enough to fully saturate the soil, only a small percentage of annual rainwater flows over the surface as runoff. What does become runoff usually travels at a slow, meandering pace allowing suspended particles and sediments to settle. In the natural condition, this process, known as the hydrologic cycle, creates a stable supply of groundwater, and runoff is naturally cleansed of impurities before arrival into creeks, streams, rivers, and bays.

The impervious surfaces associated with urbanization prevent water from infiltrating into the soil. Even the smallest rainstorms generate runoff, which also collects urban pollutants, and are concentrated in narrow channels or pipes. This rapid, concentrated waterflow affects the hydrologic cycle in four ways: increased flood potential, channel destabilization, increased concentration of pollutants, and reduced groundwater levels.

These negative impacts of urban runoff can be mitigated by providing opportunities for stormwater to come into contact with the soil. Vegetated swales are one common, well-documented technique to achieve this goal and help restore the natural hydrologic cycle.



The Conveyance Approach

The conventional stormwater management practice over the past fifty years has been the conveyance approach, which treats runoff as a waste product and seeks to move this water off-site as quickly as possible. This “get rid of the water” approach results in paving land areas with impermeable surfaces so that water does not enter the subsoil. Rather it is collected and concentrated through a network of impervious gutters, drainage structures, and underground pipes.

Because the system is entirely impermeable, suspended pollutants and sediments have no opportunity to be dispersed or filtered and are concentrated in the rapidly flowing runoff. When the system reaches its outfall, this polluted water is emptied rapidly into a natural water body at a single, concentrated point.

Regulatory Context

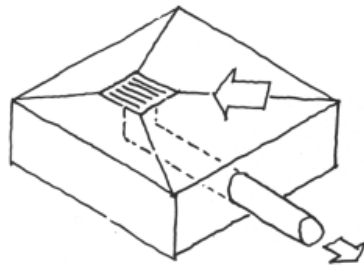
With the progress made in the past twenty-five years in controlling pollution from factories and other industrial point sources, this concentration of pollutants from various dispersed sources—“non-point source” pollution—is today responsible for up to eighty percent of the pollution in waters of the United States.¹

The Clean Water Act of 1972, as amended in 1987, mandates that the discharge of pollutants into waters of the United States is effectively prohibited unless the discharge is in compliance with a National Pollutant Discharge Elimination System (NPDES) permit. Because urban runoff contains pollutants, Phase II regulations require most cities and most large development projects to obtain an NPDES permit in order to discharge stormwater runoff.

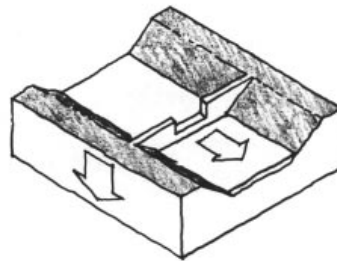
The Municipal NPDES permit program requires that subject municipalities “develop, implement, and enforce controls to reduce the discharge of pollutants from municipal separate storm sewers which receive discharges from areas of new development and significant redevelopment... [including] after construction is completed.”²

Within this regulatory context, land developers and municipal permitting agencies are required to implement techniques that reduce water pollution carried in runoff. These techniques may include storage (detention), filtration, and infiltration practices.

Conveyance Approach



Infiltration Approach



The Infiltration Approach

An infiltration stormwater system seeks to infiltrate runoff into the soil by allowing it to flow slowly over permeable surfaces. Ideally, these permeable surfaces are designed to double as recreational and landscape areas during dry weather. Because the infiltration network allows much of the runoff to return to the soil, overall runoff volume is reduced, and more water is available to replenish groundwater and maintain stream baseflows. The slow flow of runoff allows pollutants to settle into the soil where they are naturally mitigated. The reduced volume of runoff that remains takes a long time to reach the outfall, and when it empties into a natural water body its pollutant load is greatly reduced.

There are many strategies for implementing this infiltration approach. They include the use of permeable pavements (such as porous asphalt, extended detention basins, and wet ponds) and landscape filtration systems (such as vegetated or grassy swales).

Vegetated swales are especially useful in “disconnecting” impervious areas from each other and from a conventional pipe system. By inserting vegetated swales where appropriate in an overall storm drain system, the impact of the contributing impervious land areas on environmental quality can be mitigated.

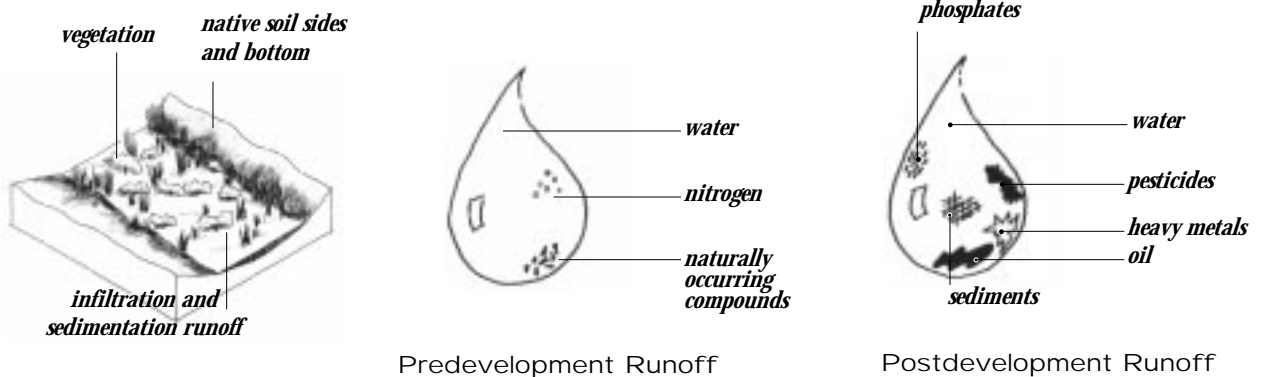
2. BENEFITS OF VEGETATED SWALES

Swales Reduce Peak Flows

Vegetated swales reduce peak flows by slowing runoff, by incorporating microstorage elements such as ponding behind check dams, and by infiltrating water into the ground. Unlike curb-and-gutter drainage systems, water in swales must flow over the relatively rough ground surface and through dense vegetation. Each of these acts to slow water velocities, reducing the rate at which runoff is conveyed downstream.

Vegetated swales can also be designed to infiltrate water into the ground, recharging groundwater and restoring or maintaining the baseflow of water into streams. Creating regular low baseflow in streams, rather than periodic peak flows followed by periods of reduced baseflow, can improve stream quality and riparian habitat.

Swales can incorporate check dams or other microstorage features to increase the amount of stormwater runoff that is captured. The use of microstorage, while not likely a significant factor in moderating large floods, can help mitigate changes to the runoff hydrograph caused by development for smaller storms. This can reduce the required size of storm drains, saving a project developer money, and reduce or eliminate impacts to habitat downstream.



Swales Reduce Pollutants

Cities have long been concerned with pollutants in urban stormwater runoff. As early as 1939, the City of Oakland, California, began a "drive against the dumping of oil and other wastes harmful to wildlife into sewer systems which empty into the Bay."³

All urban land uses contribute pollutants to urban stormwater runoff. For example, pesticides, herbicides, and fertilizers come from residential lawns, commercial landscaping, and recreational facilities like golf courses. Heavy metals come from cars and roofs and industrial sites. Oil and grease drip regularly from cars onto streets and are occasionally dumped into storm drains by residents. Pathogens and bacteria in runoff can come from pet waste or sanitary sewer overflows.

In small amounts, such pollutants are easily absorbed into the environment. Pollutant concentrations in urban runoff, however, can exceed those in raw sewage. Even at low concentrations, chronic loading of stormwater runoff with pollutants can have toxic effects. Nutrients can cause algae blooms that subsequently deprive streams and lakes of dissolved oxygen, resulting in fish kills and the death of other aquatic organisms. Oil and grease can cause visual impacts such as sheens and kill or injure aquatic organisms, including bottom feeders. Heavy metals can be toxic to aquatic life and may bioaccumulate in fish or plants, leading to effects over the long term, even when discharged at low concentrations in each individual runoff event. Sediment can carry other pollutants or act as a nutrient source itself. All of these pollutants can adversely impact wildlife and cause a decline in stream health.

POLLUTANTS	SOURCES	IMPACTS
Sediment	1, 2, 3, 4	Transports attached nutrients; increases turbidity and reduces light penetration; decreases submerged aquatic vegetation; impairs respiration of fish and aquatic invertebrates; impairs commercial, recreational fishing resources; silts up BMPs, degrades the benthic community.
Nutrients	1, 2, 3, 4, 5, 6	Eutrophication; lowers dissolved oxygen levels; fish kills and benthic habitat destruction; surface algal scum; unpleasant odor.
Bacteria and Viruses	2, 4, 5, 6	Contaminates drinking water; closes beaches and shellfish beds.
Oxygen-demanding Substances	2, 3, 4, 5, 6	Eutrophication; fish kills; changes to aquatic food chain, loss of biodiversity, surface algal scum, and unpleasant odor.
Oil and Grease	1, 2, 3, 4, 5, 6	Aquatic organism mortality; collect in bottom sediments and affect benthic communities; limit fishing for bottom-feeders.
Heavy Metals	1, 2, 3, 4, 5, 6	Toxic to aquatic life; potential groundwater contaminants; danger of bioaccumulation.
Toxins: Priority Pollutants	Material-dependent	Similar effects as above (other toxic chemicals, including pesticides, phenols, and polycyclic aromatic hydrocarbons (PAHs)).
Floatables	2, 3, 4, 6	Contain concentrations of heavy metals, pesticides, and bacteria. Create eyesore (floating litter).
Temperature	N/A	Alters the conditions necessary for organisms to survive; decrease biodiversity and ecosystem stability.
Salt	1	Typically from winter road salting; harms or kills plants and trees, and may harm animals.

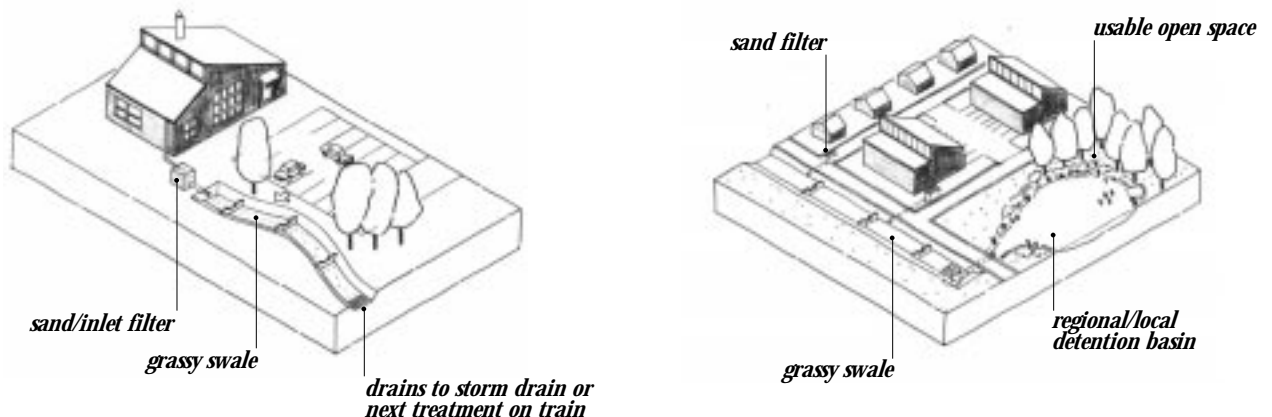
TABLE 1: THE SOURCES AND IMPACTS OF POLLUTANTS COMMONLY FOUND IN URBAN RUNOFF⁴
Key: 1: Automobile/atmospheric deposition; 2: Urban housekeeping/landscaping practices; 3: Industrial activities; 4: Construction activities; 5: Nonstormwater [sewer] connections; 6: Accidental spills and illegal dumping.

How Swales Achieve Pollutant Removal

Grassy swales can remove and immobilize or break down a large portion of pollutants found in urban stormwater runoff. Swales have achieved high levels of removal of sediment [total suspended solids or t.s.s.] and oil and grease. Swales can also remove a moderate percentage of metals and nutrients in runoff. This lower level of removal compared to sediment or oil and grease is due partly to the large percentage of metals and nutrients that appear in soluble form in runoff.

Swales can achieve good removal of metals or nutrients that are attached to sediment particles. However, when these pollutants are in soluble form, they are largely removed by infiltrating flow—and the pollutants—into the ground. This approach uses the soil to filter pollutants from runoff. While some removal occurs without infiltration, through contact between runoff and swale vegetation or the soil surface, the best removal rates for soluble pollutants occur when flow can be infiltrated into the ground. Since most swales infiltrate only a portion of their flow, removal rates for pollutants in soluble form are lower than those for sediment or oil and grease.

Overall, grassy swales provide good treatment of stormwater runoff without the extensive maintenance required for some other stormwater BMPs. However, removal rates improve when swales are well maintained, as the residence time of water in a swale increases, and when a swale is used as one element of a “treatment train” of BMPs through which stormwater runoff flows before it is discharged. By draining runoff on the surface, grassy swales also serve an educational purpose by making residents or users aware of pollutants such as oil or trash that are deposited in the swale. While many people might not give much thought to pouring oil, paint, or other pollutants into a storm drain, most think twice before pouring them into a grassy swale.



NUTRIENTS

Nutrients, including nitrogen and phosphorus, appear in urban runoff in soluble form as well as attached to sediment particles, and are removed by both settling and infiltration. They are then broken down and stored in the soil or taken up by plants. Some nutrient remobilization may occur in the winter when plants die. However, periodic mowing of swales and removal of the mowed vegetation can reduce remobilization. As a general rule, the more flow a swale infiltrates into the ground, the more nutrients will be removed.

METALS

Like nutrients, metals appear in both soluble form and attached to sediment particles. The removal of metals by swales can be maximized by:

- maximizing the amount of water captured by a swale through infiltration;
- increasing the pH of a swale's flow—basic flows drop out more metals;
- increasing the cation exchange capacity and pH of the swale's soil—soils with more organic matter remove a greater amount of metals; and
- maximizing the density of a swale's vegetative cover.

Studies of heavy metals removal by swales have typically found values ranging from twenty to sixty percent of runoff concentrations, with the higher range of pollutant levels common for well-designed and maintained swales, and the lower range seen for swales with patches of bare soil or short residence times.

An important concern with respect to this removal is whether the heavy metals will accumulate to toxic levels in the swale and whether they will migrate into and contaminate the underlying groundwater.

By removing heavy metals, a grassy swale also acts to concentrate them. Some metals may be taken into the swale vegetation at low concentrations and removed with periodic mowing and removal of clippings. The remaining concentrations of metals will stay attached to soil particles. Research has found that most metals in this state are poorly soluble. Therefore, they are not expected to migrate into and potentially contaminate groundwater. Further, studies of swales in Florida, Maryland, and Virginia (including swales in sandy, loamy, and clayey soils), found that metals accumulated only in the top several inches of soil even in sandy soils. The clayey and loamy soils—including soils in one swale adjacent to a busy four-lane highway—showed even sharper drop-offs in metal concentrations from the surface, with metals accumulating only in the top two inches of soil.⁵

Metals have not been found to accumulate to toxic levels in grassy swales. Fifteen years after its construction in 1971, metals levels in a grassy swale adjacent to a four-lane highway carrying 29,000 vehicles per twelve hours were far below the required standards of metals in municipal wastewater sludges recommended for agriculture usage, with the exception of lead, which was at the standard. The lead may have come from the use of leaded gasoline, and the subsequent elimination of leaded gasoline suggests that concentrations of lead would not be as high in swales constructed now.

Concentrations of trace metals in residential swales eight to 14 years old were well below those found in the highway swale, with the exception of zinc, which had come not from urban runoff, but which had leached from galvanized culverts. All concentrations in the residential and highway swales were far below the standard for hazardous materials.

In general, soils have the capacity to capture the low concentrations of metals in urban stormwater runoff, and metals are not expected to accumulate to hazardous levels.

OIL AND GREASE

Swales can remove a high percentage of oil and grease in urban runoff through bacterial action that occurs when runoff contacts swale vegetation and soil. One study found a removal rate of about seventy-five percent in a swale with a residence time of approximately 9 minutes. Minimum oil and grease removal dropped to forty-nine percent when runoff from the same watershed flowed through a swale with a residence time of approximately four-and-a-half minutes.⁶ Removal efficiency increased as concentrations of oil, grease, and (TPH) in the runoff increased, but removal rates of greater than forty-nine percent were seen even at concentrations of oil and grease as low as 3 mg/l. This is important because oil and grease concentrations in stormwater runoff are typically less than 20 mg/l. At this concentration, some other stormwater BMPs are unable to significantly reduce oil and grease present in stormwater. Current oil/water separator designs, for example, are unable to reduce oil concentrations below 20 mg/l.

PATHOGENS

Grassy swales have not been found to significantly reduce concentrations of escherichia coli bacteria. However, few studies have been done on pathogen removal by swales. One study did analyze e. coli concentrations in flow through a grassy swale. Concentrations increased through the swale, and the report authors speculated that the increase was due to “pet droppings and possible bacterial multiplication within the swale,” but there is no conclusive information as to whether swales will or will not remove pathogens.

SWALE DESIGN ELEMENT	WHY DOES IT WORK?
Increased residence time provided by check dam storage or increased swale length.	Allows sediment more time to settle and be captured by the swale; provides more contact with the soil surface to remove soluble pollutants; allows for increased infiltration.
Increased infiltration provided by check dam storage or swale length.	Soluble pollutants are best removed by infiltration; swales show increased capture of sediment as more flow indicates.
Organics in soil. Dense vegetative cover.	Increase the soil's ability to capture soluble metals. Increase the flow path runoff must travel through the swale, increasing residence time, and reduces resuspension of captured particles.
Periodic mowing and removal of swale vegetation.	Removes captured nutrients and metals taken into vegetation.

TABLE 2: HOW SWALES ACHIEVE POLLUTANT REMOVAL



3. APPROPRIATE APPLICATIONS FOR VEGETATED SWALES

Vegetated swales are grass-lined or vegetated earthen channels designed specifically to convey water and to remove pollutants. Swales can be used in any project where they can be designed to have a stable, vegetated bed and banks that are not eroded by the conveyed flows. Further, they must have a relatively shallow longitudinal slope and relatively shallow side slopes, allowing them to convey flows slowly enough to achieve water quality benefits. Within these constraints, swales can be included in the landscape areas of many projects.

Swales have been implemented in projects including: street and highway medians and edges; parking lot landscape medians and edges; residential subdivisions, houses, and apartments; commercial projects, including office parks and campuses, malls, strip malls, and stand-alone big box retail; recreational uses, including golf courses; schools; industrial sites, including warehouses and other light industrial sites.

Projects where it **may be inappropriate** to implement grassy swales include:

- Steep slopes;
- fill areas;
- high-density or “ultra-urban” projects where there is limited landscape area for swales;
- sites where concentrated flows would erode a swale’s vegetation; and
- sites with very sandy soils where the swale channel would be subject to erosion or bank sloughing even when water flows at low velocities.

4. HYDRAULICS AND GRADING

Hydraulic Design Principles

Grassy swales must both convey and treat the stormwater runoff they convey, unlike lined channels or underground storm drains, which are designed only to convey peak flows. In order to meet both of these objectives, swales must be sized not to erode during peak flows, but also to convey smaller flows slowly enough to treat them. An effective swale design consists of three components:

- Conceptual, engineering, and planting design;
- construction of the swale at the project site, including swale grading, construction of check dams, if any, and establishment of vegetation; and
- periodic inspection and maintenance of the built swale.

CONCEPTUAL, ENGINEERING, AND PLANTING DESIGN

This initial stage of grassy swale design should occur during the planning process of a project.

The goals of this stage are to develop a swale design such that the finished swale will:

- Remain stable under normal operation and carry the peak design flow without eroding or overflowing;
- provide water quality treatment for a smaller water quality design storm; and
- aesthetically fit into and operate at a given site.

In the conceptual design phase, the swale is placed into the overall site plan. The designer determines what portions of the site will drain into each swale and how the swales fit into the site's drainage plan. Given the site's constraints, the designer should maximize the swale's length in order to improve water management. During this and subsequent design and construction phases, the swale's landscape architect should maintain good communication with any other designers, engineers, or site managers who will be working on the swale to ensure that they understand the concept and the swale's role in the site's drainage plan.

In the engineering design phase, the designer takes the conceptual site design information and uses it to develop quantitative design dimensions for the swale. Municipalities have typically developed standards for designing stable vegetated open earth channels that take into account local soil types, vegetation, amount and velocity of flow, channel slope, and other design variables. General standards for stable swale channels are presented below, and a worksheet has been provided to calculate the appropriate design dimensions for a grassy swale.

WATER QUALITY VOLUME (WQV)

The most polluted urban runoff is usually generated by small storms, or by the first portion of a storm cycle. The oils, metals, and other pollutants accumulated over a dry period are washed off rooftops, roadways, and other surfaces in the first light rain or in the first minutes of a large storm. In subsequent storm cycles this pattern is repeated, with the first rains carrying the highest concentration of pollutants. Thus, treating this “first flush” of runoff is the key to controlling nonpoint source pollution.

In the past, stormwater management has focused almost exclusively on flood protection. Systems that can accommodate these peak flows are more than adequate to convey small storms, which occur much more frequently. So, the small storm and its impacts can be easily overlooked.

Yet, small storms, because of their frequency and cumulative impacts, make the largest contribution to total annual runoff and have the greatest impact on water quality.

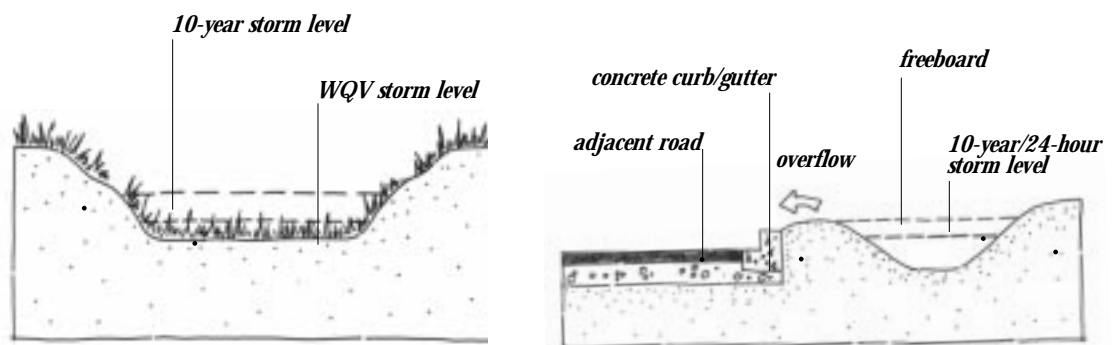
For this reason, stormwater design must consider both the peak volumes for flood control, as well as WQV for pollution control.

The WQV is established by local or regional agencies and varies depending on local conditions. It is defined as the amount of runoff that must be treated before being released into a conveyance storm drain network or receiving water.

There are three common ways to define WQV:

- as a proportion of total annual runoff from a site (e.g., an eighty percent capture rate);
- as a depth of rainfall falling on a site (e.g., three-quarters inch of rain); and
- as the runoff from a storm with a particular recurrence interval (e.g., a two-year storm).

The Water Environment Federation/American Society of Civil Engineers in their jointly published *Urban Runoff Quality Management* (1998)⁷ adopted an eighty percent annual capture rate as a standard of practice for WQV. This translates into approximately the first one-half to one-and-a-half inches of rain depending on annual rainfall and local rainfall patterns. It can also be translated as a two-year recurrence interval storm, or the size storm that has a fifty percent chance of occurring in any given year.



The Center for Watershed Protection in Silver Springs, Maryland, recommends a ninety percent annual capture rate. Under this rule, grassy swales are sized to treat ninety percent of the annual volume of runoff in a watershed.

The depth of the water quality storm varies according to local rainfall, climate, and regulations. In the Chesapeake Bay region, analysis of daily precipitation for four locations over an eleven-year period found that the water quality storm under the ninety percent rule was the one-inch rainfall. An analysis of daily precipitation for two locations over a thirteen-year period in the San Francisco Bay area found that the water quality storm under the ninety percent rule was the 1.20" rainfall.⁹ In Florida, swales are required to infiltrate eighty percent of the three year, one-hour design storm (between one-and-a-half and two inches).¹⁰ Many municipalities recommend that swales infiltrate the first one-half inches of runoff.¹¹

The swale inlet can be designed to allow peak flows to bypass the swale and be conveyed by a conventional conveyance system. This also prevents the larger, higher velocity flows of large storms from washing out the sediments or eroding the vegetation in the swale.

To determine the appropriate design storm for a particular area, consult local rainfall data or contact a local municipality or flood control, public works, or stormwater agency for the required standard. While the design storm is typically expressed as a depth, the associated rainfall intensity is also required to design the channel cross section. The swale will treat runoff only as fast as it arrives at the swale, and this is governed in part by how much rain falls on the ground over a given period of time.

PEAK FLOW DESIGN STORM

Swales are a part of the larger storm drain system that drains water from developed areas. Therefore, they must also be sized to convey a peak flow design storm without eroding. The design storm is often the ten-year, twenty-four-hour storm, although municipalities may have adopted other standards for their swales or open channels. As with the water quality design storm, the local municipality, planning department, flood control, public works, or stormwater agency will provide the required standards.

Like any urban drainage system, given a large enough storm, swales will overflow. Swales designed to convey the ten-year, twenty-four-hour—the standard used for storm sewers in many municipalities—can be expected to briefly overflow about once every ten years. Where this is of concern, measures can be taken to reduce the problems such overflow would create. These might include:

Overflow onto adjacent roads or parking areas. If a swale runs adjacent to a paved roadway or parking area, it can be designed so that a portion of the pavement accepts overflow from the swale. This is similar to how crowned streets carry overflows from gutters along their edges during large storm peaks.

Overflow onto adjacent landscape. Locate the swale within a project's landscape or lawn areas, so that overflows lead only to brief ponding in the landscape. For example, swales in parks or recreational areas can be designed to overflow onto an adjacent grassy area or pathway "flood plain."

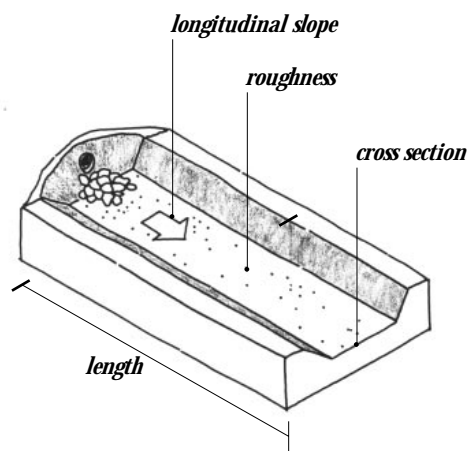
Dual drainage system. A dual drainage system makes separate accommodation for WQV and the peak flow. This can be achieved either by an overflow outlet, a weir, or a bypass system.

For example, in Folsom, California, a dual drainage system combines grassy swales with conventional curb-and-gutter system on an arterial street. In this case, water is drained from streets along a conventional curb-and-gutter system. However, at each inlet location are two catch basins. The first, an

uphill basin, is sized to accommodate the first flush of rainfall from the two-year storm event. This catch basin outflows to a grassy swale running parallel to the street. Constituents are filtered as water passes through the swale to the outlet, which directs flow back into the main storm drainage system. Runoff in excess of the two-year storm event is captured by the second catch basin, downstream, that is sized for the ten-year storm and is directly connected to the storm drain.

Geometric Design Principles

The basic components of grassy swale design include: longitudinal slope, swale cross section (shape), length, and roughness.



LONGITUDINAL SLOPE

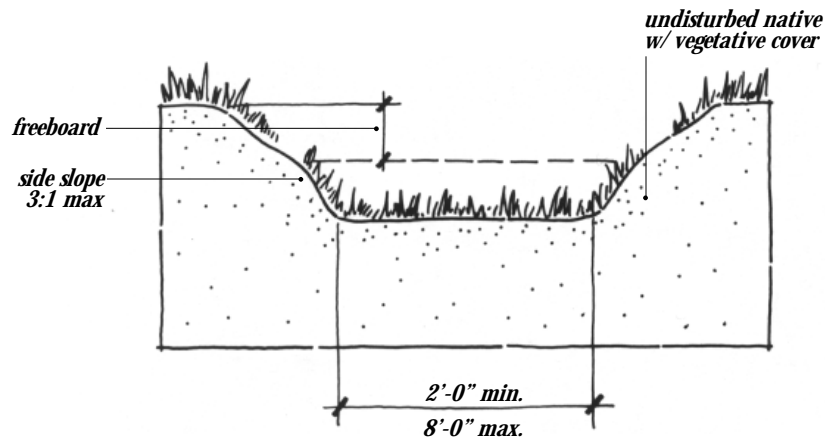
The longitudinal slope of a vegetated swale is a critical design element that effects the design of the swale and its performance. Appropriate slopes s typically range from one percent to six percent.

Optimal: $0.01 < s < 0.02$. The optimal longitudinal slope of vegetated or grassy swales is between one and two percent. Low slopes limit erosion by reducing water velocities and increase pollutant removal by increasing residence time, or “contact time” of water in the swale. As longitudinal slope and discharge velocity increase, erosion may increase and pollutant removal rates may decrease.

Marginal: $s < 0.01$. On slopes less than or equal to one percent, drainage is marginal, and standing water may be present if the swale remains wet for long periods. To limit standing water, an underdrain can be installed using perforated pipe. Once the soil is saturated, the perforated pipe collects and carries excess water out of the swale. Underdrains are particularly useful for residential areas, where wet or soggy swales may be viewed as problems.

Steep: $0.02 < s < 0.06$. Swales can be used on slopes between two and six percent, but they require special treatment to reduce the speed of flow. This is typically achieved by check dams or weirs spaced approximately every fifty to 100 feet along the length of the swale. These check dams reduce velocity, increase residence time, protect plant material from erosion, and enhance pollutant removal.

Excessive: $s > 0.06$. Vegetated swales are not recommended on slopes greater than six percent.



SWALE CROSS SECTION (SHAPE)

There are four basic cross sections for open channel drainage: rectangular, triangular, trapezoidal, and parabolic, each with different hydraulic properties.

Trapezoidal cross sections are the most common shape for vegetated or grassy swales because they are easy to construct, offer good hydraulic performance, facilitate maintenance, and are aesthetically pleasing. Triangular cross sections can also be appropriate if the side slopes are very gentle (approximately 10:1 or shallower). Rectangular cross sections are generally not used for grassy swales because they are difficult to construct and maintain, and because the vertical side slopes present a relatively high public liability.



SIDE SLOPES

Proper side slopes of a vegetated swale are important for several reasons. They limit erosion, facilitate maintenance, enhance aesthetics, and reduce public liability risks. In general, shallower side slopes are more desirable, though they increase the amount of area required for the swale.

A 3:1 slope (horizontal:vertical) is considered the steepest to limit erosion and/or sloughing of the slopes. 5:1 slope is considered the steepest slope that allows regular mowing.

BOTTOM WIDTH

A wide, flat swale bottom maximizes the available treatment area and pollutant removal while also providing ease of maintenance.

Minimum: If the swale will be mowed, the bottom should be at least two feet wide.

Maximum: The swale bottom should be less than eight feet wide, unless it will be hand finished. This will avoid rilling and gullyng.

DEPTH

The swale should be at least six inches deeper than the maximum design flow depth. This additional depth is known as “freeboard,” and provides a safety factor to prevent the swale from overflowing onto adjacent areas if the channel becomes obstructed or if runoff volumes exceed the design size.

LENGTH AND RESIDENCE TIME

The time it takes water to flow from its inlet into the swale to the swale’s outlet is the “residence time.”

Residence time for vegetated swales should be at least five minutes. The designer should seek to maximize a swale’s length, since this will increase the residence time, or “contact time” of runoff with the swale. In general, the greater the residence time, the greater a swale’s ability to remove pollutants from runoff.

For example, one study found a removal rate of about seventy-five percent of oil and grease in a swale with a residence time of approximately nine minutes. Minimum oil and grease removal dropped to forty-nine percent when runoff from the same watershed flowed through a swale with a residence time of approximately four-and-a-half minutes.

WATER VELOCITY

The speed at which water flows in the swale is its velocity. Velocity is calculated for two storm sizes: water quality design storm and the peak flow design storm. Velocity should be less than or equal to one-and-a-half feet per second for the water quality design storm, and below five feet per second or the erosive velocity of the channel for the peak flow design storm. This is generally three to six feet per second depending on vegetation type and the use or erosion control fabric or other stabilization method. Erosion may be a problem if average discharge velocities frequently exceed three feet per second. Where velocities make erosion a concern, erosion control fabrics or geotextiles may be used to achieve added erosion resistance while still allowing the growth of a dense stand of vegetation.

ROUGHNESS: MANNING'S EQUATION "*n*"

Manning's equation is a generally accepted method to quantify uniform flow rates. Manning's *n* is a numerical value (of no given units) to adjust flow rates for a given roughness of a channel with constant flow. Manning's equation calculates the average velocity of water in a channel as a function of the channel's slope, the hydraulic radius for a particular flow, and the channel roughness.¹²

$$V = 1.49 \frac{R^{2/3} S^{1/2}}{n}$$

where:

V = average velocity across the cross section (in feet per second)

S = longitudinal channel slope (in feet/feet)

R = hydraulic radius of the channel (in feet); $R = A/W_p$ where,

A = cross sectional area (square feet) through which water is flowing

W_p = wetted perimeter (ft), the cross sectional length of surface in contact with water

n = Manning's roughness coefficient

The roughness coefficient (*n*) indicates how much a material resists flow. Typical values for *n* range from 0.013 for concrete pipe to 0.80 for woods with dense underbrush. Values for *n* in vegetated swales are typically in the range of 0.03 for short turf grass and 0.40 for dense grasses such as Bermuda or creeping lovegrass. A generally accepted Manning's *n* for grassy swales is 0.20.¹³ In order to accurately determine channel geometry and estimate average velocity in a swale, an appropriate Manning's *n* should be used (see Table 2). [Table adapted from Ferguson, 1998].

An accurate estimate of Manning's *n* is important because:

- The estimate will help determine swale geometry and the amount of space a swale occupies on a site.
- An overestimate of *n* may create flooding problems for relatively low-return period storms.
- An underestimate of *n* may result in a swale with velocities above the maximum permitted for the swale vegetation. This may result in erosion, loss of channel stability, and release of pollutants from the swale.

CONVEYANCE MATERIAL	<i>n</i>
Concrete pipe	0.013
Corrugated metal pipe	0.024
Brick	0.014-0.017
Concrete swale, trowel finish	0.012-0.014
Random stone in mortar	0.020-0.023
Dry rubble (riprap) (Chow 1959, 111)	0.033
Dry rubble (riprap) (Table 2 in Abt et al., 1988):	
1 in.-1.25 in. crushed stone on 1-2% slope	0.024
1 in.-1.25 in. crushed stone on 10% slope	0.055
2.2 in.-2.8 in. crushed stone on 2% slope	0.025
2.2 in.-2.8 in. crushed stone on 8-10% slope	0.030
Asphalt	0.013-0.016
Earth with short grass, few weeds (turf)	0.022-0.027
Earth with dense weeds and high brush	0.08-0.12
Earth, clean bottom, brush on sides	0.05-0.08
Sheet flow; consider cover to height of 0.1 ft only (SCS 1986, Table 3.1):	
Concrete, asphalt, gravel, or bare soil	0.011
Dense grasses such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures	0.24
Bermuda grass	0.41
Natural range	0.13
Woods with light underbrush	0.40
Woods with dense underbrush	0.80
Large natural stream channels (adapted from Barnes 1967):	
Earthen banks with some brush	0.026
Banks covered with low reeds and grass	0.027
Banks covered with low weeds and brush	0.030
Banks and bed of uniform smooth stones	0.032
Banks and bed of smooth stones; some debris and brush	0.037
Banks thickly covered with woody brush and trees	0.040-0.060
Angular boulders in channel bed	0.041-0.050
Bed mostly of boulders that deflect flow	0.055-0.075
Small stream channels(Dunne and Leopold 1978, Table 16.1):	
Winding channels considerably covered with small growth	0.035
Streams with bank or aquatic vegetation	0.040-0.050
Mountain streams in clean loose cobbles	0.040-0.050
Irregular alignment and cross section, obstructed by trees and brush	0.100
Very irregular alignment and cross section, many roots, trees, logs, drift on bottom	0.150-0.200
Densely wooded floodplain (generalized from Arcement and Schneider 1989):	
Negligible undergrowth, all trees large, soil surface smooth	0.10
Negligible undergrowth, mix of large and small trees	0.12-0.15
Dense undergrowth	0.20

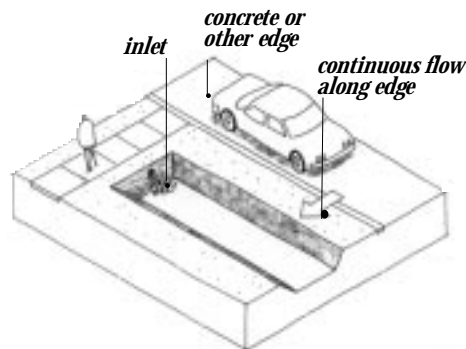
TABLE 2: VALUES OF ROUGHNESS FACTOR *n* IN MANNING'S EQUATION
(from Table 2 of U.S. Federal Highway Administration, 1973b, and Table B-6, p.577, of U.S. Bureau of Reclamation, 1974, except where shown)

INLETS

The optimal method of directing water into a swale is to provide for continuous inflow along the entire length of the swale. This is easy to achieve by eliminating curbs next to streets and parking lots. In this way, inflows are spread over a wide area, erosion is minimized, and pollutants are dispersed widely among the vegetation.

When a concentrated inlet such as a pipe or curb cut is necessary, an energy dissipater and flow spreader such as cobbles or gravel should be used where the water enters the swale. This will limit erosion and reduce the need for maintenance.

The asphalt edge of a street or parking lot that drains directly into a swale may crack over time due to plant growth or occasional car traffic. To avoid this problem, a concrete or stone band (or other hard edge) can be placed to finish the asphalt edge. The top of the band should be at the grade of the asphalt to allow for water to pass over the band and into the swale.



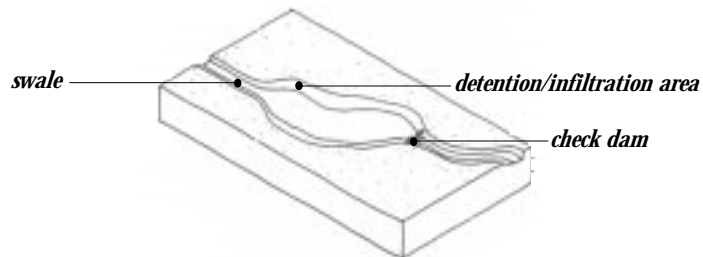
OUTLETS

Swales may be empty directly into receiving waters, but more often they are directed to other conveyance or storage structures, including storm drain inlets, that collect water for subsequent conveyance in the underground storm drain system to other water quality BMPs as a part of a treatment train, and larger open channels.

DETENTION AND INFILTRATION

Swales may be constructed with periodic broad, shallow areas to detain and provide increased treatment for flow. High soil infiltration rates also provide increased treatment by allowing high short-term ponding and decreasing the amount of water that exits a swale. Detention, increased ponding, and infiltration increase settling and increase the amount of pollutants that come in contact with the top layer of soil, fostering increased ion-exchange and pollutant removal.

However, soils with high infiltration rates are not required for swale construction—moderate pollutant removal rates have been found in swales constructed on clay soils¹⁴. In general, swales on clay or other soils with low infiltration rates would be expected to remove a lower portion of soluble pollutants from runoff.



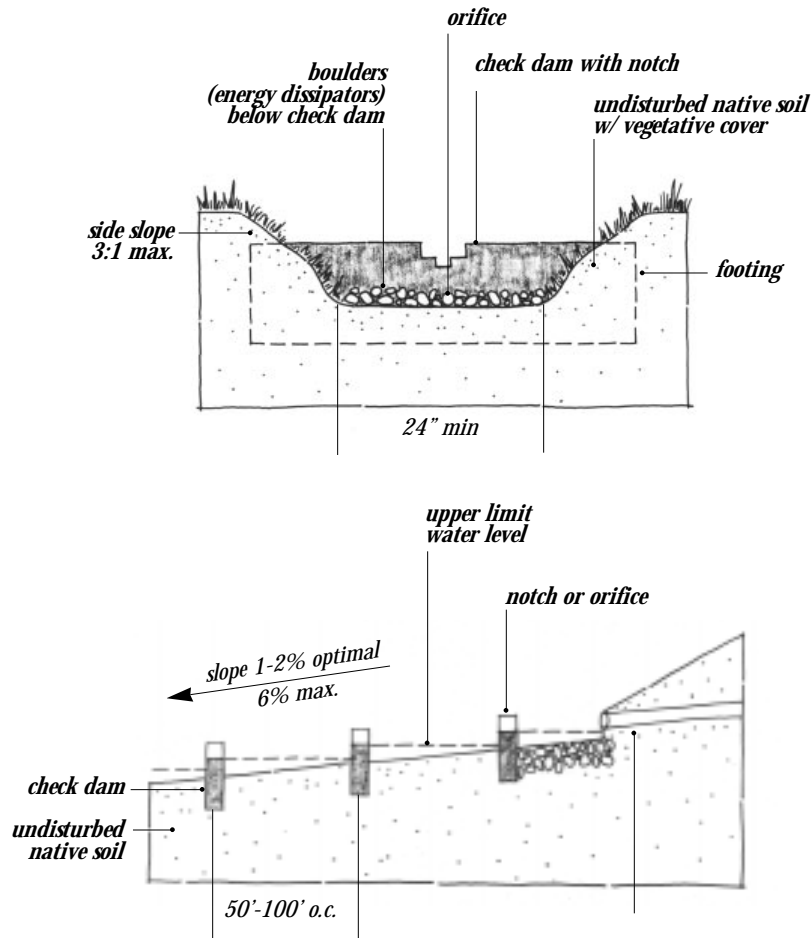
CHECK DAMS/WEIRS

Check dams, or weirs, pool water upstream of the weir, increasing residence time and infiltration. A number of check dam designs have been implemented in the field, including earthen berms, notched concrete weirs, board check dams, and stone check dams. Check dams should include an orifice for very low flows and to minimize long-term ponding that may foster mosquito growth, and should contain an energy dissipater such as gravel on their downstream side.¹⁵

The frequency of placement and design of check dams should be governed by longitudinal channel slope and geometry. To obtain maximum storage from stable check dams, they should be located such that the upstream limit of ponding from one check dam is just below the downstream edge of the adjacent check dam. [insert Figure 14 here] To prevent mosquito development, check dams should be designed to pond water to a depth that will infiltrate within twenty-four hours of the end of a storm.

Further, channel design should allow for a minimum of one-half feet of freeboard above the top of the check dam at the design flow, taking into account storage. It may be necessary to armor the sides of larger swales at and just downstream of the check dam with rocks or gravel that will protect the channel sides and act as energy dissipaters in the case of high flows. As in any channel, check dams should be extended into the channel sides to prevent outflanking.

Within the above design constraints, then, the swale should be designed to treat a water quality design storm and to transport a peak flow design storm.



SWALE AESTHETICS

In urban areas, grassy swales can be a departure from the monolithic curb-and-gutter and underground storm drain systems with which we are familiar. This can cause concern in residents and occupants of sites where swales are a part of the drainage infrastructure.

It is important to design swales with a site's subsequent users in mind. Wetland swale designs that may be appropriate adjacent to a parking lot on a commercial site may not be as readily accepted as a part of front or back yards in a residential setting. Also, education about the purpose of a swale can be a useful part of the overall project, particularly if the swale represents a departure from standard curb-and-gutter drainage.

Construction and Establishment

CONSTRUCTION

At the construction stage, the swale's soil is prepared, the swale is graded, the inlets and outlets are finished, and additional elements such as underdrains or check dams are constructed. Also, the swale is vegetated to prevent erosion and enhance treatment.

Even the best-designed projects can encounter problems at the construction stage. These may result from:

- Crews unfamiliar with the design concept behind grassy swales;
- overcompaction of the swale subsoil;
- poor timing of swale construction, such that the swale is inundated with sediment-laden runoff; and
- poor preparation of the swale channel to accept flows.

The construction period is also typically the period when greatest erosion occurs. If a swale is located downstream from a construction site, it may collect sediment from the site. This is an indication of how effective the swale is—sediment that settles in the swale is sediment that does not flow off-site into receiving waters. Prior to the completion of construction, sediment can be excavated from the swale and redistributed as topsoil on-site.

EROSION CONTROL

It is crucial to provide or develop adequate erosion control in the swale at the construction stage to prevent subsequent erosion. This can be achieved through planting or mechanical means. Planting can be from sod, seed, cuttings, or potted plants.

Sod. When installed correctly, sod provides immediate protection, although the seams may subsequently need to be reseeded. The soil should be properly prepared, and an appropriate sod mix should be chosen for a site's soils. The graded swale channel should be free of stones or clods greater than one-inch in diameter. Sod strips should be laid perpendicular to the direction of flow, and the sod should be rolled or tamped after it is laid. The sod should be secured with staples or pegs on 3:1 or greater side slopes, or in areas of expected high velocity flows.¹⁶

Seed. Seed is typically scarified into the soil or hydroseeded. It is advisable to irrigate seed lightly to establish a dense cover prior to the rainy season or opening the swale to flow.

Cuttings. Some vegetation can be grown from cuttings in moist soils. These are typically woody plant materials such as willows or dogwoods.

Container grown/balled and burlapped plants. Bunch grasses, rushes and shrubs or trees are most commonly planted from containers. These containers range in size from four-inch liners to box or burlap specimens.

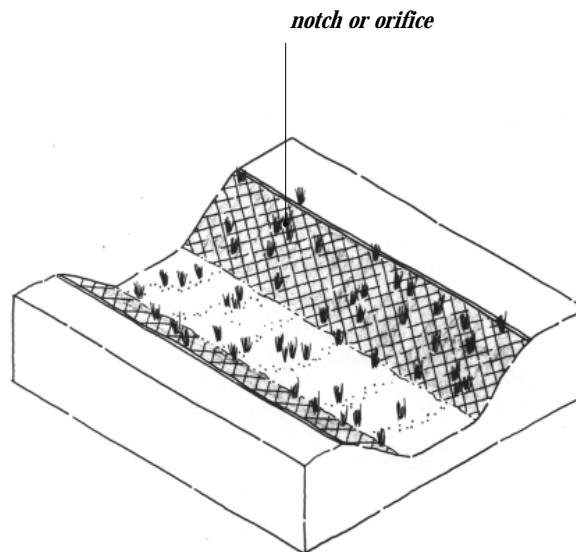
Mechanical erosion control. A wide variety of erosion control fabrics are on the market, such as: mulches; organic, biodegradable, and non-biodegradable blankets and netting; and soil-filled turf reinforcement mats. Tackified mulches may be appropriate for low-velocity swales, but care should be used, as they will add to the nutrient load in the swale over the long term and may be subject to erosion down the swale.

Erosion control blankets and netting can be made of jute, coconut fibers, straw, excelsior, and various plastics, or a combination thereof, and are usually installed staked into the ground. They may include a seed mixture or be installed over seeded ground. Biodegradable blankets or nets usually degrade within a few years, stabilizing the swale over the short term as a dense stand of vegetation develops, but providing no long-term protection. These products tend to work well in the range of velocities seen in grassy swales.

Turf reinforcement mats (TRMs)—flexible, synthetic mats filled with soil—are another erosion control option. They provide long-term channel and vegetation stabilization at velocities on the order of fourteen to twenty feet per second. Since swales must be designed to lower velocities to retain water quality benefits, TRMs are usually not necessary, but might be used on a higher-velocity grassed channel further downstream.

Biotechnical channel stabilization methods other than grassy stabilization, such as willow staking, may be used in combination with the above short-term erosion control materials.

Check dams reduce the speed of flow and the flow's ability to erode the swale, but this benefit occurs mostly following the establishment of vegetation in a swale. Check dams may not reduce velocities enough to prevent erosion of seeded bare soil.



5. PLANT MATERIALS AND MAINTENANCE

Function of Vegetation

The vegetation planted along a swale maintains channel stability and improves the swale's ability to filter pollutants from stormwater. For both of these purposes, it is important that swale vegetation meets four criteria. It must:

- Provide a dense cover and a fibrous root or rhizome structure that holds the soil in place and resists erosion;
- stand upright, at least during water-quality level flows, to provide maximum residence time and pollutant removal;
- tolerate a swale's soil conditions; and
- tolerate periodic inundation.¹⁷

Design Considerations

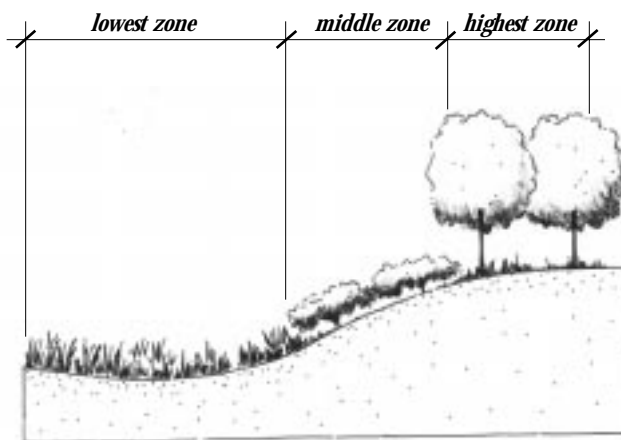
In urban settings, swale vegetation must also meet aesthetic and functional criteria by selecting the appropriate plant for the use, water cycle, and aesthetic goals. Planting design considerations include:

Sight-line. Especially along parking lots and streets, many municipalities require setbacks from intersections, prefer visibility for police surveillance, and have height requirements along pedestrian walkways.

Aesthetics. Swales and their plant materials can present unique and different visual characteristics from conventional drainage or landscape design. Turf grass lawns, woody perennials, drought-tolerant, riparian or exotic plants, and cobbles can all be used, depending on the desired aesthetic effect. The overall planting layout will dictate an aesthetic to the swale—regular, linear planting for a uniform corporate appearance; natural, clustered planting for a softer, more natural appearance.

Native species versus exotic species. Native plant species are ideal for use in swale design. Proper selection of native species for swales can provide year-round vegetative cover without need for supplemental irrigation or fertilization. Furthermore, native species usually provide high habitat value for indigenous birds and other animals. Exotic species can also be appropriate, though some can become invasive if allowed to proliferate. Local municipal agencies or environmental restoration groups can provide guidance on appropriate species. Local landscape ordinances often provide lists of acceptable and non-acceptable plants and grasses.

Planting in accordance with flow and velocity requirements of swale. Selection of turf or



woody plants depends on the desired capacity and residence time of the swale. Generally, woody plant materials should be planted on the side slopes of the swale. Woody plants are not recommended for the vicinity of inflow locations because they tend to collect debris that can block the flow.¹⁸ Plant trees primarily along the edge of the swale, with an understory of shrubs and grasses underneath.

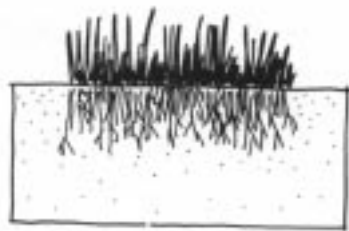
Plant material compatible with water availability of the swale. Swales are generally composed of three basic zones: highest (xeric), middle (mesic), and lowest (hydric). Plant the lowest zone with species that can tolerate standing water and fluctuating water levels. Plant the middle zone with species that tolerate slightly drier conditions and more infrequent fluctuating water levels. Middle zone plants, along the slopes, are often selected for erosion control. Plant the highest zone with species adapted for drier conditions.¹⁹

Plant Types

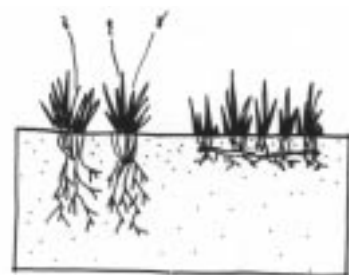
GRASSES

Grass meets many of the functional criteria for swale vegetation, such as dense cover, fibrous root or rhizome structure, and upright growth form. This plant material must be seeded for uniform coverage at rates high enough to provide a dense stand of grass.

When planting grass, the goal is to maximize the chances of intercepting light, early-season rains that establish grass so that there is full establishment before the first erosive rains of the wet season. Supplemental irrigation, geotextiles such as jute matting, and straw mulching may be needed to provide physical protection of the seed and slope, if seeded too late.



annual grass



perennial grass

Annual grasses. Annual grasses are fast-germinating and fast-growing plants that spread quickly and extensively through seed dispersal. The plants react immediately to moisture, producing a fast ground cover following the first rains. They are appropriate for situations requiring quick, temporary channel protection and where full, even coverage is desired. Plant growth is stimulated by mowing or light use. This can be beneficial during dry periods as plants require less water when kept small.²⁰

Perennial grasses. Perennial grasses grow more slowly than annual grasses. The growth period of perennial grasses corresponds with available moisture and favorable temperatures—late winter to midspring for western states, late spring and summer for the midwestern and eastern states. When the supply of soil surface water disappears during drought, shallow-rooted perennial grasses die back to the underground runners, root masses, and stem bases for this period of dormancy.

Perennial grasses are generally sod-forming or bunch-grasses. Sod-forming grasses develop stems and shoots from underground rhizomes. Bunch grass shoots originate at the basal nodes and extend up within the hollow sheaths of old dried stems. Bunch grasses grow in clumps and require dense stands to cover the ground completely.²¹

Woody plant materials. Woody plants such as shrubs and trees are appropriate for planting on the side slopes of swales, as they withstand flooding and stabilize soils. They provide shade and cover, enhancing the habitat value of



woody plants

the swale. When planted in the appropriate zones, woody plants can model the natural pattern of a stream. This can aid public understanding that the swale drainage concept is similar to a stream, with an inflow and an outflow. They are effective at absorbing and storing organic compounds.

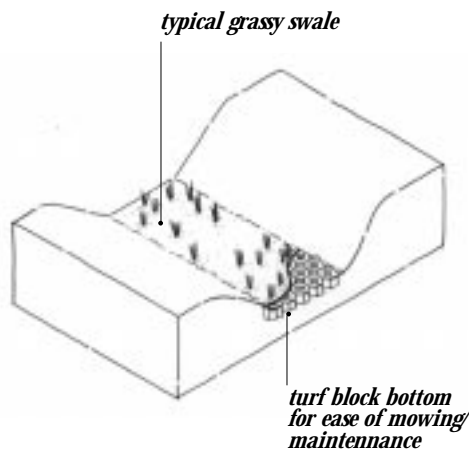
Tree canopy should be limited to areas in which facility managers do not need visibility across the swale for security.

Irrigation for arid climates. Plants for swales in arid climates may require irrigation for establishment and for dry periods. To ensure seed germination and grass establishment, temporary irrigation can be used to help establish grass. In areas with significant dry seasons, plan for a permanent irrigation system and schedule to provide supplemental irrigation throughout the dry season.

Maintenance

Typical maintenance practices for swales include attention to both plant material and the swale's structure.

General plant maintenance includes regular mowing, irrigation, and pruning. Regular mowing stimulates plant growth, encouraging dense coverage. Removal of grass clippings following this practice removes pollutants that have been absorbed by the grass blades. Fertilizers and herbicides are a source of organic compounds and should be avoided as much as possible.



Attending to the swale's structure is critical to its effectiveness as a drainage and pollutant removal system. Maintenance activities include periodic inspection of surface drainage systems to ensure clear flowlines (removal of sediment buildup); repair of surfaces that have been damaged by erosion, rodents, vehicles or other causes; soil cultivation or aeration; care of plant materials; replacement of dead plants; and replenishment of mulch cover. Inspections and repair to swales should be scheduled before the first seasonal rains, and during and after each major storm.

If trash and debris is left to accumulate, it can impede the flow of water, create sediment buildup, and create an unsightly landscape that may result in poor public perception of the swale.

In some urban settings, the constant inflow of irrigation tailings, runoff from air-conditioning condensate, or other minor flows can make maintenance difficult. This "nuisance flow" or "urban slobber" keeps the swale wet and muddy, causing equipment to get stuck or to create tracks that concentrate flow. Maintenance crews may be resistant to mowing in the middle, resulting in

unsightly tall grass/weeds and poor public perception of the swale system. Swale maintenance may require some adjustment on the part of traditional maintenance practices and design for these practices can be incorporated into the swale. Turf block bottoms can be included to provide structural support for mowers, and systems can be implemented to divert flows to allow for maintenance.

Water Quality Effect: Monitoring and Performance

Pollutant removal in swales is measured in two ways. First, reduction in pollutant concentrations in water entering and exiting the swale can be measured. Second, a mass balance of pollutants in the swale may be completed. The latter measurement is important in considering swale pollutant removal, because measuring reduced concentrations in water entering and exiting the swale does not take into account the infiltration of pollutants that may occur along the length of the swale.²²

One can measure pollutant removal in swales by measuring pollutant concentrations in the runoff flowing into the swale, that flowing out, and by accounting for the runoff and pollutants that infiltrate into the swale along its length. This could be accomplished by measuring the difference in the amount of water flowing into the upstream end and out of the downstream end of a swale.

6. KEYS TO SUCCESS



Successful application of vegetated swales involves the coordination of many disciplines and activities. It requires careful follow-through from concept to design to construction and maintenance. Because vegetated swales often represent a change from the current conventional practice, designers must also overcome many barriers before these ideas are accepted.

Frequently Asked Questions

Because this approach is different than the conventional stormwater management approach of conveying water off-site as quickly as possible—“getting rid of the water”—it often raises questions. A few of the most frequently asked questions are addressed below.

IF POLLUTANTS INFILTRATE INTO THE SOIL, WILL THERE BE A PROBLEM WITH CONTAMINATED SOIL OR GROUNDWATER IN THE LONG TERM?

Not usually, especially in residential areas. The risk of contamination is a function of a compound's relative mobility, concentration, and solubility. In residential areas, the concentrations of most pollutants are generally low, and capturing them in the ground where they will eventually degrade is usually the best way to manage them. A recent study published by the U.S. Environmental Protection Agency EPA found that residential areas pose the least risk of groundwater contamination from infiltration practices. This study found that the risk from compounds with greatest potential for groundwater pollution—nitrate-nitrogen, pesticides, organic compounds and heavy metals—was generally low provided that runoff percolates through the soil layer. Runoff from some sites in residential communities with higher concentrations of pollutants, such as car wash facilities and service stations, may not be suitable for infiltration or vegetated swales.

IF WATER IS STANDING IN POOLS OR SWALES, WON'T THEY BREED MOSQUITOES?

Not if they are properly designed and maintained. Vegetated swales should have a maximum residence time of twenty-four to forty-eight hours, meaning that they are designed to dry up within that time frame after a storm. Also, the moving water in vegetated swales doesn't present a good environment for mosquitoes to breed.

WHAT ABOUT COST? AREN'T SWALES EXPENSIVE TO BUILD?

No. A grassy swale costs in the range of one-tenth the cost of a pipe and catch basin system (approximately \$3 per linear foot vs. \$30, depending on circumstances). If the swale is used in place of the conventional storm drain, it will yield a cost savings. If there is a dual system, or complicated overflow mechanisms, it may increase some elements of the project cost.

Overall, however, infiltration, detention, and biofiltration yield significant cost benefits when downstream effects, pollution control, storm drain fees, and other “externalities” are considered.

AREN'T SWALES EXPENSIVE TO MAINTAIN? AND WHO'S RESPONSIBLE FOR MAINTAINING THEM?

Though swales do require regular maintenance, it can often be incorporated in normal landscape maintenance routines. Overall, the maintenance requirements of a properly designed and constructed swale can be comparable to other landscapes, though a different kind of maintenance may be required.

Maintenance responsibility will depend on the swale's design and location. Swales located on private property will be maintained by the homeowner. Swales along streets or in parks may be maintained by a public agency. Still others may be the responsibility of a homeowners' association or management company. In all cases, adequate maintenance and proper education are critical to the long-

term viability. Once people understand the design intent and are given guidance on its proper maintenance, public acceptance increases and maintenance effort can be optimized.

WHAT ABOUT LIABILITY?

Properly designed and maintained vegetated swales present very limited risk. Risk of drowning is very low because they are designed to hold only a few inches of water, and they become dry within a few hours after a storm. They should be sited so that they do not interfere with pedestrian circulation, though they can be an amenity running alongside a greenbelt or walkway. If the sides are properly sloped at a shallow angle, there is very little risk that someone can trip or fall into the swale.

There are many examples of vegetated swales that have been operating continuously without incident or litigation. For example, Village Homes, in Davis, California, was built in the mid-1970s using a surface drainage system that includes infiltration basins and swales in private gardens, community lawns, and children's playgrounds. For over twenty years this system has functioned successfully in a residential environment with no injuries or litigation associated with the storm drain system.

Avoiding Common Problems

While swales can be straightforward to build and plant, lack of experience with swale construction can result in some errors which can be easily avoided. Maintaining good communication with the site manager and construction crew(s) is important.

Simple errors can include:

Neglecting the thickness of the sod. If a swale designed for sod planting is graded without considering the thickness of the sod in setting the finished grade, the swale bed will be approximately two inches higher than the design grade. This can result in a reverse flow into the surrounding drainage area, such as an adjacent street, rather than vice versa.

Dumping construction sediment in the swale. If a finished swale is open to flow before the rest of a construction site is stabilized, sediment can accumulate in the swale, leading to subsequent rilling or the death and erosion of vegetation. Similarly, unvegetated swales that are used to convey runoff during construction should be regraded and vegetated before being used to treat and convey postconstruction runoff.

Inadequate establishment period. If a planted swale is opened to flow before the vegetation has become established, erosion or damage to the planting can occur. In situations where there is a marginal establishment period, or if the onset of seasonal rains does not allow for sufficient plant establishment, vegetation can be stabilized using an erosion control or geotextile fabric.

Improper heights of check dams. If overflow elevations of check dams or weirs are set too high, the swale will hold too much water behind the dam. This can lead to flooding of adjacent areas, or an extended residence time, which, in turn can lead to mosquitoes and other maintenance problems. If the overflow elevations are set too low, inadequate storage behind the dam will result.

In one example, a construction crew purposely set weir elevations below the level indicated on drawings, explaining to the designer that, as drawn, "water will back up behind the dam." Because the contractor was used to thinking in the conveyance paradigm, he believed that failing to "get rid of the water" was a design flaw. Once the purpose of the swale was explained, the contractor understood the design intent and the weir heights were adjusted.

Inadequate communication between design disciplines. Proper swale design requires collaboration between design disciplines, especially the civil engineer and landscape architect. If these plans are not well coordinated, design flaws can be introduced that may not be realized until construction is complete.

For example, an office building project was designed by a landscape architect with a grassy swale and detention basin to drain a small surface parking lot. This initial conceptual design was given to the project's civil engineer for sizing and incorporation on the utility and grading plans. The engineer, thinking that if a little runoff was a good thing, then even more would be better, routed all of the building's roof and parking lot runoff into the basin. This design change was not discovered until after construction when it was observed that the basin stayed full of water, causing the vegetation to die, and mosquitoes began breeding. Since construction was complete, the only solution remaining was to fill the basin with soil and pipe runoff from the parking lot to a nearby conventional underground storm drain. This failure could have easily been avoided by careful, continuous communication between the civil engineer and the landscape architect.

Inadequate inspection and maintenance. Swales should be periodically mowed and occasionally inspected and reseeded to ensure that a strong vegetative cover is being maintained or to repair small eroded patches.

Other regular maintenance practices include debris clearing, checking of inlets and outlets, and regular inspection of check dams and weirs.

In some areas, such as arid parts of California, turfgrass swales require regular irrigation. These irrigation systems also require maintenance. If a swale is planted with native vegetation, irrigation may not be required, although it may be desirable to maintain a regular appearance or to help with the establishment of vegetation when the swale is first constructed.

Inadequate public education. Swales represent a change in people's expectations about storm drainage. If they understand how swales are intended to work, and their purpose, they are more likely to accept them. This acceptance can be fostered through education.

For example, in a recently completed residential development residents complained to the local jurisdiction about the swale's soggy appearance. Residents were also concerned that soap suds and water from their neighbors' car washing was visible as it flowed down the swales to the storm drain. The city responded with public meetings and a printed brochure on grassy swales to educate home buyers on the reasons swales have been designed into the development and the water quality functions they serve.

Checklist for Success

DESIGN STAGE

- Establish a stormwater management awareness among all disciplines in the design team.
- Hold regular cross-discipline coordination meetings to evaluate overall stormwater management solutions as design develops.
- Consult with local nursery person or horticulturist to determine appropriate plant material selection for the site's microclimate and hydrologic regime.
- Verify that stormwater systems are sized appropriately for the given WQV, and that residence time will be within acceptable limits.
- Carefully coordinate related design elements, especially:
 - underground utilities and surface drainage;
 - curb cuts and catch basins;
 - materials and pavement selection;
 - downspouts, area drains, and roof drains; and
 - grading of roads, parking, and adjacent landscape areas.
- Check proposed stormwater solutions with geotechnical engineer to verify suitability given site soil conditions.

CONSTRUCTION DOCUMENTS STAGE

- Ensure details and specifications are coordinated across disciplines (e.g., civil engineering and landscape architecture).
- If plans call for unconventional detailing, such as notched curbs, be sure they are clearly and boldly identified on the drawings as different from conventional details (or contractor may not notice the difference).
- Double-check all calculations for proper sizing and function.
- If using manufactured products, such as turf block, take advantage of manufacturer's design consultation services, if available.

CONSTRUCTION STAGE

- Hold a prebid meeting with all contractors to review principal design elements and site conditions.
- Hold a preconstruction meeting with selected contractor to review construction documents in detail, especially details that differ from those conventionally used.
- Explain to the contractor the design intent of the various stormwater management designs (if they understand why something is designed a certain way, they are more likely to build it the way it's designed).

- Insist on meeting with the job foreman, not just the contractor's estimator or client service representative (the foreman will be the one actually supervising the work).
- Make periodic site visits during construction to ensure that designs are being correctly implemented.

POSTCONSTRUCTION STAGE

- Hold a project closing meeting with the contractor to verify that designs were correctly implemented and to learn how they could be improved.
- Hold a meeting with the owner or the owner's maintenance staff to explain the stormwater system.
- Provide the owner and the maintenance staff with a management handbook describing how the stormwater system is designed to work and how to maintain it.
- Make postoccupancy visits to evaluate long-term performance.



WORKSHEET FOR GRASSY SWALE DESIGN

Introduction

Grassy swales must be designed to treat a small water quality storm and to convey larger peak flows.

Treatment standards can be residence time-based or volume-based, and simple design methods for both are outlined below. Under a residence time-based standard, the swale is designed to provide a given minimum residence time for the water quality design storm. The target residence time should be ten minutes, unless site conditions preclude achieving that. Then the goal should be to maximize residence time within the site constraints.

Under the volume-based standard, the swale is designed to capture the runoff from the water quality design storm. The runoff is then infiltrated or slowly released over the six to twenty-four hours following a storm.

The methods below calculate peak flow capacities for swales that are open channels. For swales that incorporate significant flow restrictions such as small-diameter pipes or large check dams, use your knowledge and experience or check with a civil engineer to determine that the peak flow capacity will be maintained.

Design Process Overview (potential flow chart-type graphic)

IA. RATE-BASED PROCESS (WATER QUALITY DESIGN STORM)

- Find the water quality design storm.
- Calculate the rainfall intensity for the given storm.
- Calculate the expected runoff rate for the storm.
- Calculate the flow rate in the swale.
- Design the swale within the standard slope, channel width, and other design and site constraints to maximize residence time (perform several iterations of the detailed channel design process to determine whether residence time has been maximized).

IB. RATE-BASED PROCESS (PEAK FLOW DESIGN STORM)

Complete these steps after the swale has been designed for the water quality design storm.

- Find the peak flow design storm.
- Calculate the rainfall intensity for the storm.
- Calculate the expected runoff rate for the storm.
- Calculate the flow rate in the swale.
- Using the channel design you have developed in (Ia), check to see whether the channel will convey the Peak Flow Design Storm without eroding.

II. VOLUME-BASED PROCESS

- Find the water quality design storm.
- Calculate the expected total volume of runoff from the water quality design storm.

- Design the swale within the standard design and site constraints to store the expected total volume of runoff from the water quality design storm.
- Check that the swale will either infiltrate or slowly release the stored volume of water within the twenty-four hours following the storm.
- To check this design for stability during peak flows, complete process (Ib).

WHAT YOU WILL NEED:

Information

Area of the site that will drain into the swale.

Percent on-site of each general class of urban surface (e.g., lawns, parking lots, roads) in the drainage area.

Average slope of the site, in percent.

The length of the longest flow path in the drainage area of water to the swale.

Technical Reference 55, *Urban Hydrology for Small Watersheds*, 1986.

Available from the USDA Natural Resources Conservation Service. Can be downloaded from the “Technical Tools” section of their Web page. Their home page is located at: www.nrcg.nrcs.usda.gov.

IA. RATE-BASED METHOD

1. Find the size (P) of the water quality design storm from a local agency, or assume it is the one-inch storm (P = 1").
2. Calculate the water quality design depth (Q). From the given storm, how much water will run off the drainage area and need to be treated? Runoff coefficients for specific storms are given in the table below (from Claytor and Schueler 1996).

SURFACE TYPE	RUNOFF COEFFICIENT	AREA	
		X	=
		X	=
		X	=
		X	=
		X	=
		X	=
		X	=

Total (add the numbers in column 4): _____

Divide the Total by the total drainage area:

Avg. Runoff Coefficient (R) = Total / Drainage Area = _____

Water Quality Design Depth (Q) = P x R = _____

RAINFALL (INCHES)	FLAT ROOFS AND LARGE UNPAVED PARKING LOTS	PITCHED ROOFS AND LARGE IMPERVIOUS AREAS (E.G., LG. PARKING LOTS, STRIP MALLS, ETC.)	SMALL IMPERVIOUS AREAS AND NARROW STREETS	SANDY SOILS	SILTY SOILS	CLAYE Y SOILS
	0.75	.82	.97	.66	.02	.11
1.00	.84	.97	.70	.02	.11	.21
1.25	.86	.98	.74	.03	.13	.22
1.50	.88	.99	.77	.05	.15	.24

3. Calculate the Curve Number (CN) for the drainage area, using the information in chapter 2 of TR-55.

SURFACE TYPE	CURVE NUMBER	AREA	
		X	=
		X	=
		X	=
		X	=
		X	=
		X	=
		X	=

Total (add the numbers in column 4): _____

Divide the Total by the total drainage area:

Avg. Curve Number (CN) = Total / Drainage Area = _____

4. Find the time of concentration (t_c) for water to reach the swale using the information in chapter 3 of TR-55. You will need to know the average slope of the drainage area and the longest distance water flows over the area to reach the swale. This equation may generate a very short time of concentration. Assume a minimum t_c of 0.1 hours, or about five minutes.

t_c = (Path length) / (Average Runoff Velocity) = _____

5. Find the peak discharge using the graph in TR-55, chapter 4. Note that q_u is given in “csm,” or cubic feet per second per square mile of drainage area per inch of rainfall (i.e., volume of water discharged per amount of drainage area per amount of rain. As the amount of rain and the size of the drainage area increase, the volume of water discharged also increases).

$$q_u = \underline{\hspace{2cm}}$$

6. Using the peak discharge (q_u), calculate the water quality design flow (Q_p) in the swale. This is the peak water quality design flow expected to reach the swale, and the one you will use to design the swale.

$$Q_p = q_u \times A \times Q$$

where:

Q_p = the water quality design flow in the swale, in cubic feet per second.

q_u = the peak discharge, in csm.

A = the drainage area, in square miles.

1 sq. mi. = 640 acres (to convert acres to sq. miles, divide acres by 640)

1 sq. mi. = 27,878,400 square feet

(to convert sq. ft. to sq. miles, divide by 27, 878, 400).

Q = the water quality design depth, in inches.

$$Q_p = q_u \times A \times Q = \underline{\hspace{1cm}} \times \underline{\hspace{1cm}} \times \underline{\hspace{1cm}} = \underline{\hspace{2cm}}$$

7. Channel Design. Use Manning’s equation, shown below, to estimate the velocity of water in the swale. The target velocities are shown in the table below.

$$Q_c = 1.49 R^{2/3} S^{1/2} A / n$$

where:

Q_c = the calculated flow in the swale (in cubic feet per second)

A = the cross sectional area of flow (in square feet)

R = hydraulic radius of the channel (in feet)

R is equal to A divided by the wetted perimeter of the swale (in feet) (see illustration).

S = longitudinal channel slope

n = Manning’s roughness coefficient (see table).

DESIGN STORM	VELOCITY (IN FEET PER SECOND)	MANNING’S <i>n</i>
Water Quality Design Storm	less than or equal to 1.0 fps.	0.15
2 year, 24-hour storm	less than or equal to about 4-5 fps.	0.03-0.15
10 year, 24-hour storm	less than or equal to 7 fps.	0.03-0.05

a. First iteration:

Select a given channel type (trapezoidal, parabolic, etc.) and sizing, based on the design standards and site constraints.

Assume a swale flow depth of 0.3 feet (4").

If the site’s slope is < 2%, assume a swale slope (S) equal to the site’s slope. If the site’s slope is >2%, assume a swale slope equal to one percent.

Calculate A, the cross sectional area of flow, assuming the given swale flow depth and using the design you have selected.

Calculate the wetted perimeter of flow (the part of the channel that is wetted by flow).

Calculate R, the hydraulic radius ($R = A /$ wetted perimeter).

Plug A, R, S, and n into Manning’s equation to determine Q_c .

Check to see how Q_c compares with Q_p , the flow for which you are designing.

b. Subsequent iterations:

Adjust slope, flow depth, and/or the channel width until the Q_c you have calculated is equal, or almost equal, to Q_p .

If Q_c is greater than Q_p , decrease slope, flow depth, or channel width and recalculate as above.

If Q_c is less than Q_p , increase slope, flow depth, or channel width and recalculate as above.

c. Velocity test:

Divide Q_c by A to find the average velocity (V) of flow in the channel. Compare it with the standards in the channel. If V is greater than the design standard listed for the storm flow you are testing, then decrease the slope or increase the width of the channel and recalculate as above until V meets the standard.

1B. RATE-BASED METHOD

Follow the same steps as in 1a, but substituting the two-year or ten-year storm information for the water quality design storm information.

2. VOLUME-BASED METHOD

- Find the size (P) of the water quality design storm from a local agency, or assume it is the one-inch storm (P = 1").
- Calculate the water quality design depth (Q). From the given storm, how much water will run off the drainage area and need to be treated? Runoff coefficients are given in the table below (from Claytor and Schueler 1996).

SURFACE TYPE	RUNOFF COEFFICIENT	AREA	
	x		=
	x		=
	x		=
	x		=
	x		=
	x		=
	x		=

Total (add the numbers in column 4): _____

Divide the Total by the total drainage area:

$$\text{Avg. Runoff Coefficient (R)} = \text{Total} / \text{Drainage Area} = \underline{\hspace{2cm}}$$

$$\text{Water Quality Design Depth (Q)} = P \times R = \underline{\hspace{2cm}}$$

- Calculate the water quality design volume (vol), the volume that must be captured for treatment by the swale:

$$\text{Water quality design volume (vol)} = \text{Drainage Area} \times Q = \underline{\hspace{2cm}}$$

- Design the swale, including check dams and/or other detention measures within the swale, to capture this volume of water.
- Check that the infiltration into the swale and/or slow discharge from the weirs and check dams will discharge the volume of water captured within six to twenty-four hours following the storm.
- Use Rate-Based Method 1a to ensure that two- and ten-year flows will not reach erosive velocities.



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¹ US EPA National Water Quality Inventory, Report to Congress, 1994.

² Federal Register, Vol. 55, No. 222, 4799-48091, Nov. 16, 1990.

³ Oakland Tribune, "Fight opens on oil pollution," May 10, 1939.

⁴ Compiled from CDM 1993, EPA 1993, and Horner et al. 1994.

⁵ Wigington et al. 1986; Yousef et al. 1990; Schueler 1994, 1994a.

⁶ Washington 1992.

⁷ WEF/ASCE 1998.

⁸ Claytor and Schueler 1996.

⁹ Lichten 1997.

¹⁰ Livingston et al. 1988.

¹¹ Claytor and Schueler 1996.

¹² Adapted from Ferguson 1998; Harris & Dines 1998; and WEF/ASCE 1998.

¹³ WEF/ASCE 1998.

¹⁴ Oakland 1983 and Horner 1988.

¹⁵ Schueler 1987.

¹⁶ Carroll and Krenitsky 1993.

¹⁷ ABAG 1994, Chan and Kay 1981, Urbonas and Stahre 1993, Schueler 1992, Claytor and Schueler 1996, Berlin 1997.

¹⁸ Schueler 1996.

¹⁹ Schueler 1996, 6-15.

²⁰ Bakker 1971, Lichten 1995.

²¹ Bakker, Elna 1971. *An Island Called California*. University of California Press, Berkeley, Calif.

²² Pitt and McLean (1986) noted that while pollutant concentrations did not change through open channels in metropolitan Toronto, [open channels] did produce twenty-five percent less annual runoff. This effect was particularly evident for storms smaller than a half inch** (in Claytor and Schueler 1996).

²³ Pitt 1996.

SELF-STUDY EXAM

1. How does rapid, concentrated water flow affect the hydrologic cycle?
 - a. increases flood potential
 - b. destabilizes channel
 - c. increases concentration of pollutants
 - d. reduces groundwater levels
 - e. all of the above

2. Which of the following improves pollutant removal rates for swales?
 - a. proper maintenance
 - b. increasing the residence time of water in the swale
 - c. including the swale as part of a treatment train.
 - d. all of the above

3. Which site condition may be inappropriate for a vegetated swale?
 - a. gradually sloping sites
 - b. areas of fill
 - c. suburban sites
 - d. sites with very loamy soils

4. In most areas of the United States, small storms, because of their frequency and cumulative impacts, make the largest contribution to total annual runoff.
True or False

5. Storm water systems must only consider the peak flood control volume.
True or False

6. The Water Quality Volume (WQV) is:
 - a. the amount of noise that water makes when flowing over a check dam or weir
 - b. the volume of water flowing past a certain point in the treatment train
 - c. the amount of runoff that must be treated for water quality protection
 - d. the speed of the flow of water at a certain point in the treatment train

7. List the three common ways to define WQV:
 - 1.
 - 2.
 - 3.

8. The four basic components of swale design are:
- 1.
 - 2.
 - 3.
 - 4.
9. What is the maximum recommended longitudinal slope for a swale without the use of check dams or weirs?
- a. 1%
 - b. 2%
 - c. 4%
 - d. 6%
10. The recommended cross-section for a vegetated swale is:
- a. trapezoidal
 - b. triangular
 - c. parabolic
 - d. rectangular
 - e. convex
11. What is the minimum recommended width of the bottom of a swale that is to be mowed?
- a. 6 inches
 - b. 2 feet
 - c. 3 feet
 - d. 6 feet
12. List three reasons why shallower side slopes are more desirable in the construction of swales.
- 1.
 - 2.
 - 3.
13. To limit erosion and/or sloughing, the steepest recommended side slope of a vegetated swale is:
- a. 5:1
 - b. 3:1
 - c. 2:1
 - d. 1:1

14. To facilitate regular mowing, the steepest recommended side slope of a grassy swale is:
- a. 5:1
 - b. 3:1
 - c. 2:1
 - d. 1:1
15. Freeboard is:
- a. the forming boards that are stripped and discarded in making a concrete weir
 - b. an additional depth of flow capacity to prevent the swale from overflowing
 - c. a fence along a swale to keep people from falling into the water
 - d. the height of a waterfall over a weir
16. Residence time is:
- a. the periodicity of regular swale maintenance in residential subdivisions
 - b. the time it takes for the soil in the swale to be saturated
 - c. the time it takes water to flow in a swale from the inlet to the outlet
 - d. the time it takes for mosquitoes to breed in a swale
17. The optimal method of directing water into a swale is:
- a. to provide for continuous inflow along the entire length of the swale
 - b. to concentrate water into one inlet
 - c. to drop water from a high level over a weir
 - d. to allow water to bubble up from below
18. List one reason why it is better to direct water into a swale by providing a continuous inflow along the entire length of the swale.
19. When a concentrated inlet, such as a pipe or curb cut, is used in designing a swale, it is important to include:
- a. a filter to maintain clean water in the swale
 - b. cobbles or gravel as an energy dissipator
 - c. woody plants to slow the flow of the water
 - d. a weir to pool the water

20. A check dam should be designed to:
- help prevent flooding of a swale system
 - improve quality of water treatment
 - increase residence time
 - increase infiltration
 - all of the above
21. List three types of check dam designs that have been implemented in the field:
- -
 -
22. An orifice or notch should be included in a check dam when:
- there is a high concentration of pollutants present.
 - there is a high flow in the swale.
 - there is a low flow in the swale.
 - the swale slope is greater than 2%.
23. List three potential problems to be aware of during the construction stage:
- -
 -
24. Erosion control techniques should be developed and applied following the completion of the constructed swale.
True or False
25. List 3 methods of developing erosion control in a swale:
- -
 -

26. It is beneficial to remove the grass clippings from the swale after mowing.
True or False
27. Plants used in the middle zone of a swale must have which of the following characteristics:
- a. tolerate regular standing water
 - b. tolerate fluctuating water levels
 - c. shallow root systems
 - d. withstand periodic mowing and foot traffic
28. Which of the following is true regarding vegetation in the swale:
- a. Sod strips should be layed parallel to the direction of flow.
 - b. Woody plants should not be planted in vicinity of the inflow or outflow.
 - c. Seed is always the best turf alternative in a swale.
 - d. Woody plants should be not planted along side slopes of the swale.
 - e. All of the above
29. Which of the following is true about grasses:
- a. Perennial grasses have a very shallow root system.
 - b. Annual grasses only last for a single season.
 - c. Annual grasses provide a quick, even, temporary cover.
 - d. Annual and perennial grasses should not be combined.