CHAPTER six

Stormwater Management and Water Quality Design

OVERVIEW

Changes in land use require designers to give careful consideration to stormwater management issues. The development of previously undisturbed areas or changes in land usage and drainage patterns can lead to localized flooding, stream channel destabilization, erosion, pollution, siltation, and sedimentation. All of these negative effects on the environment can and must be avoided by the careful design of an effective stormwater management system.

An efficient stormwater management plan considers both the quantity and quality of runoff collected. An efficient and cost-effective stormwater management program may entail a variety of design elements depending on site conditions, land use, and local regulations. Many of the components used in stormwater management systems can be manufactured using corrugated steel pipe (CSP). Stormwater management techniques can include structural design elements such as detention, retention, flow control, inlet protection, routing considerations, and water quality devices. Using CSP structures for design elements is an effective technique for achieving stormwater quantity and quality control.

■ Typical CSP underground detention system.

This chapter, while not intended to be a comprehensive evaluation of stormwater management practices, will examine various effective components using CSP that can be incorporated into a stormwater management program to satisfy most site development stormwater management needs.

CSP underground detention.

Urban stormwater runoff can commonly contain some of the following pollutants:

Bacteria: Bacteria are generated from animal and human waste, and can cause the degradation of receiving water bodies to the point that beaches and shellfish beds must be closed and increased costs may be incurred in the treatment of drinking water.

Chlorides: Salts that are applied to roads and parking lots in the winter appear in stormwater runoff in levels that can be higher than tolerable by many freshwater organisms.

Hydrocarbons: Oil and grease that leak from motor vehicles contain a wide variety of hydrocarbons that may be toxic to natural organisms.

Metals: Cadmium, copper, zinc and lead can often be found in the stormwater runoff from urban areas. All of these metals can be toxic to aquatic life when found in high enough concentrations.

Nutrients: Urban runoff has higher than normal levels of phosphorous and nitrogen, which in excessive levels can lead to increased algal growth in the receiving water bodies. Excessive algal growth can block sunlight from reaching underwater grasses and cause the depletion of oxygen. This process is called eutrophication.

Organic Carbon: Organic material, such as leaves and grass clippings get washed off of impervious surfaces during a storm. When these materials reach slow moving water bodies they settle out and decompose. The decomposition process depletes oxygen from the water. Water that has been depleted of oxygen can not support aquatic life.

Pesticides: Pesticides that are commonly used for landscaping and agricultural uses may be incorrectly applied and then washed off by stormwater. Pesticide laden stormwater is toxic to aquatic life.

Suspended Solids: Stormwater falling on impervious surfaces washes off sediment. Other pollutants will often bind to these sediments which will then be deposited into receiving water bodies. Suspended solids will remain in solution depleting water quality and other sediments will sink to the bottom diminishing the depth available for aquatic life.

Thermal Impacts: Because paved areas retain heat in higher quantities than natural groundcovers, the runoff from developed areas is typically higher than pre-development levels. Introducing higher temperature water to receiving water bodies can adversely affect cold water fisheries.

Trash and Debris: Trash and debris, while not necessarily toxic to living organisms can detract from the natural beauty of the environment and have significant impacts to socio-economic well being and tourism.

While it is not the intent of this chapter to present solutions that address all of these pollutants, the stormwater management systems discussed herein when used alone or in combination may help to prevent or ameliorate the effects of some of the pollutants.

The proper design of stormwater management systems must be undertaken to address both the quantities of pre-development, versus post-development flows and the quality of the post development discharges.

TERMINOLOGY

The following definitions apply throughout this chapter:

Best Management Practice (BMP): A Best Management Practice is a system of controls that seeks to prevent or mitigate water pollution from stormwater runoff.

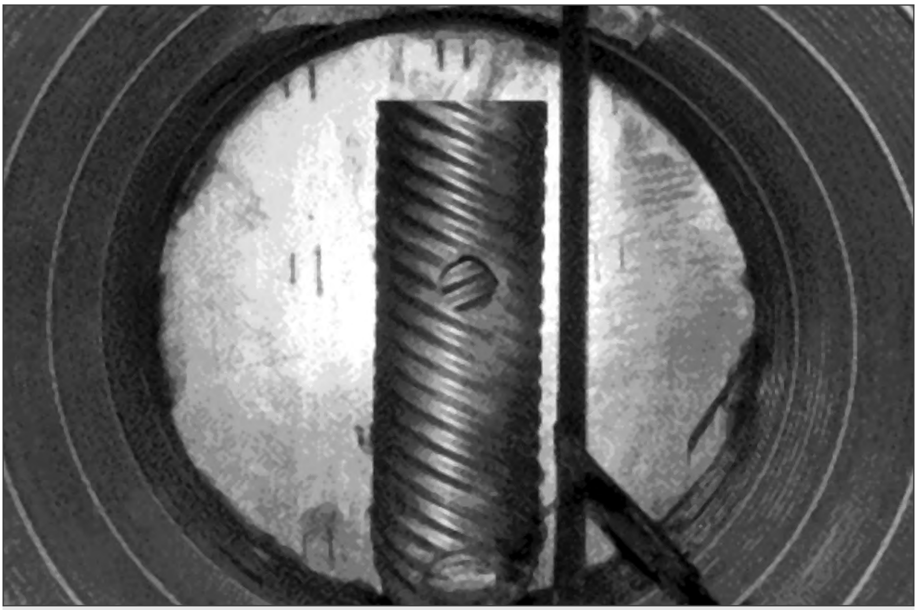
Non-point source discharge: Non-point discharge develops as rainwater, snowmelt or irrigation flows over land surfaces and through the ground, accumulating pollutants and then depositing those pollutants into receiving water bodies. Non-point sources deliver pollutants to surface waters from diffuse sources, including atmospheric deposition.

Total Maximum Daily Load (TMDL): The term TMDL refers to the calculated maximum amount of pollutants a water body may receive to attain or maintain its designated use.

Pre-development discharge: The pre-development discharge rate is the rate of stormwater flow from a project site prior to development activities that may be calculated using acceptable engineering practices. The discharge rate is affected by the return frequency of a particular storm event and its associated rainfall intensity, the cover of the land surface and its slope.

Post-development discharge: Quite often when land is developed there is an increase in the amount of impervious surface cover in the post-development state. That increased impervious area will alter the total amount of stormwater runoff from the development area. In most regulatory jurisdictions there are requirements that the rate of post-development runoff leaving a project site shall not exceed the pre-development discharge rate.

Detention System: A detention system provides a means of storing or detaining stormwater for a controlled release. Detention systems may consist of on-site ponds or below ground structures. CSP for below ground structures provides an economical, structurally sound method of collecting, storing and discharging stormwater that allows for greater utilization of land over an above ground storage system. Frequently, these systems are used under parking lots and recreation areas to maximize land usage. The purpose of a detention system is to manage the difference in the flow rates between the post-development and pre-development conditions. A detention system is designed to provide a proper volume of storage to attenuate the difference between a calculated peak post-development flow and an allowed pre-development flow rate. By providing the proper flow controls to limit the outflow from a detention system and the necessary volume of storage, the post-development flow rate may be managed to not exceed the pre-development rate.



■ Detention outlet control structure.

Typical CSP underground detention system being installed.

Retention System: A retention system consists of either (1) a sump graded into the landscape of a development site or (2) a below ground infiltration structure. The purpose of a retention system is to retain on the project site any increase in post-development versus pre-development stormwater runoff and allow the volume of retained stormwater to infiltrate into the surrounding soils. This allows for the recharging of underground aquifers and prevents downstream flooding from runoff on the post-developed site. Retention systems may only be used where there is adequate soil porosity to allow for the infiltration of the stormwater into the soil in a reasonable period of time. CSP provides an excellent method of achieving underground retention while allowing for utilization of the land above the system.

Water Quality devices: A variety of structures designed to remove pollutants through hydrodynamic forces or filtration. Water quality devices have differing capabilities for removing pollutants. They are useful as pretreatment and polishing systems, depending on their removal efficiencies and local regulations. Pre-treatment systems generally remove sediment, trash, debris and other suspended materials prior to detention or retention systems. Post-treatment or polishing systems are used to remove suspended materials as well as dissolved metals, nutrients, bacteria and chemicals. Post-treatment systems may be used as a stand alone system or in conjunction with detention or retention systems. CSP structures used for water quality include oil/sediment separators and sand filters. Oil/sediment separators are hydrodynamic structures which have been shown to be effective in sediment control and removal of floatables such as trash, debris and oils. Properly designed sand filters have been shown to effectively remove sediment and floatables, similar to the effectiveness of oil/sediment separators. They can also remove suspended and dissolved materials such as dissolved metals, nitrates, phosphates and organic material.

CSP sand filter system

HISTORY AND BACKGROUND

In 1972 amendments to the Federal Water Pollution Control Act, also know as the Clean Water Act, prohibited any discharges of pollutants to waters of the United States from a point source, unless the discharge was covered by a National Pollutant Discharge Elimination System (NPDES) permit. Initial efforts to curb pollution through the Clean Water Act concentrated on improving the quality of discharges from municipal sewage treatment plants and some industrial activities.

With the growing awareness that point sources were not the only significant source of pollutants, the Clean Water Act was amended in 1987 to address the impacts from stormwater runoff.

Phase I of NPDES

In 1990 the U.S. Environmental Protection Agency (EPA) developed Phase I of the NPDES Stormwater Program. The Phase I program addressed sources of stormwater runoff that had the greatest potential to negatively impact water quality. Under Phase I, the EPA required NPDES permit coverage for stormwater discharges from:

- Medium and large municipal separate storm sewer systems (MS4s) located in

incorporated places or counties with populations of 100,000 or more
- Eleven categories of industrial activities which includes construction activities that disturb five acres or more of land.

Phase II of NPDES

The Phase II Final Rule, published in the Federal Register on December 8, 1999, and enacted on March 10, 2003, requires NPDES permit coverage for stormwater discharges from:

- Certain regulated small municipal separate stormwater systems, and
- Construction activities disturbing between one and five acres of land (i.e., small construction activities).

Additionally, EPA Phase II guidelines list six areas that are to be addressed:

1. Public Education and Outreach
2. Public Partnership/ Involvement
3. Illicit Detection and Elimination
4. Construction Site Runoff Control
5. Post-Construction Runoff Control
6. Pollution Prevention/ Good Housekeeping

It is the above referenced Item 5 that this chapter most appropriately addresses. The ability to control post-construction runoff is dependent on the effective use of Best Management Practices (BMPs). These BMPs may be either structural or method based. The method based BMPs are outlines that may be used to control pollution discharges through the proper handling of materials and spill cleanup procedures. The structural BMPs may be proprietary, manufactured systems or they may be land-based that take advantage of ponds, swales and other water handling methods to produce a higher quality stormwater discharge.

Although most states are authorized to implement the NPDES stormwater program, there are several that have opted not to do so. In those states and territories that have opted to not implement the NPDES stormwater program, the EPA is the delegated authority.

HYDROLOGIC AND HYDRAULIC CONSIDERATIONS

The hydrologic and hydraulic design of construction sites using CSP is generally understood and has been covered in this manual in Chapters 3 and 5, respectively. This chapter will not reiterate those practices but will instead examine the various considerations necessary to evaluate and design water quality and quantity structures used for management of stormwater runoff. In general, the hydrologic considerations for stormwater management on construction sites require that the post-developed runoff be equal to or less than the pre-developed conditions (quantity control). This can be accomplished through a variety of designs including detention systems and retention systems. For water quality, regulations define a water quality volume to be treated as the first flush.

Hydrologic Considerations

Most municipalities and states have individual guidelines on the hydrologic parameters and design methods that must be used for water quantity and water quality. For water quantity control, the major consideration is determining the pre-development and post-development hydrograph.

For water quality designs, determining the water quality treatment volume is generally termed the first flush. The most common used definition is based on a volume over the watershed such as the first 1/2 inch of rainfall. Alternatively, the water quality treatment volume may be specified using the volume difference between the pre-developed and post developed run-off hydrographs for a specified rainfall intensity, duration, and return period. Regardless of the parameters and design methods, the calculations are considered for individual watersheds, sub-divided throughout the site.

Pre-Treatment and Post-Treatment Hydraulics

The hydraulics affecting underground structures used in stormwater management systems generally fall into two categories: pre-treatment systems and post-treatment systems. Pre-treatment systems address water quality prior to storage or discharge from the site. These systems are concerned with only removing suspended pollutants from the water quality volume and may incorporate a bypass to accommodate large flows. Post-treatment or polishing systems can be any system designed to remove either suspended pollutants or dissolved pollutants. Filtration systems such as retention systems and sand filters manufactured using CSP are effective post-treatment methods.

COMPONENTS OF STORMWATER AND WATER QUALITY SYSTEMS

Detention/Retention Systems

As defined above, detention systems are systems that collect stormwater runoff from a site and control the release of the water at or below the pre-developed downstream discharge. Retention systems are systems that collect and hold stormwater until it can be released into the existing groundwater system. These systems do not have an outlet or limit the maximum discharge, so downstream flow patterns remain unchanged or reduced from the pre-developed flow patterns.

Typical CSP underground detention system.

Although there are a variety of products and methods available for detention and retention systems, piping systems offer several advantages. Land for development can be costly, and underground piping systems for retention or detention allow for more efficient use of land. Parking lots, landscaping, parks, and recreation areas can be utilized in the area over the storage system. Also, when comparing underground systems with above ground ponds, underground systems minimize the potential for insect breeding and eliminate the need for protective fencing. Underground piping systems are easily inspected and maintained to insure the long term performance of the hydrology and hydraulics of the site.

Recent developments provide detention facilities that are designed for optimal stormwater discharge rates. By quickly matching their actual discharge to the maximum regulated levels, these systems may reduce required storage capacity. They provide similar savings in below or above ground land use and construction costs. Underground detention systems not only reduce the space necessary for new facilities, they can be adopted to existing buried systems and ponds to expand capacities, allowing expansion of an existing development without adding storage capacity. These systems function automatically through flow controls. They do not require power, incur operator costs, or added maintenance costs.

Oil/Sediment Separator Structures

Oil/Sediment structures are useful as pre-treatment for the removal of sediment and floatables. They are basic treatment systems that remove sediment and debris in fluids using the principals of Stoke's law and Hazen's principal. Basically, Stoke's law analysis the rise (for floatable) or fall (for particles) in fluids based on their relative density to that of the fluid, the viscosity of the fluid and the shape of the floatable or particle. Therefore, using Stoke's law, the required velocity for settlement to occur can be calculated. Once the required settling velocity is determined, Hazen's principals can be applied to size an oil/water separator. Hazen's principal assumes that for a given flow and velocity, a separation area will be required to achieve the desired settlement. For stormwater applications, it is important to incorporate flow controls to insure the actual velocity through an oil/water separator is maintained to achieve the removal of floatables and particles.

To size oil/water separators, the design water quality flow, Qwq, should be provided, based on local or state regulations for first flush requirements. The only other data required is the targeted removal efficiency of the oil/water separator. In lieu of specific local regulations, since oil/water separators are generally considered pre-treatment devices, removal of a 50 sieve to a 200 sieve particle size is common. Higher removal rates may be designed but their actual efficiency is lessened, given the wide range of flows that occur in stormwater runoff.

Floatables such as oils, are captured in a separate chamber using a siphon or inverted weir. The primary function of these systems is to remove larger sediment and grit prior to entry into a stormwater storage system (retention or detention system) to enhance water quality and to prevent potential clogging of the storage system.

Sand Filters

Properly designed sand filters provide excellent filtration and pretreatment for stormwater quality. Sand filters remove debris and sediment in a separation chamber. Oils and floatables are removed using filtration through a sand medium, which can also be effective in removing some bacteria and dissolved chemicals. Therefore sand filters can be used for pretreatment or polishing systems. Sand filters are designed to treat a volume of water over a specific period of time. Various filtration media can be used in these systems. However, coarse grained sands are the most common because of their ability to maintain permeability and to effectively remove fine grained materials and some dissolved metals and chemicals. A typical sand filter design includes a pre-treatment sediment basin, a temporary ponding chamber, a filter bed with an underdrain and a clear well outlet. Most systems incorporate provisions for large flow by-pass and cleanouts for maintaining the system. There are three main types of sand filter designs: the Austin filter for large drainage areas (up to 20 acres), the Washington, DC sand filter, and the Delaware sand filter. The latter two are for smaller, urban drainage areas (1 acre or less). The Austin sand filter uses a sediment pond or an underground system with the sand filter as a polishing system. The Washington, DC and Delaware sand filters are similar in design and are a stand alone or combination water quality treatment system. Individual system designs are dependent on local regulations but the principals for design of sand filters are somewhat universal in application. In general, the concept is to calculate the volume of water to treat and the surface area required to treat that volume in a specified period of time. The time period should be based on a reasonable expectation of the interval between storm events and is usually over a 24 hour period. Longer periods may be used, as pollutants and sediment will not accumulate in this short an interval.

DESIGN OF COMPONENTS SYSTEMS

Detention/Retention Systems

Design of retention and detention systems is easily accomplished once the required data is obtained. The required data is the same for both retention and detention systems, but the designs vary slightly based on the outlet design.

Detention Design

Determine the required storage volume, V_{ds}, using the difference in the area of the post-developed versus the pre-developed hydrograph for a given design storm. An example of a typical pre-development and post-developed hydrograph is shown as Figure 6.1.

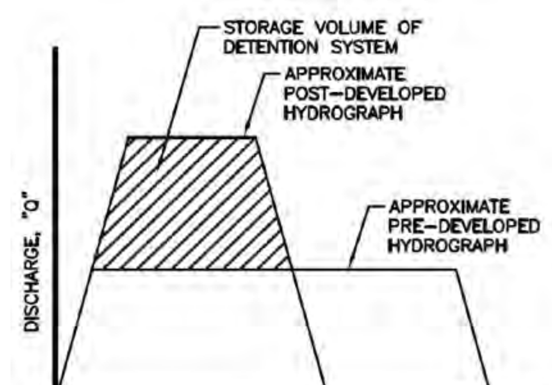


Figure 6.1 Post-developed vs. pre-developed hydrograph.

The pipe diameter, length, and number and extent of laterals can be determined from the following dimensional data:

- Inlet and outlet elevation
- Minimum cover required for pipe
- Length and width of area available for detention system

The design proceeds in the following steps:

(1.) Pipe Diameter. In general, the largest diameter and longest run of pipe will give the most economical design, as it will minimize the number of fabricated fittings for manifold headers. Select the largest diameter pipe as the difference in the inlet invert and the outlet invert. Make sure that elevations are such that minimum cover for the pipe can be provided.

$$D_{max} = \text{inlet invert} - \text{outlet invert}$$

(2.) Pipe Length. From the selected diameter, determine the total length of pipe required, L_{det}, using the storage capacity, SC, tabulated in Table 6.1.

$$L_{det} = V_{ds}/SC$$

(3.) Controlling Surface Dimension. From the area available for the detention system, select the controlling dimension, either length, L, or width, W.

(4.) Surface Area. The area required for the detention system is determined as the surface area per storage volume for the selected diameter. The surface area required per storage capacity is the ratio of center to center pipe spacing (s) per unit length divided by the storage capacity, SC, and can be calculated as:

$$A_{det} = V_{ds} * s/SC$$

(5.) Pipe Length and Width. Determine required length, L_{pipe}, or width, W_{pipe}, as follows:

For controlling length known, L_{pipe} is the available length less excavation overcut and width of header(s);

$$L_{pipe} = L - 2*d - n_{header}*OD$$

where:
- L = available length for detention
- d = distance, trench sidewall to pipe (18 inches typical)
- OD = average pipe outside diameter
- n_{header} = number of manifold headers

For controlling width known, W_{pipe} is available width less excavation overcut;

$$W_{system} = W - 2*d$$

where:
- W = available width for detention
- d = distance, trench sidewall to pipe (18 inches typical)

(6.) Laterals. Determine number of laterals (n) as:

$n = L_{det} / L_{pipe}$ (round down to nearest whole number > 1) for length control

or, $n = L_{det} / W_{system}$ (round down to nearest whole number > 1) for width control

(7.) Volume Check. Rounding down to the nearest whole number of laterals allows for the storage capacity in manifold headers. Detention systems use manifold headers to distribute stormwater between laterals. The number of manifolds used can be expressed as n_{header}. Therefore, the total storage volume provided, V_{det}, can be checked to insure the volume provided exceeds the required storage volume, V_{ds}, as:

$$V_{det} = \Sigma\ [\ (SC * L_{pipe} * n) + SC * (W_{ds} - 2*d) * n_{header}] \geq V_{ds}$$

Usually only one manifold header is required since the water level will equalize through the system. Using manifold headers on each end to increase flow routing through the system, however, is generally not economical due to increased fabrication costs and increased construction costs due to variations in manufacturing tolerances for pipe lengths.

Table 6.1

Pipe storage capacity (ft^3/foot of length)

Pipe Size	Pipe Spacing *	2 2/3 x 1/2	3 x 1	5 x 1	SRP 7 1/2 x 3/4
12	12	0.82	---	---	---
15	12	1.27	---	---	---
18	12	1.82	---	---	1.95
21	12	2.46	---	---	2.62
24	12	3.21	---	---	3.38
27	12	4.05	---	---	4.25
30	18	4.99	---	---	5.21
33	18	6.03	---	---	6.27
36	18	7.17	7.27	7.27	7.43
42	18	9.74	9.85	9.85	10.04
48	24	12.70	12.83	12.83	13.04
54	24	16.05	16.20	16.20	16.44
60	24	19.80	19.96	19.96	20.23
66	36	23.94	24.12	24.12	24.41
72	36	28.47	28.67	28.67	28.99
78	36	33.40	33.61	33.61	33.95
84	36	38.71	38.94	38.94	39.31
90	36	---	44.67	44.67	45.07
96	36	---	50.79	50.79	51.21
102	36	---	57.30	57.30	57.75
108	36	---	64.21	64.21	64.68
114	36	---	71.51	71.51	---
120	36	---	79.20	79.20	---
126	36	---	87.28	87.28	---
132	36	---	95.75	95.75	---
138	36	---	104.62	104.62	---
144	36	---	113.88	113.88	---

*Note: Typical pipe spacing may be reduced depending on the backfill material and compaction used for a specific project.

An example problem of a CSP detention system is included in the Section entitled Design Examples later in this chapter.

Retention Design

Retention system design is similar to detention system design except for the consideration of the additional storage area provided by the void area in the backfill and the permeability of the native soil. Selection of the required retention storage volume, V_{rs}, depends on whether an outlet replicating the pre-developed discharge is provided. If no outlet is provided, the required retention storage volume equals the total area under the post-developed hydrograph less the rate of percolation of the native soil, Figure 6.2. For the case where an outlet replicates the pre-discharge hydrograph, the required storage volume equals the difference between the post-developed and pre-developed hydrograph, Figure 6.3. The retention storage volume, V_{rs}, equals the pipe storage volume plus the storage volume in the voids of the backfill.

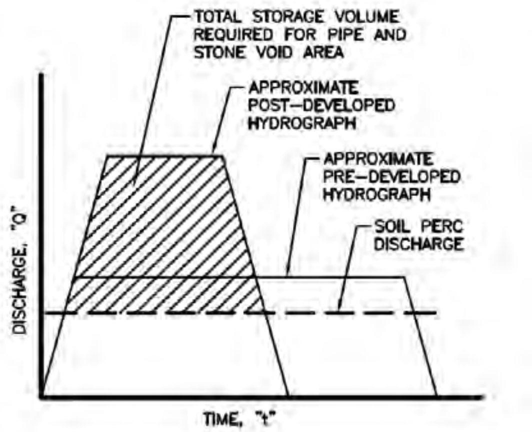


Figure 6.2 Post-developed vs. pre-developed hydrograph retention without outlet.

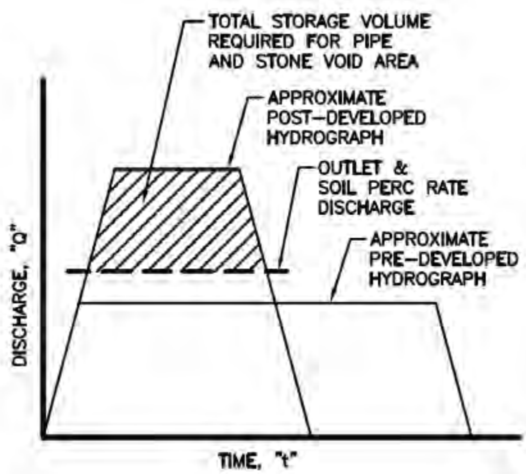


Figure 6.3 Post-developed vs. pre-developed hydrograph retention with outlet.

The pipe diameter, length, and number and extent of laterals can be determined from the following dimensional data:

- Inlet invert elevation
- Elevation of infiltration bed
- Minimum cover
- Length and width available for retention area
- Depth to water table

The design proceeds in the following steps:

(1.) Pipe Diameter. The largest diameter pipe will generally result in the greatest storage volume and the most economical installation. Select the diameter as the difference between the inlet invert less the elevation of the infiltration bed. Minimum cover should be checked for the diameter selected.

$$D_{max} = \text{inlet elev.} - \text{infiltration bed elev.}$$

(2.) Surface Area. From the selected diameter, determine the required surface area of the bed using the ratio of the center to center pipe spacing divided by the storage capacity of the pipe and backfill void space. The backfill void space varies depending on the backfill material used. Typical values for backfill porosities are listed in Table 2. Most aggregate producers can provide recommendations for porosity based on ASTM test methods. The surface (bed) area, A_{ret}, required for a retention system can be approximated as:

$$A_{ret} = V_{rs} * s/(SC + [(OD + s)*(OD + t) - SC]*n)$$

where:
V_{rs} = volume required for retention
s = center to center pipe spacing
SC = storage capacity of pipe
OD = average pipe outside diameter
t = bedding thickness
n = porosity (void) ratio of backfill

The storage capacity of the pipe and backfill can be represented by the denominator in the equation above and is used in subsequent calculations. For convenience, the retention storage capacity, SC_{ret}, should be computed as follows:

$$SC_{ret} = SC + [(OD + s)*(OD + t) - SC]*n$$

(3.) Pipe Length and Width. Determine the total length of pipe required for the retention system, L_{ret},:

$$L_{ret} = V_{rs} / SC_{ret}$$

For controlling length known, L_{pipe} is available length less excavation overcut and width of header(s)

$$L_{pipe} = L - 2*d - n_{header}*OD$$

where: L = available length for retention
d = distance, trench sidewall to pipe (18 inches typical)
OD = average pipe outside diameter
n_{header} = number of manifold headers

For controlling width known, W_{system} is available width less excavation overcut

$$W_{system} = W - 2*d$$

where: W= available width for retention
d = distance, trench sidewall to pipe (18 inches typical)

(4.) Laterals. Determine number of laterals (n) as:

For controlling length known

$n = L_{ret} / L_{pipe}$ (round down to nearest whole number > 1)

$W_{system} = L_{ret} / n$ (round down to nearest whole number increments that matches pipe spacing)

or, for controlling width known

$n = W_{system} / (OD + s)$ (round down to nearest whole number > 1)

$L_{pipe} = L_{ret} / n$ (round down to nearest whole number in 5 ft increments for optimum fabrication)

(5.) Volume Check. Rounding down to the nearest whole number of laterals allows for the storage capacity in manifold headers. Retention systems use manifold headers to distribute stormwater between laterals. The number of manifolds used can be expressed as n_{header}. Therefore, the total storage volume provided, V_{ret}, can be checked to insure the volume provided exceeds the required storage volume, V_{rs}, as:

$$V_{ret} = \Sigma \left[(SC_{ret} * L_{pipe} * n) + SC * (W_{ds} - 2*d) * n_{header} \right] \geq V_{rs}$$

An example problem of a CSP retention system is included in the Section entitled Design Examples later in this chapter.

Table 6.2

Typical porosity for various backfill materials*

Description	Porosity (*n*)
Uniform Graded Sand, Compacted	0.35
Well Graded Sand, Compacted	0.30
Uniform Graded Stone, Compacted	0.40
Well Graded Stone, Compacted	0.28

Note: Values are for typical backfill materials based on specific gradations for aggregates available from most quarries.

Oil/Sediment Structure Design

The design of oil/sediment structures is based on either the rise rate of floatables (oils) or the fall rate of solids (sediment), depending on the targeted removal criteria. Regardless, the calculation for either the rise rate or fall rate is accomplished using Stoke's Law. The required velocity for the rise rate or fall rate is determined based on particle size and its relative density to the stormwater as:

$$V_{(rise/fall)} = [g(\rho_w - \rho_{r/f})d^2/18\mu]$$

where:
- $V_{(rise/fall)}$ = rise or fall rate of targeted removal material (ft/sec)
- g = acceleration due to gravity (ft/sec^2)
- ρ_w = density of water (slug/ft^3)
- $\rho_{r/f}$ = density of targeted material (slug/ft^3)
- d = diameter of targeted material (ft)
- μ = viscosity of water at 68°F

Once the required velocity for settlement is determined, the horizontal settlement area required to achieve separation can be calculated. The horizontal area as opposed to cross-sectional area controls separation. An excellent derivation of the theory of separation using Stoke's Law and the horizontal area of an oil-water separator is presented in the American Petroleum Institute's Publication 421, Feb 1990, and is adapted here for use in circular pipe oil-water separators.

Separation occurs when residence time, t_r, exceeds the residence time, t_s.

$$t_s \leq t_r$$

Theoretically, a particle only has to fall below the elevation of the weir to settle, since at that point the particle would impact the weir and terminate its horizontal velocity and fall. However, to account for velocity acceleration over the weir, it is advisable to assume settlement would not occur until the particle falls farther below the weir. For oil-water separators, the weir is set a minimum of 1 foot below the top of the pipe or at the invert of the inlet pipe, whichever is greater. Therefore, it is conservative to assume settlement

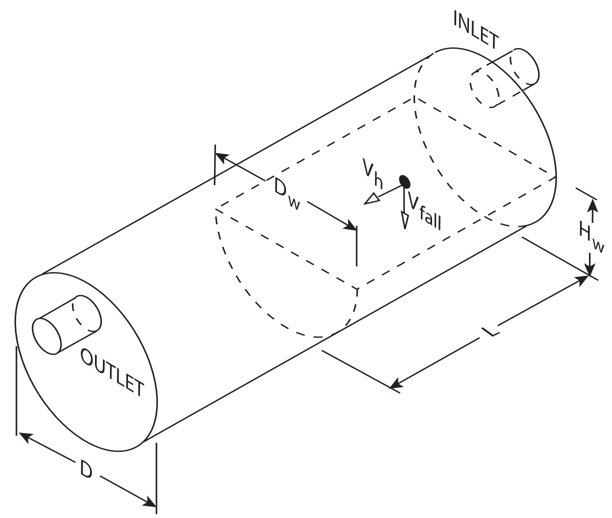


Figure 6.4 Schematic for oil-water separator.

will occur when the particle drops to one-half the diameter. The separation time, t_s, and residence time, t_r, can be calculated from the particle velocities, V_{fall} and V_H, and separation length, L (Figure 6.4), as:

$$t_s = d/2*V_{fall}$$

$$t_r = L/V_H$$

Therefore, to insure separation

$$d/2*V_{fall} \leq L/V_H$$

Solving for the settling velocity

$$V_{fall} \geq V_H\ (d/2*L)$$

Now for continuity, the horizontal velocity (assuming uniform flow) is the flow divided by the cross-sectional area:

$$V_H = Q_{wq}/\pi*(d^2/4)$$

By substitution

$$V_{fall} \geq Q_{wq}\ *d/(2*L*\pi*d^2/4) = 2Q_{wq}/(L*\pi*d)$$

The horizontal area, A_H, at the center of the pipe is:

$$A_H = L*d$$

This assumes uniform flow through the pipe. However, API recommends a dimensionless factor of 1.2 to 1.75 be applied. Since the relative length to diameter is usually large, and to make the factor of $2/\pi$ uniform, a 1.57 factor is recommended. Then, the velocity necessary for settlement becomes:

$$V_{fall} \geq Q_{wq} /(L*d) = Q_{wq} /A_H$$

Now, the velocity calculated by Stoke's Law can be determined to be less than V_{fall}:

$$V_{(rise/fall)} = [g(\rho_w - \rho_{r/f})d^2/18\mu] \leq Q_{wq} /(L*d) = Q_{wq} /A_H$$

Once the required velocity through the oil/sediment is known, the size of the oil/sediment structure is based on the plan view area of the oil/sediment chamber. The time the targeted particle resides in the oil/sediment chamber must be less than the time required for the rise or fall to occur.

An example problem of a CSP oil-water separator system is included in the section entitled Design Examples later in this chapter.

Sand Filter Design

The design for sand filters will focus on small stand alone treatment systems using the Washington, DC and Delaware sand filter systems. This design can easily be adapted to larger systems used in combination with detention systems for storage and pretreatment. The basic information needed for design is the water quality volume, W_{QV}, and the duration of the discharge through the filter media. This chapter will not attempt to select a W_{QV} as that is usually dictated by the local regulatory agency. However, based on typical applications, the volumetric approach most commonly used is to select a rainfall volume for the percent impervious of the drainage area, which will allow calculating the volume on the watershed to be treated. This would be the first flush in a volumetric approach which has been discussed in earlier sections of this chapter. Once the volume to be treated is calculated, selection and design of the sand filter system is relatively straightforward by varying proportional relationships between surface area and permeability.

Design calculations may proceed as follows.

(1.) Determine minimum surface area of sand filter:

$$A_f = W_{QV}*d_{fg}/[k*(h_f + d_{fg})*t_f]$$

where: W_{QV} = water quality volume

d_{fg} = depth of filter media (sand & gravel)
k = permeability of filter media, typically between 2 to 4 ft/day (3.5 ft/day normally used for design)
h_f = average height of water above sand filter (distance from top of filter to overflow)/2
t_f = filtration time (user defined, typically 40 hrs)

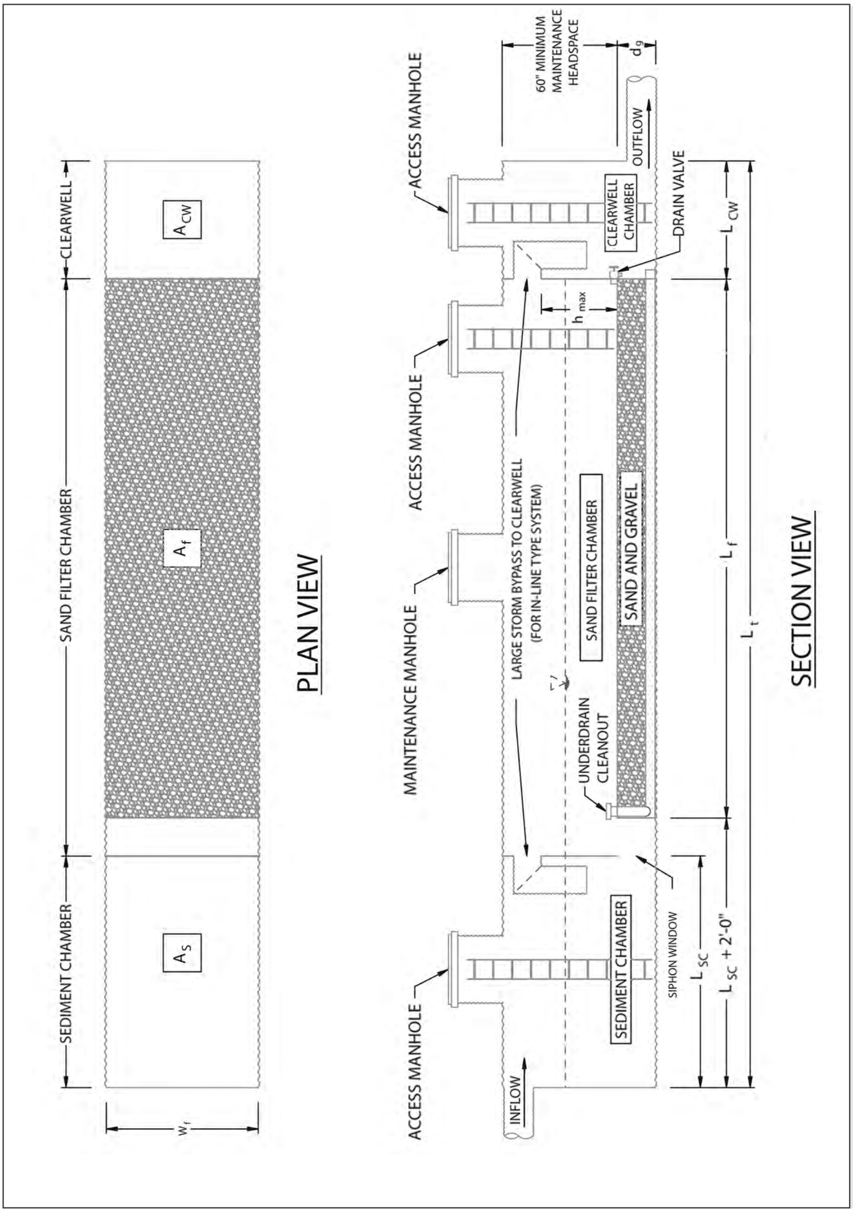


Figure 6.5 Typical sand filter.

(2.) Determine width of sand filter:

$$W_f = 2[2 * r * d_{fg} - d_{fg}^2]^{1/2}$$

where: r = radius of pipe
d_{fg} = depth of filter media (sand & gravel)

(3.) Determine length of sand filter:

$$L_f = A_f / W_f$$

(4.) Determine length of sediment chamber:

Since sand filters are designed for long filtration times (t_f), sediment chambers are sized as a percentage of the water quality volume, typically 20% of the water quality volume.

An example problem of a CSP sand filter system is included in the section entitled Design Examples later in this chapter.

INSPECTION, OPERATION AND MAINTENANCE

Stormwater Management Systems

Most stormwater management systems are designed to be self-operating without the need for maintenance personnel to be involved in day-to-day operations. This is especially beneficial because of the sporadic nature of rainfall occurrences. It is undesirable to have a stormwater management system that requires human intervention when weather conditions might be the most adverse. Although there are some emergency flow control devices that require manual operation, the most effective designs are those that automate even the emergency devices. An example of this is the use of an emergency stop valve at a bulk petroleum distribution facility. Normal operations at one of these facilities may allow stormwater runoff to flow unrestricted from the site to a receiving water body. To prevent a catastrophic spill at this type of facility there may be a valve that could be manually closed to allow spilled materials to be contained within a secondary containment system. What would be preferable to the manual valve would be a commercially available automatic valve that would sense the difference in the specific gravities between ordinary stormwater runoff and the lighter petroleum products and automatically close, thus allowing for the retention of the spilled material on site.

The operation of other stormwater management systems may be as simple as ensuring that drainage piping and culverts remain free of accumulated debris, to as complex as the rehabilitation of failing culverts. To ensure the proper operation of storm drains and culverts, visual inspections of all facilities within a given jurisdiction should be undertaken on a yearly basis. Reports of flooding upstream of structures should be compiled and tracked and used for a regular analysis of the particular system.

If frequent flooding is reported upstream of a particular structure, then consideration should be given to a more extensive inspection, which may require the use of video cameras. Video cameras may be introduced to a culvert or drain line and can provide a record of the interior of the structure with corresponding stationing that can be used to identify problem areas.

Maintenance of culverts quite often requires the use of high pressure water jets and vacuum trucks to free and remove accumulated debris. High pressure water jets often employ the use of jetting heads that will direct a spray backward towards the starting point of the operation and propel the head forward into the culvert. As the jetting head moves forward the water that is directed backward moves debris toward the starting point where it may be vacuumed out. In some cases a rotary root cutter may be used to remove roots that may find their way into the cracks between pipe sections.

Failing culverts are often replaced by a full depth excavation and replacement. Sometimes it is more cost-effective to repair the culvert with a relining operation. In this case a pipe of somewhat smaller diameter is inserted into the culvert, sometime employing the use of guide rails to maintain the correct position within the culvert. When the relining pipe is completed inserted into the culvert, a grout mix is pumped through plugs in the structure to create a self contained replacement culvert. In this manner, the strength of the replacement pipe may be relied upon to carry the full load.

Water Quality Systems

The maintenance of water quality systems depends upon the nature of their construction. Land based systems that employ wet ponds, swales or detention ponds will require excavation of accumulated debris, the replacement of soils, and replanting of native vegetation or wetland plants. Manufactured systems are typically more easily maintained through the use of a vacuum truck and high pressure water.

In the case of either land based, or manufactured systems, detailed inspection and maintenance logs should be kept to allow for the review of successfulness of the devices and to assist in the scheduling of future maintenance events.

DESIGN EXAMPLES

Detention System Design Example Using Corrugated Steel Pipe

Given: Inlet elevation = 100.0 ft
Outlet elevation = 95.3 ft
Detention Volume Required Vds = 3,500 ft^3
Available length for detention system = 45ft
See section on Detention Design for equations used below.

Determine maximum pipe diameter:

D_{max} = 100.00 – 95.3 = 4.7 ft (note system size could be increased by size of inlet pipe)

Try 54 inch diameter 3x1 inch corrugated steel pipe
From Table 6.1, Storage Capacity, SC = 16.2 ft^3/ft

Calculate total pipe length required, L_{det}:

L_{det} = 3,500/16.2 = 216 ft

From the available length for the detention system, calculate actual length of detention system with manifold header on each end:

L_{pipe} = 45 – 2 (1.5) – 2 (56/12) = 32.7 ft   Use 32 ft laterals.

Determine number of laterals, n:

n = 216/32 = 6.75   Use 6 laterals.

Determine width of system header:

W_{sys} = 6 (56/12) + 5 (2.25) = 39.25 ft header

Calculate total storage volume provided:

V_{det} = [32 (16.2) (6)] + [(39.25) (16.2) (2)] = 4382 ft^3 > 3,500

Since there were two headers, the volume provided is greater than required and it may be possible to eliminate a lateral to provide a more economical system. Therefore, recalculate with 5 laterals.

W_{sys} = 5 (56/12) + 4 (2.25) = 32.33 ft header

And

V_{det} = [32 (16.2) (5)] + [(32.33) (16.2) (2)] = 3639 ft^3 > 3,500 required

Therefore; use 54 inch diameter 3x1 inch corrugated steel pipe with five 32 foot laterals and two manifold headers as shown in Figure 6.6.

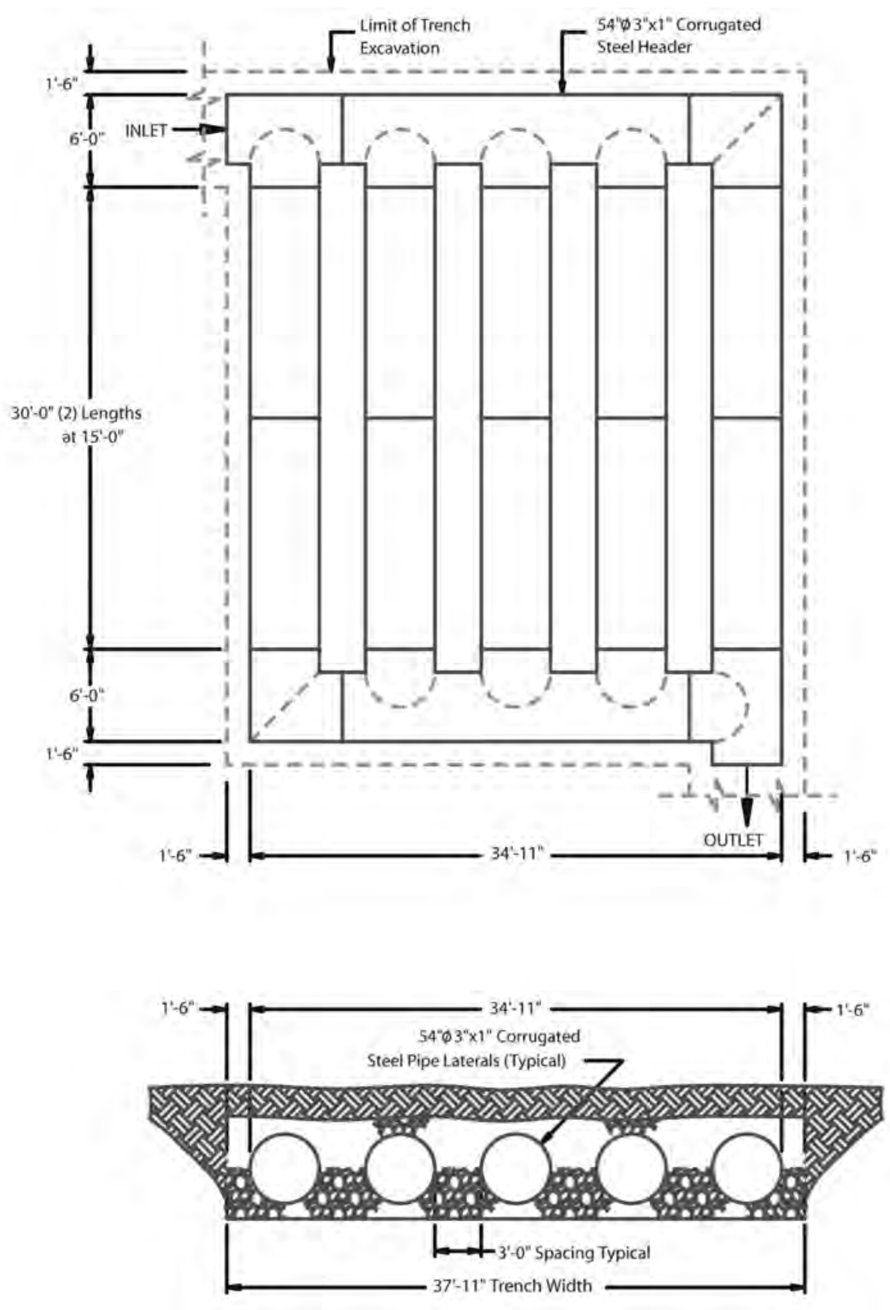


Figure 6.6 Detention system layout for design example.

Retention System Design Example Using Corrugated Steel Pipe

Given: Inlet elevation = 60.0 ft
Infiltration bed elevation = 52.0 ft
Retention Volume Required V_{rs} = 150,000 ft^3
Available width for retention system = 100 ft
See section on Retention Design for equations used below.

Determine maximum pipe diameter:

D_{max} = 60.00 – 52.0 = 8.0 ft (note system size could be increased by size of inlet pipe)

Try 96 inch diameter 5x1 inch perforated corrugated steel pipe with 1 1/2 inch clean washed stone having a void ratio of 40%. From Table 6.1, Storage Capacity, SC = 50.79 cf.

Calculate Area of retention bed, A_{ret}:

$$A_{ret} = [150{,}000\ (98 + 36)/12] / [50.79 + [(98 + 36)\ (98 + 6)/144 - 50.79]\ (0.40)] = 24{,}210\ ft^2$$

Determine total length of perforated pipe required for retention system:

$$L_{ret} = 150{,}000/[50.79 + [(98 + 36)\ (98 + 6)/144 - 50.79]\ (0.40)] = 2168\ ft$$

Since the width is limited to 100 ft, determine actual retention system width, W_{sys}:

$$W_{sys} = 100 - 2\ (1.5) = 97\ ft$$

Determine number of laterals required, n:

$n = 97/[(98+36)/12] = 8.7$ Use 8 laterals with one header.

Determine length of laterals, L_{pipe}:

$L_{pipe} = 2168/8 = 271$ ft Try 265 ft. laterals.

Determine retention volume provided, V_{ret}:

$$V_{ret} = 265\ (8)\ [50.79 + [(98 + 36)\ (98 + 6)/144 - 50.79]\ (0.40)] + 50.79\ [(98)(8)/12 + (36)\ (7)/12] = 151{,}057\ cfs > 150{,}000\ ft^3\ OK$$

Use 8 laterals of 96 inch diameter 5x1 inch perforated corrugated steel pipe at 265 feet long with 1 1/2 inch clean washed stone backfill. To insure adequacy of the design, the infiltration rate of a 97 foot by 265 foot bed should be verified.

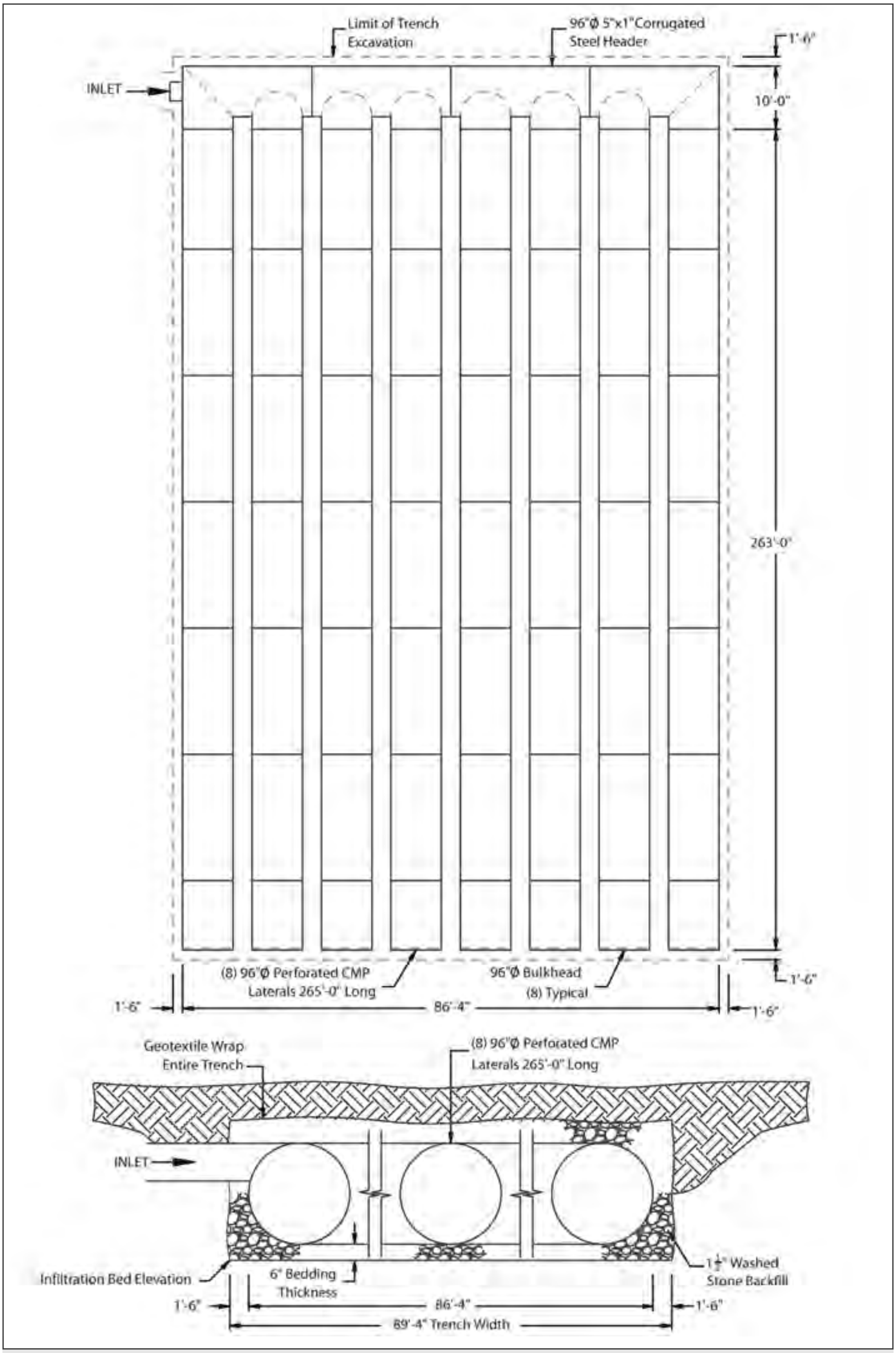


Figure 6.7 Retention system layout for design example.

Design of CSP Oil/Sediment Separator Structure

Given: Targeted particle size = 140 sieve = 0.000342 ft
Water quality flow, Qwq = 2.3 ft^3/s
Density – soil, rsoil = 120 lb/ft3
Density – water, rwater = 62.4 lb/ft3
Viscosity of water @ 68o F, m = 2.1 x 10-5 lbf-sec/ft^2
See section on Oil/Sediment Separator Structure Design for discussion of equations used below.

Convert density to slug/ft^3, 1 slug = 32.17405 ft/sec^2:

Density – soil, ρ_{soil} = 120/32.17405 = 3.73 slug/ft^3

Density – water, ρ_{water} = 62.4/32.17405 = 1.94 slug/ft^3

Determine required settling velocity:

$$V_{(rise/fall)} = g(\rho_{soil} - \rho_{water})d^2/18\ \mu$$
$$= 32.2(3.73\text{-}1.94)(0.000342)^2/18(2.1\text{x}10^{-5})$$
$$= 0.0178 \text{ ft/sec}$$

Determine horizontal settlement area required:

$V_{(rise/fall)} > Q_{wq}/(A_H)$
Assumes particle falls 1/2 of pipe diameter and turbulence factor of 1.57.

$0.0178 > 2.3/(A_H)$

Solving for A_H

$A_H > 2.3/0.0178 = 129.2\ ft^2$

Try 48" diameter pipe and find length :

L = 129.2/4 = 32.3 ft

Note: If turbulence is eliminated and fall is limited to the top of the weir (1 ft) L = 32.3/1.57(2/1) = 10.29 ft. However, this is not as conservative. Additionally, in lieu of sizing the oil chamber, it is common practice to make them 1/3 of the sediment chamber since the predominant runoff for most sites is sediment.

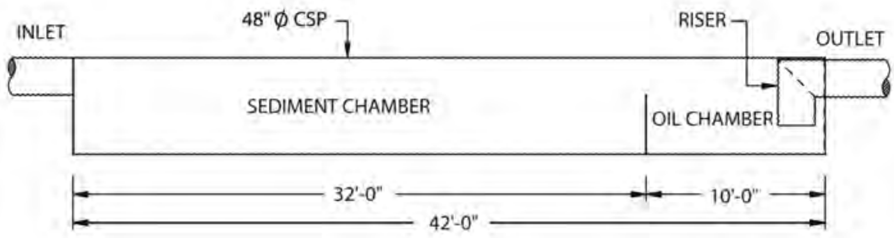


Figure 6.8 Schematic of Oil/Water Separator

Design of CSP Sand Filter

Given: Assume a 1 acre site that is 80% impervious and a 1 inch rainfall. The inlet is an 18 inch diameter pipe with the invert 2 feet below grade. The maximum distance to the outfall is 8 feet below the invert of the inlet pipe. Try a 96 inch diameter sand filter.

d_{fg} = depth of filter (typically 1.5 to 2.0 ft) = 2.0 ft

k = permeability of filter media = 3.5
(typically 2 to 4 ft/day, 3.5 ft/day normally used for design)

t_f = filtration time (user defined, typically 24 to 48 hours) = 48 hours

See section on Sand Filter Design for equations used below.

Determine water quality volume:

$$W_{QV} = (\%\ \text{impervious}/100)(\text{rainfall})(\text{site acres})(43{,}560\ \text{ft}^2/\text{acre})$$
$$= (80/100)(1/12)(1)(43{,}560)$$
$$= 2{,}904\ \text{ft}^3$$

Determine height to bypass, h_{max}:

$$h_{max} = D - d_{fg} - \text{dinlet}$$
$$h_{max} = (96/12) - 2 - 1.5 = 4.5\ \text{ft}$$

Average height over filter, h_f:

$$h_f = h_{max}/2$$
$$h_f = 4.5/2 = 2.25\ \text{ft}$$

Determine minimum surface area:

$$A_f = W_{QV} d_{fg} / [k(h_f + d_{fg}) t_f]$$
$$= 2{,}904\ (2)/[(3.5)(2.25{+}2)(48/24)] = 195.2\ ft^2$$

Determine width of filtration bed:

$$W = 2(2rd_{fg} - d_{fg}^{2})^{1/2}$$
$$= 2[2(4)(2.0) - (2.0)^2]^{1/2}$$
$$= 6.93\ ft$$

Determine length of filtration bed:

L = 195.2/6.93 = 28.2 ft Say 28.5 ft

Determine sediment chamber length as 20% of W_{QV}:

Volume required = 2,904(0.20) = 581 ft^3

Length of chord at h_{max} elevation
c = 2 [(8/2) – 2.52]1/2 = 6.24 ft

Area in sediment chamber = $1/2\ \pi\ (8/2)^2 + 1/2\ (6.48 + 8)(8/2 - 1.5) = 43.2\ ft^2$

Length of sediment chamber = 581/43.2 = 13.4 ft. Say 13.5 ft

Total length of sand filter structure including a 5 foot length of clearwell for access:

L = 28.5 + 2 + 13.5 + 5 = 49.0

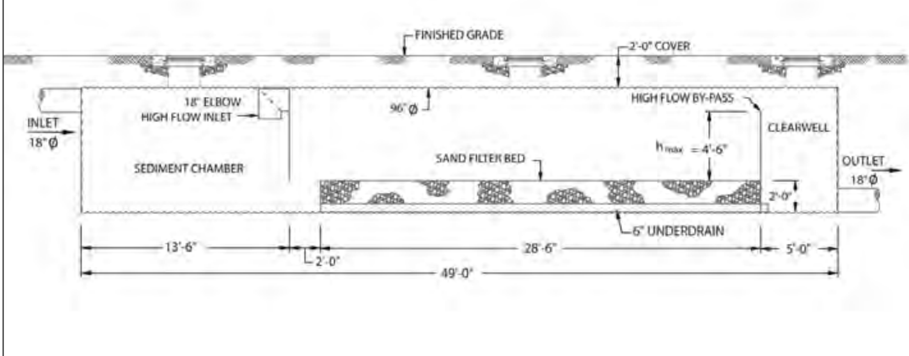


Figure 6.9 Sand filter layout for design example.

BIBLIOGRAPHY

American Petroleum Institute, "Design and Operation of Oil-Water Separators," Publication 421, Feb. 1990.

US Environmental Protection Agency, "Stormwater Technology Fact Sheet – Sand Filters", Sept. 1999.

Typical CSP underground detention system for a new housing development.

■ **Figure 7.1** A corrugated steel long span structure will soon be a stream crossing under a freeway.