

Chapter 2

Control Measure Selection

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1.0 Control Measure Selection

This chapter provides requirements for selecting control measures for all new development or redevelopment projects for which construction activities disturb greater than or equal to 1 acre, including projects less than 1 acre that are part of a larger common plan of development or sale. These requirements are to be incorporated into qualifying development projects during the planning phase of a project. Control measure selection involves many factors such as physical site characteristics, treatment objectives, aesthetics, safety, maintenance requirements, and cost. Typically, there is not a single answer to the question of which control measure (or control measures) should be selected for a site; there are usually multiple solutions ranging from stand-alone control measures to treatment trains that combine multiple control measures to achieve the water quality objectives. Factors that must be considered when selecting control measures are the focus of this chapter.

1.1 Physical Site Characteristics

The first step in control measure selection is identification of physical characteristics of a site including topography, soils, contributing drainage area, groundwater, baseflows, wetlands, existing drainageways, and development conditions in the tributary watershed (e.g., construction activity). A fundamental concept of Low Impact Development (LID) is preservation and protection of site features including wetlands, drainageways, soils that are conducive to infiltration, tree canopy, etc., that provide water quality and other benefits. LID stormwater treatment systems are also designed to take advantage of these natural resources. For example, if a portion of a site is known to have soils with high permeability, this area may be well-suited for rain gardens or permeable pavement. Areas of existing wetlands, which would be difficult to develop from a Section 404 permitting perspective, could be considered for polishing of runoff following control measure treatment, providing additional water quality treatment for the site, while at the same time enhancing the existing wetlands with additional water supply in the form of treated runoff.

Some physical site characteristics that provide opportunities for control measures or constrain control measure selection include:

- **Soils:** Soils with good permeability, most typically associated with Hydrologic Soil Groups (HSGs) A and B provide opportunities for infiltration of runoff and are well-suited for infiltration-based control measures such as rain gardens, permeable pavement systems, sand filter, grass swales, and buffers, often without the need for an underdrain system. Even when soil permeability is low, these types of control measures may be feasible if soils are amended to increase permeability or if an underdrain system is used. In some cases, however, soils restrict the use of infiltration based control measures. When soils with moderate to high swell potential are present, infiltration should be avoided to minimize damage to adjacent structures due to water-induced swelling. In some cases, infiltration based designs can still be used if an impermeable liner and underdrain system are included in the design; however, when the risk of damage to adjacent infrastructure is high, infiltration based control measures may not be appropriate. In all cases, consult with a geotechnical engineer when designing infiltration control measures near structures. Consultation with a geotechnical engineer is necessary for evaluating the suitability of soils for different control measure types and establishing minimum distances between infiltration control measures and structures.
- **Watershed Size:** The contributing drainage area is an important consideration both on the site level and at the regional level. On the site level, there is a practical minimum size for certain control measures, largely related to the ability to drain the WQCV over the required drain time. For example,

it is technically possible to size the WQCV for an extended detention basin for a half-acre site; however, designing a functional outlet to release the WQCV over a 40-hour drain time is practically impossible due to the very small orifices that would be required. For this size watershed, a filtering control measure, such as a rain garden, would be more appropriate. Because of their tendency for excessive clogging, extended detention basins (EDBs) are not approved for use for sites containing less than two impervious acres.

At the other end of the spectrum, there must be a limit on the maximum drainage area for a sub-regional facility to ensure adequate treatment of rainfall events that may produce runoff from only a portion of the area draining to the control measure. If the overall drainage area is too large, events that produce runoff from only a portion of the contributing area will pass through the control measure outlet (sized for the full drainage area) without adequate residence time in the control measure.

- **Groundwater:** Shallow groundwater on a site presents challenges for control measures that rely on infiltration and for control measures that are intended to be dry between storm events. Shallow groundwater may limit the ability to infiltrate runoff or result in unwanted groundwater storage in areas intended for storage of the WQCV (e.g., porous sub-base of a permeable pavement system or in the bottom of an otherwise dry facility such as an extended detention basin). Conversely, for some types of control measures such as wetland channels or constructed wetland basins, groundwater can be beneficial by providing saturation of the root zone and/or a source of baseflow. Groundwater quality protection is an issue that should be considered for infiltration-based control measures. Infiltration control measures may not be appropriate for land uses that involve storage or use of materials that have the potential to contaminate groundwater underlying a site (i.e., "hot spot" runoff from fueling stations, materials storage areas, etc.). If groundwater or soil contamination exists on a site and it will not be remediated or removed as a part of construction, it may be necessary to avoid infiltration-based control measures or use a durable liner to prevent infiltration into contaminated areas. Design of stormwater facilities shall evaluate the potential impacts of groundwater. Investigations shall be performed to determine the potential impacts, and the results used to design stormwater facilities that function well with the site's groundwater status.
- **Base Flows:** Base flows are necessary for the success of some control measures such as constructed wetland ponds, retention ponds and wetland channels. Without baseflows, these control measures will become dry and unable to support wetland vegetation. For these control measures, a hydrologic budget, which accounts for the water inflow, outflow and storage shall be evaluated. Water rights are also required for these types of control measures in Colorado.
- **Watershed Development Activities (or otherwise erosive conditions):** When development in the watershed is phased or when erosive conditions such as steep slopes, sparse vegetation, and sandy soils exist in the watershed, a treatment train approach is encouraged. Control measures that utilize filtration should be protected until the upstream watershed is completely stabilized. When naturally erosive conditions exist in the developed watershed, pretreatment measures designed to capture sediment are highly recommended. The designer shall consider existing, interim and future conditions to select the most appropriate control measures.

1.2 Space Constraints

Space constraints are frequently cited as feasibility issues for control measures, especially for high-density, setback to setback development and redevelopment sites. In some cases, constraints due to space limitations arise because adequate spaces for control measures are not considered early enough in the planning process. This is most common when a site plan for new or re-development is developed and control measures are squeezed into the remaining spaces. The most effective and integrated control

measure designs begin by determining areas of a site that are best suited for control measures (e.g., natural low areas, areas with well-drained soils) and then designing the layout of roads, buildings, and other site features around the existing drainage and stormwater resources of the site. Allocating a small amount of land to water quality infrastructure during early planning stages will result in better integration of water quality facilities with other site features. The Four Step Process is still required for sites with space constraints as applicable according to Chapter 1.

1.3 Targeted Pollutants and Control Measure Processes

Control measures have the ability to remove pollutants from runoff through a variety of physical, chemical and biological processes. The processes associated with a control measure dictate which pollutants the control measure will be effective at controlling. Primary processes include peak attenuation, sedimentation, filtration, straining, adsorption/absorption, biological uptake and hydrologic processes including infiltration and evapotranspiration. For many sites, a primary goal of control measures is to remove gross solids, suspended sediment and associated particulate fractions of pollutants from runoff. Processes including straining, sedimentation, and infiltration/filtration are effective for addressing these pollutants. When dissolved pollutants are targeted, other processes including adsorption/absorption and biological uptake are necessary. These processes are generally sensitive to media composition and contact time, oxidation/reduction potential, pH and other factors. In addition to pollutant removal capabilities, many control measures offer channel stability benefits in the form of reduced runoff volume and/or reduced peak flow rates for frequently occurring events. Brief descriptions of several key processes, generally categorized according to hydrologic and pollutant removal functions are listed below:

Hydrologic Processes

1. **Flow Attenuation:** Control measures that capture and slowly release the WQCV help to reduce peak discharges. In addition to slowing runoff, volume reduction may also be provided to varying extents in control measures providing the WQCV.
2. **Infiltration:** Control measures that infiltrate runoff reduce both runoff peaks and surface runoff volumes. The extent to which runoff is reduced depends on a variety of factors such as whether the control measure is equipped with an underdrain and the characteristics and long-term condition of the infiltrating media. Examples of infiltrating control measures include (unlined) sand filters, bioretention and permeable pavements. Water quality treatment processes associated with infiltration can include filtration and sorption.
3. **Evapotranspiration:** Runoff can be reduced through the combined effects of evaporation and transpiration in vegetated control measures. Plants extract water from soils in the root zone and transpire it to the atmosphere. Evapotranspiration is the hydrologic process provided by vegetated control measures, whereas biological uptake may help to reduce pollutants in runoff.

Pollutant Removal/Treatment Processes

1. **Sedimentation:** Gravitational separation of particulates from urban runoff, or sedimentation, is a key treatment process by control measures that capture and slowly release runoff. Settling velocities are a function of characteristics such as particle size, shape, density, fluid density, and viscosity. Smaller particles under 60 microns in size (fine silts and clays) (Stahre and Urbonas, 1990) can account for approximately 80% of the metals in stormwater attached or adsorbed along with other contaminants and can require long periods of time to settle out of suspension. Extended detention allows smaller

particles to agglomerate into larger ones (Randall et al, 1982), and for some of the dissolved and liquid state pollutants to adsorb to suspended particles, thus removing a larger proportion of them through sedimentation. Sedimentation is the primary pollutant removal mechanism for many treatment control measures including extended detention basins, retention ponds, and constructed wetland basins.

2. **Straining:** Straining is physical removal or retention of particulates from runoff as it passes through a control measure. For example, grass swales and grass buffers provide straining of sediment and coarse solids in runoff. Straining can be characterized as coarse filtration.
3. **Filtration:** Filtration removes particles as water flows through media (often sand or engineered soils). A wide variety of physical and chemical mechanisms may occur along with filtration, depending on the filter media. Metcalf and Eddy (2003) describe processes associated with filtration as including straining, sedimentation, impaction, interception, adhesion, flocculation, chemical adsorption, physical adsorption, and biological growth. Filtration is a primary treatment process provided by infiltration control measures. Particulates are removed at the ground surface and upper soil horizon by filtration, while soluble constituents can be absorbed into the soil, at least in part, as the runoff infiltrates into the ground. Site-specific soil characteristics, such as permeability, cation exchange potential, and depth to groundwater or bedrock are important characteristics to consider for filtration (and infiltration) control measures. Examples of filtering control measures include sand filters, bioretention, and permeable pavements with a sand filter layer.
4. **Adsorption/Absorption:** In the context of control measures, sorption processes describe the interaction of waterborne constituents with surrounding materials (e.g., soil, water). Absorption is the incorporation of a substance in one state into another of a different state (e.g., liquids being absorbed by a solid). Adsorption is the physical adherence or bonding of ions and molecules onto the surface of another molecule. Many factors such as pH, temperature and ionic state affect the chemical equilibrium in control measures and the extent to which these processes provide pollutant removal. Sorption processes often play primary roles in control measures such as constructed wetland basins, retention ponds, and bioretention systems. Opportunities may exist to optimize performance of control measures through the use of engineered media or chemical addition to enhance sorption processes.
5. **Biological Uptake:** Biological uptake and storage processes include the assimilation of organic and inorganic constituents by plants and microbes. Plants and microbes require soluble and dissolved constituents such as nutrients and minerals for growth. These constituents are ingested or taken up from the water column or growing medium (soil) and concentrated through bacterial action, phytoplankton growth, and other biochemical processes. In some instances, plants can be harvested to remove the constituents permanently. In addition, certain biological activities can reduce toxicity of some pollutants and/or possible adverse effects on higher aquatic species. Unfortunately, not much is understood yet about how biological uptake or activity interacts with stormwater during the relatively brief periods it is in contact with the biological media in most control measures, with the possible exception of retention ponds between storm events (Hartigan, 1989). Bioretention, constructed wetlands, and retention ponds are all examples of control measures that provide biological uptake.

Table 2-1 lists processes that are associated with control measures in this manual.

When selecting control measures, it is important to have realistic expectations of effluent pollutant concentrations. The International Stormwater BMP Database provides control measure performance information that is updated periodically and summarized in Table 2-2. Control measures also provide

varying degrees of volume reduction benefits. Both pollutant concentration reduction and volume reduction are key components in the whole life cycle cost tool *BMP-REALCOST.xls* (Roesner and Olson 2009) discussed later in this chapter.

It is critical to recognize that for control measures to function effectively, meet performance expectations, and provide for public safety, control measures must:

1. Be designed according to DCM, Volume 2 criteria, taking into account site-specific conditions (e.g., high groundwater, expansive clays and long-term availability of water).
2. Be constructed as designed. This is important for all control measures, but appears to be particularly critical for permeable pavements, rain gardens and infiltration-oriented facilities.
3. Be properly maintained to function as designed. Although all control measures require maintenance, infiltration-oriented facilities are particularly susceptible to clogging without proper maintenance. Maintenance is not only essential for proper functioning, but also for aesthetic and safety reasons. Inspection of facilities is an important step to identify and plan for needed maintenance.

Table 2-1. Primary, Secondary and Incidental Treatment Process Provided by Control Measures

	Hydrologic Processes			Treatment Processes				
	Peak	Volume		Physical			Chemical	Biological
UDFCD BMP	Flow Attenuation	Infiltration	Evapo-transpiration	Sedimentation	Filtration	Straining	Adsorption/Absorption	Biological Uptake
Grass Swale	I	S	I	S	S	P	S	S
Grass Buffer	I	S	I	S	S	P	S	S
Constructed Wetland Channel	I	N/A	P	P	S	P	S	P
Green Roof	P	S	P	N/A	P	N/A	I	P
Permeable Pavement Systems	P	P	N/A	S	P	N/A	N/A	N/A
Bioretention	P	P	S	P	P	S	S ¹	P
Extended Detention Basin	P	I	I	P	N/A	S	S	I
Sand Filter	P	P	I	P	P	N/A	S ¹	N/A
Constructed Wetland Pond	P	I	P	P	S	S	P	P
Retention Pond	P	I	P	P	N/A	N/A	P	S
Underground BMPs	Variable	N/A	N/A	Variable	Variable	Variable	Variable	N/A

Notes:

P = Primary; S = Secondary, I = Incidental; N/A = Not Applicable

¹ Depending on media

Table 2-2. Control Measure Effluent EMCs (Source: International Stormwater BMP

Solids and Nutrients (milligrams/liter)										
BMP Category	Sample Type	Total Suspended Solids	Total Dissolved Solids	Nitrogen, Total	Total Kjeldahl Nitrogen (TKN)	Nitrogen, Ammonia as N	Nitrogen, Nitrate (NO3) as N*	Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N*	Phosphorus as P, Total	Phosphorus, Orthophosphate as P
Bioretention (w/Underdrain)	Inflow	44.6 (41.8-53.3, n=6)	NC	1.46 (1.24-1.63, n=7)	1.22 (1.00-1.33, n=8)	0.19 (0.16-0.23, n=8)	NC	0.30 (0.25-0.38, n=10)	0.13 (0.12-0.17, n=12)	0.04 (0.01-0.10, n=7)
	Outflow	12.9 (6.8-17.3, n=6)	NC	1.15 (0.92-2.98, n=7)	0.94 (0.60-2.09, n=8)	0.06 (0.05-0.38, n=8)	NC	0.21 (0.14-0.29, n=10)	0.13 (0.08-0.19, n=12)	0.06 (0.03-0.33, n=7)
Grass Buffer	Inflow	52.3 (50.0-63.3, n=14)	57.5 (32.0-89.3, n=12)	NC	1.40 (1.15-2.10, n=13)	0.38 (0.23-0.64, n=10)	0.44 (0.42-0.92, n=13)	NC	0.18 (0.09-0.25, n=14)	0.04 (0.03-0.06, n=10)
	Outflow	22.3 (15.0-28.3, n=14)	88.0 (73.3-110.0, n=12)	NC	1.20 (0.95-1.50, n=13)	0.25 (0.13-0.36, n=9)	0.33 (0.23-0.78, n=13)	NC	0.30 (0.11-0.56, n=14)	0.10 (0.05-0.29, n=10)
Grass Swale	Inflow	54.5 (30.5-76.5, n=15)	79.5 (64.2-100.1, n=12)	NC	1.83 (1.40-2.11, n=12)	0.06 (0.02-0.09, n=4)	0.41 (0.23-0.78, n=12)	0.25 (0.19-0.37, n=4)	0.22 (0.13-0.29, n=15)	0.04 (0.03-0.04, n=3)
	Outflow	18.0 (8.9-39.5, n=19)	71.0 (34.9-85.0, n=10)	0.60 (0.55-1.34, n=6)	1.23 (0.41-1.48, n=16)	0.05 (0.03-0.06, n=8)	0.29 (0.21-0.66, n=15)	0.22 (0.18-0.31, n=8)	0.23 (0.19-0.31, n=19)	0.10 (0.08-0.12, n=7)
Detention Basin (aboveground extended det.)	Inflow	59.5 (17.8-83.8, n=18)	88.5 (85.0-98.8, n=6)	1.05 (1.04-1.25, n=3)	1.32 (0.77-1.70, n=10)	0.08 (0.04-0.10, n=5)	0.45 (0.30-0.90, n=8)	0.23 (0.17-0.50, n=5)	0.20 (0.18-0.30, n=17)	NC
	Outflow	22.0 (11.6-28.5, n=20)	85.0 (54.3-113.5, n=6)	2.54 (1.7-2.09, n=3)	1.66 (0.86-1.95, n=10)	0.09 (0.07-0.10, n=5)	0.40 (0.27-0.85, n=8)	0.17 (0.08-0.43, n=6)	0.20 (0.13-0.26, n=18)	NC
Media Filters (various types)	Inflow	44.0 (32.0-75.0, n=21)	42.0 (28.4-59.0, n=13)	1.51 (0.73-1.80, n=5)	1.53 (0.87-2.00, n=17)	0.34 (0.08-1.12, n=11)	0.38 (0.23-0.57, n=16)	0.33 (0.23-0.51, n=6)	0.20 (0.13-0.33, n=21)	0.02 (0.02-0.06, n=7)
	Outflow	8.0 (5.0-17.0, n=21)	55.0 (46.0-62.0, n=13)	0.63 (0.43-1.41, n=4)	0.80 (0.50-1.22, n=17)	0.11 (0.04-0.15, n=10)	0.66 (0.39-0.73, n=16)	0.43 (0.05-1.00, n=5)	0.11 (0.06-0.15, n=21)	0.02 (0.02-0.06, n=7)
Retention Pond (aboveground wet pond)	Inflow	44.5 (24.0-88.3, n=40)	89.0 (59.3-127.5, n=9)	1.71 (1.07-2.36, n=19)	1.18 (0.77-1.42, n=28)	0.09 (0.04-0.15, n=23)	0.43 (0.32-0.69, n=15)	0.27 (0.11-0.55, n=24)	0.23 (0.14-0.39, n=38)	0.09 (0.07-0.21, n=26)
	Outflow	12.1 (7.9-19.7, n=40)	151.3 (70.8-182.0, n=9)	1.31 (1.01-1.54, n=19)	0.99 (0.76-1.29, n=30)	0.07 (0.04-0.17, n=24)	0.19 (0.13-0.26, n=15)	0.05 (0.02-0.20, n=24)	0.11 (0.07-0.19, n=40)	0.05 (0.02-0.08, n=27)
Wetland Basin	Inflow	39.6 (24.0-56.8, n=14)	NA	1.54 (1.07-2.16, n=6)	1.10 (0.77-1.30, n=4)	0.10 (0.04-0.13, n=8)	0.32 (0.32-0.44, n=5)	0.46 (0.11-0.63, n=7)	0.12 (0.14-0.27, n=11)	0.04 (0.07-0.13, n=5)
	Outflow	12.0 (8.5-17.5, n=16)	NC	1.16 (0.98-1.39, n=6)	1.00 (0.90-1.14, n=8)	0.06 (0.04-0.10, n=8)	0.12 (0.10-0.16, n=7)	0.17 (0.05-0.34, n=7)	0.08 (0.05-0.14, n=13)	0.06 (0.02-0.25, n=7)
Permeable Pavement**	Inflow	23.5 (16.0-45.3, n=5)	NA	NC	2.40 (1.80-3.30, n=3)	NC	NC	0.59 (0.27-0.80, n=5)	0.12 (0.10-0.13, n=5)	NC
	Outflow	29.1 (16.3-34.0, n=7)	NA	NC	1.05 (0.90-1.33, n=7)	NC	NC	1.24 (1.21-1.39, n=4)	0.13 (0.10-0.19, n=5)	NC

*Some BMP studies include analyses for both NO2/NO3 and NO3; therefore, these analytes are reported separately, even though results are expected to be comparable in stormwater runoff.

Table Notes provided below part 2 of this table.

BMP Category	Sample Type	Metals (micrograms/liter)													
		Arsenic, Diss.	Arsenic, Total	Cadmium, Diss.	Cadmium, Total	Chromium, Diss.	Chromium, Total	Copper, Diss.	Copper, Total	Lead, Diss.	Lead, Total	Nickel, Diss.	Nickel, Total	Zinc, Diss.	Zinc, Total
Bioretention (w/Underdrain)	Inflow	NA	NC	NC	NC	NC	NC	NC	19.5 (15.3-35.8, n=3)	NC	NC	NC	NC	NC	68.0 (51-68.5, n=5)
	Outflow	NA	NC	NC	NC	NC	NC	NC	10.0 (7.3-16.8, n=3)	NC	NC	NC	NC	NC	8.5 (5.0-35.0, n=5)
Grass Buffer	Inflow	0.8 (0.5-1.2, n=12)	1.1 (0.9-2.3, n=12)	0.2 (0.1-0.2, n=12)	0.4 (0.3-0.8, n=12)	2.4 (1.1-4.5, n=12)	4.9 (2.9-7.4, n=13)	12.9 (6.8-17.3, n=12)	21.2 (15.0-41.0, n=13)	0.9 (0.5-2.2, n=12)	11.0 (6-35, n=13)	2.9 (1.1-3.2, n=12)	4.8 (3.4-8.4, n=12)	37.8 (12.8-70, n=12)	100.5 (53.0-245.0, n=13)
	Outflow	1.2 (0.5-2.4, n=12)	2.0 (0.7-3.0, n=12)	0.1 (0.1-0.2, n=12)	0.2 (0.1-0.2, n=12)	2.3 (1.0-3.8, n=12)	2.9 (2.0-5.5, n=13)	8.3 (4.8-11.6, n=12)	7.1 (4.8-11.6, n=12)	8.3 (6.4-21.3, n=13)	0.5 (0.5-1.3, n=12)	3.2 (1.8-6.0, n=13)	2.1 (2.0-2.3, n=12)	2.6 (2.2-3.2, n=12)	19.8 (10.7-24.3, n=12)
Grass Swale	Inflow	0.6 (0.5-2.2, n=9)	1.7 (1.6-2.7, n=9)	0.3 (0.1-0.4, n=13)	0.5 (0.4-0.9, n=14)	2.2 (1.1-3.3, n=7)	6.1 (3.6-8.8, n=7)	10.6 (8.1-15.0, n=13)	33.0 (26-34, n=13)	1.4 (0.6-6.7, n=13)	21.6 (12.5-46.4, n=14)	5.1 (4.5-6.6, n=6)	8.7 (7-12.5, n=6)	40.3 (35.3-109.0, n=13)	149.5 (43.8-243.3, n=15)
	Outflow	0.6 (0.6-1.2, n=8)	1.2 (0.9-1.7, n=8)	0.2 (0.1-0.2, n=12)	0.3 (0.2-0.4, n=13)	1.1 (1.0-3.0, n=6)	3.5 (1.7-5.0, n=6)	8.6 (5.5-9.7, n=13)	8.6 (6.7-18.5, n=17)	14.0 (7.5-18.5, n=17)	1.0 (0.5-4.1, n=13)	10.5 (1.7-12.0, n=18)	2.0 (2.0-2.3, n=5)	4.0 (3.1-4.5, n=5)	22.6 (20.1-33.2, n=13)
Detention Basin (aboveground extended det.)	Inflow	1.1 (0.9-1.2, n=5)	2.1 (1.3-2.6, n=6)	0.3 (0.2-0.4, n=8)	0.6 (0.3-1.2, n=11)	2.6 (2.0-3.2, n=3)	5.6 (3.0-6.5, n=6)	5.8 (2.6-11.8, n=8)	10.0 (4.8-33.5, n=11)	1.0 (0.5-1.4, n=8)	10.0 (1.5-41.0, n=11)	2.9 (1.9-3.9, n=4)	6.3 (5.9-4, n=5)	16.4 (6.1-53.5, n=8)	125.0 (21.5-223.3, n=11)
	Outflow	1.2 (0.9-1.2, n=5)	1.7 (1.1-1.9, n=6)	0.3 (0.2-0.4, n=9)	0.4 (0.2-0.6, n=12)	1.9 (1.7-3.0, n=9)	2.9 (1.9-3.8, n=6)	9.0 (3.0-13.0, n=9)	9.0 (6.2-20.1, n=12)	11.0 (6.2-20.1, n=12)	1.0 (0.5-1.3, n=9)	9.5 (1.3-18.6, n=12)	3.1 (2.0-3.2, n=5)	4.3 (3.2-5.4, n=6)	19.0 (7.8-54.0, n=9)
Media Filters (various types)	Inflow	0.7 (0.5-1.1, n=12)	1.1 (0.6-1.6, n=12)	0.2 (0.2-0.2, n=14)	0.4 (0.2-1.0, n=17)	1.0 (1.0-1.0, n=13)	2.1 (1.4-4.0, n=13)	6.2 (5.5-7.4, n=13)	13.5 (8.8-16.4, n=18)	1.1 (1.0-1.0, n=13)	9.0 (5.3-22.0, n=17)	2.0 (2.0-2.7, n=13)	3.9 (3.3-4.8, n=13)	42.7 (28.7-79.2, n=14)	86.0 (51.8-106.0, n=19)
	Outflow	0.7 (0.6-1.1, n=12)	1.1 (0.7-1.6, n=12)	0.2 (0.2-0.2, n=13)	0.2 (0.1-0.7, n=17)	1.0 (1.0-1.0, n=13)	1.0 (1.0-1.9, n=13)	5.8 (3.1-8.3, n=13)	7.3 (4.3-9.6, n=18)	7.3 (4.3-9.6, n=18)	1.0 (1.0-1.4, n=17)	1.6 (1.0-4.4, n=17)	2.0 (2.0-2.6, n=13)	2.9 (2.0-3.9, n=13)	12.5 (6.7-49.0, n=13)
Retention Pond (aboveground wet pond)	Inflow	NC	1.0 (1.0-1.4, n=3)	0.2 (0.2-0.4, n=3)	1.0 (0.3-2.6, n=20)	5.9 (1.6-10.0, n=4)	5.0 (3.0-7.4, n=12)	7.0 (6.0-9.5, n=7)	6.3 (4.3-10.6, n=26)	2.0 (1.0-5.1, n=11)	9.7 (4.2-26, n=33)	10.0 (6.2-10.0, n=3)	6.5 (3.6-9, n=8)	30.0 (15.5-42.6, n=8)	51.8 (43.9-78.1, n=7)
	Outflow	NC	1.0 (0.8-1.0, n=3)	0.2 (0.2-0.4, n=3)	0.4 (0.2-2.5, n=20)	5.5 (1.0-10.0, n=4)	2.2 (1.4-5.3, n=12)	5.0 (4.7-5.8, n=7)	5.4 (3.0-6.2, n=26)	1.2 (1.0-4.9, n=12)	4.7 (1.6-10.0, n=33)	10.0 (7.2-10.0, n=3)	2.5 (2.0-5.5, n=9)	2.5 (9.4-28.6, n=8)	26.0 (12.0-37.0, n=33)
Wetland Basin	Inflow	NA	NA	NC	0.3 (0.3-0.4, n=3)	NA	NA	NC	10.5 (4.3-15.9, n=4)	NC	16.0 (4.0-23.8, n=4)	NA	NA	NC	51.0 (43.9-120.6, n=7)
	Outflow	NA	NA	0.5 (0.3-0.5, n=3)	0.3 (0.1-0.5, n=5)	NA	NA	5.0 (5.0-5.7, n=3)	4.5 (3.3-5.0, n=6)	1.0 (0.8-1.0, n=3)	1.0 (1.0-2.5, n=6)	NA	NA	11.0 (11.0-13.1, n=3)	15.0 (5.0-28.9, n=9)
Permeable Pavement**	Inflow	NA	NC	NC	NA	NC	NC	5.0 (2.5-6.4, n=3)	7.0 (4.5-19.4, n=3)	0.1 (0.03-0.3, n=3)	2.5 (1.3-15.1, n=3)	NC	NC	25.0 (19.0-27.5, n=3)	50.0 (45.0-51.0, n=5)
	Outflow	NA	NC	NC	0.3 (0.3-0.4, n=3)	NC	NC	6.2 (4.5-6.4, n=4)	9.0 (3.0-14.7, n=5)	0.3 (0.04-0.5, n=4)	2.5 (1.3-9.5, n=7)	NC	NC	14.6 (13.5-16.0, n=4)	22.0 (20.0-31.6, n=7)

Table Key:

Sample Type	Description
Analyte	
Inflow	= Median inflow value
(50-63.3, n=14)	= Interquartile range, sample size
Outflow	= Median outflow value
(15-28.3, n=14)	= Interquartile range, sample size

Table Notes:

- **Permeable pavement data should be used with caution due to limited numbers of BMP studies and small numbers of storm events typically monitored at these sites. "Inflow" values are typically outflows monitored at a reference conventional paving site.
- Descriptive statistics calculated by weighting each BMP study equally. Each BMP study is represented by the median analyte value reported for all storms monitored at each BMP (i.e., "n" = number of BMP studies, as opposed to number of storm events). Depending on the analysis objectives, researchers may also choose to use a storm-weighted analysis approach, a unit treatment process-based grouping of studies, or other screening based on design parameters and site-specific characteristics.
- Analysis based on August 2010 BMP Database, which contains substantial changes relative to the 2008 BMP Database. Multiple BMPs have been re-categorized into new BMP categories; therefore, the 2008 and 2010 data analysis are not directly comparable for several BMP types.
- This table contains descriptive statistics only. Values presented in this table should not be used to draw conclusions related to statistically significant differences in performance for BMP categories. (Hypothesis testing for BMP Categories is provided separately in other BMP Database summaries available at www.bmpdatabase.org.)
- These descriptive statistics are based on different statistical measures than those used in the 2008 BMP Database tabular summary. Be aware that results will vary depending on whether a "BMP Weighted" (one median or average value represents each BMP) or "Storm Weighted" (all storms for all BMPs included in statistical calculations) approach is used, as well as whether the median or another measure of central tendency is used. Several BMP Database publications in 2010 have focused on the storm-weighted approach, which may result in some differences between this table and other published summaries.
- Values below detection limits replaced with 1/2 of detection limit.

1.4 Storage-Based Versus Conveyance-Based

Control measures in this manual generally fall into two categories: 1) storage-based and 2) conveyance-based. Storage-based control measures provide the WQCV and include bioretention/rain gardens, extended detention basins, sand filters, constructed wetland ponds, retention ponds, and permeable pavement systems. Conveyance-based control measures include grass swales, grass buffers, constructed wetlands channels and other control measures that improve quality and reduce runoff but only provide incidental storage. Conveyance-based control measures can be implemented to help achieve objectives in Step 1 of the Four Step Process. Although conveyance control measures do not satisfy Step 2 (providing the WQCV), they can reduce the volume requirements of Step 2. Storage-based control measures are critical for Step 2 of the Four Step Process. Site plans that use a combination of conveyance-based and storage-based control measures can be used to better mimic pre-development hydrology.

1.5 Runoff Reduction

Control measures that promote infiltration or that incorporate evapotranspiration have the potential to reduce the runoff generated. Runoff reduction is a fundamental objective of LID. Runoff reduction has many benefits, both in terms of hydrology and pollution control. While stormwater regulations have traditionally focused on runoff peak flow rates, emerging stormwater regulations require control measures to mimic the pre-development hydrologic budget to minimize effects of hydro-modification. From a pollution perspective, decreased runoff volume translates to decreased pollutant loads. Runoff reduction can have economic benefits, including potential reductions in storage requirements for minor and major events, reduced extent and sizing of conveyance infrastructure, and cost reductions associated with addressing channel stability issues. A computational method for quantifying volume reduction is discussed in detail in Chapter 3.

Hydromodification

The term hydro-modification refers to altered hydrology due to increased imperviousness combined with constructed conveyance systems (e.g., pipes) that convey stormwater efficiently to receiving waters. Hydromodification produces increased peaks, volume, frequency, and duration of flows, all of which can result in stream degradation, including stream bed down cutting, bank erosion, enlarged channels, and disconnection of streams from the floodplain. These factors lead to loss of stream and riparian habitat, reduced aquatic diversity, and can adversely impact the beneficial uses of our waterways.

Infiltration-based control measures can be designed with or without underdrains, depending on soil permeability and other site conditions. The most substantial volume reductions are generally associated with control measures that have permeable sub-soils and allow infiltration to deeper soil strata and eventually groundwater. For control measures that have underdrains, there is still potential for volume reduction although to a lesser degree. As runoff infiltrates through control measure soils to the underdrain, moisture is retained by soils. The moisture eventually evaporates, or is taken up by vegetation, resulting in volume reduction. Runoff that drains from these soils via gravity to the underdrain system behaves like interflow from a hydrologic perspective with a delayed response that reduces peak rates. Although the runoff collected in the underdrain system is ultimately discharged to the surface, on the time scale of a storm event, there are volume reduction benefits.

Although effects of evapotranspiration are inconsequential on the time scale of a storm event, on an annual basis, volume reduction due to evapotranspiration for vegetated control measures such as retention and constructed wetland ponds can be an important component of the hydrologic budget. Between

events, evapotranspiration lowers soil moisture content and permanent pool storage, providing additional storage capacity for subsequent events.

Other surface control measures also provide volume reduction through a combination of infiltration, use by the vegetation and evaporation. Runoff reduction provided by a particular control measure type will be influenced by site-specific conditions and control measure design features. National research is ongoing with regard to estimating volume reduction provided by various control measure types. Based on analysis of control measure studies contained in the International Stormwater BMP Database, Geosyntec and WWE (2010) reported that normally-dry vegetated control measures (filter strips, vegetated swales, bioretention, and grass lined detention basins) appear to have substantial potential for runoff volume reduction on a long-term basis, on the order of 30 percent for filter strips and grass-lined detention basins, 40 percent for grass swales, and greater than 50 percent for bioretention with underdrains. Bioretention facilities without underdrains would be expected to provide greater runoff volume reduction.

1.6 Pretreatment

Forebays, as described and designed in the USDCM, are required for extended detention basins, constructed wetland basins, and retention ponds unless a variance request is submitted and approved. The purpose of forebays is to settle out coarse sediment prior to reaching the main body of the facility. During construction, source control including good housekeeping can be more effective than pre-treatment. It is extremely important that high sediment loading be controlled for control measures that rely on infiltration, including permeable pavement systems, rain gardens, and sand filter extended detention basins. These facilities should not be brought on-line until the end of the construction phase when the tributary drainage area has been stabilized with permanent surfaces and landscaping.

1.7 Treatment Train

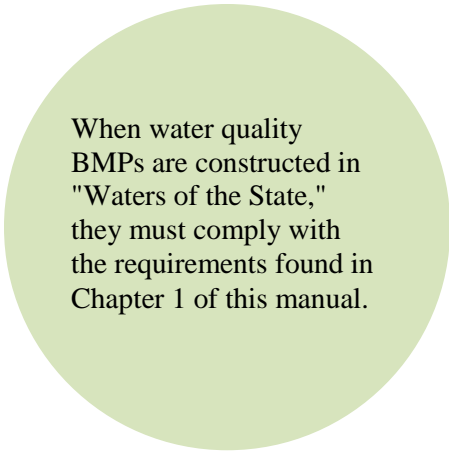
The term "treatment train" refers to multiple control measures in series (e.g., a disconnected roof downspout draining to a grass swale draining to a constructed wetland basin.) Engineering research over the past decade has demonstrated that treatment trains are one of the most effective methods for management of stormwater quality (WERF 2004). Advantages of treatment trains include:

- **Multiple processes for pollutant removal:** There is no "silver bullet" for a control measure that will address all pollutants of concern as a stand-alone practice. Treatment trains that link together complementary processes expand the range of pollutants that can be treated with a water quality system and increase the overall efficiency of the system for pollutant removal.
- **Redundancy:** Given the natural variability of the volume, rate and quality of stormwater runoff and the variability in control measure performance, using multiple practices in a treatment train can provide more consistent treatment of runoff than a single practice and provide redundancy in the event that one component of a treatment train is not functioning as intended.
- **Maintenance:** Control measures that remove trash, debris, coarse sediments and other gross solids are a common first stage of a treatment train. From a maintenance perspective, this is advantageous since this first stage creates a well-defined, relatively small area that can be cleaned out routinely. Down-gradient components of the treatment train can be maintained less frequently and will benefit from reduced potential for clogging and accumulation of trash and debris.

1.8 Inline Versus Offline Facility Locations

The location of WQCV facilities within a development site and watershed requires thought and planning. Ideally this decision-making occurs during a master planning process. Master plans and other reports may depict a recommended approach for implementing WQCV on a watershed basis. Such reports may call for a few large regional WQCV facilities, smaller sub-regional facilities, or an onsite approach. Early in the development process, the developer or owner shall determine if a master planning study has been completed that addresses water quality and follow the plan's recommendations.

When a master plan identifying the type and location of water quality facilities has not been completed, these facilities are required to be implemented on a sub-regional or off-line basis to ensure protection of Waters of the State. Locating control measures offline requires that all onsite catchment areas flow through a control measure prior to combining with flows from the upstream (offsite) watershed. Be aware, when water quality control measures are constructed in "Waters of the State," as identified in an approved DBPS or other master planning document, they must comply with the requirements found in Chapter 1 of this manual.



When water quality BMPs are constructed in "Waters of the State," they must comply with the requirements found in Chapter 1 of this manual.

The maximum watershed recommended for a water quality facility is approximately one square mile.

1.9 Integration with Flood Control

In addition to water quality, most projects will require detention for flood control, whether on-site, or in a sub-regional facility. In many cases, it is efficient to combine flood control and water quality facilities because the land requirements for a combined facility are typically smaller than for two separate facilities. Wherever possible, it is recommended WQCV facilities be incorporated into flood control detention facilities.

Jurisdictions in the Denver area use different approaches for sizing volumes within a combined water quality and quantity detention facility. This varies from requiring no more than the 100-year detention volume, even though the WQCV is incorporated within it, to requiring the 100-year detention volume plus the full WQCV.

The *Storage* chapter in Volume 1 provides design criteria for sizing detention storage facilities when the WQCV is integrated with flood control storage. Full spectrum detention shows more promise in controlling the peak flow rates in receiving waterways than the multi-stage designs described above. Full spectrum detention not only addresses the WQCV for controlling water quality and runoff from frequently occurring runoff events, but also extends that control for all return periods through the 100-year event and more closely matches historic peak flows downstream and helps to mitigate increases in runoff volume by releasing the excess volume over many hours.

Finally, designers should also be aware that water quality control measures, especially those that promote

infiltration, could result in volume reductions for flood storage. These volume reductions are most pronounced for frequently occurring events, but even in the major event, some reduction in detention storage volume can be achieved if volume-reduction control measures are widely used on a site. Additional discussion on volume reduction benefits, including a methodology for quantifying effects on detention storage volumes, is provided in Chapter 3.

1.9.1 Sedimentation Control Measures

Combination outlets are relatively straightforward for most control measures in this manual. For control measures that utilize sedimentation (e.g. EDBs, constructed wetland ponds, and retention ponds) see BMP Fact Sheet T-12. This Fact Sheet shows examples and details for combined quality/quantity outlet structures.

1.9.2 Infiltration/Filtration Control Measures

For other types of control measures (e.g. rain gardens, sand filters, permeable pavement systems, and other control measures utilizing processes other than sedimentation), design of a combination outlet structure generally consists of multiple orifices to provide controlled release of WQCV as well as the minor and major storm event. Incorporation of full spectrum detention into these structures requires reservoir routing. The Colorado Springs Permanent Control Measures spreadsheet available on the City website can be used for this design. When incorporating flood control into permeable pavement systems, the design can be simplified when a near 0% slope on the pavement surface can be achieved. The flatter the pavement the fewer structures required. This includes lateral barriers as well as outlet controls since each pavement cell typically requires its own outlet structure. When incorporating flood control into a rain garden, the flood control volume can be placed on top of or downstream of the rain garden. Locating the flood control volume downstream can reduce the total depth of the rain garden, which will result in a more attractive control measure, and also benefit the vegetation in the flood control area because inundation and associated sedimentation will be less frequent, limited to events exceeding the WQCV.

1.10 Land Use, Compatibility with Surroundings, and Safety

Stormwater quality areas can add interest and diversity to a site, serving multiple purposes in addition to providing water quality functions. Gardens, plazas, rooftops, and even parking lots can become amenities and provide visual interest while performing stormwater quality functions and reinforcing urban design goals for the neighborhood and community. The integration of control measures and associated landforms, walls, landscape, and materials can reflect the standards and patterns of a neighborhood and help to create lively, safe, and pedestrian-oriented districts. The quality and appearance of stormwater quality facilities should reflect the surrounding land use type, the immediate context, and the proximity of the site to important civic spaces. Aesthetics will be a more critical factor in highly visible urban commercial and office areas than at a heavy industrial site. The standard of design and construction should maintain and enhance property values without compromising function (WWE et al. 2004).

Public access to control measures shall be considered from a safety perspective. The highest priority of engineers and public officials is to protect public health, safety, and welfare. Stormwater quality facilities must be designed and maintained in a manner that does not pose health or safety hazards to the public. As an example, steeply sloped and/or walled ponds should be avoided. Where this is not possible, emergency egress, lighting and other safety considerations shall be incorporated. Facilities shall be designed to reduce the likelihood and extent of shallow standing water that can result in mosquito breeding, which can be a nuisance and a public health concern (e.g., West Nile virus). The potential for nuisances, odors and prolonged soggy conditions shall be evaluated for control measures, especially in

areas with high pedestrian traffic or visibility.

1.11 Maintenance and Sustainability

Maintenance shall be considered early in the planning and design phase. Even when control measures are thoughtfully designed and properly installed, they can become eyesores, breed mosquitoes, and cease to function if not properly maintained. Control measures can be more effectively maintained when they are designed to allow easy access for inspection and maintenance and to take into consideration factors such as property ownership, easements, visibility from easily accessible points, slope, vehicle access, and other factors. For example, fully consider how and with what equipment control measures will be maintained in the future. Clear, legally-binding written agreements assigning maintenance responsibilities and committing adequate funds for maintenance are also critical (WWE et al. 2004). This is discussed in greater detail in Chapter 6. The right of access to perform emergency repairs/maintenance is required on privately owned and maintained control measures should it become necessary.

Sustainability of control measures is based on a variety of considerations related to how the control measure will perform over time. For example, vegetation choices for control measures determine the extent of supplemental irrigation required. Choosing native or drought-tolerant plants and seed mixes (as recommended in the *Revegetation* chapter of Volume 1) helps to minimize irrigation requirements following plant establishment. Other sustainability considerations include watershed conditions. For example, in watersheds with ongoing development, clogging of infiltration control measures is a concern. In such cases, a decision must be made regarding either how to protect and maintain infiltration control measures, or whether to allow use of infiltration practices under these conditions.

1.12 Costs

Costs are a fundamental consideration for control measure selection, but often the evaluation of costs during planning and design phases of a project focuses narrowly on up-front, capital costs. A more holistic evaluation of life-cycle costs including operation, maintenance and rehabilitation is prudent and is discussed in greater detail in Section 4 of this chapter. From a municipal perspective, cost considerations are even broader, involving costs associated with off-site infrastructure, channel stabilization and/or rehabilitation, and protection of community resources from effects of runoff from urban areas.

2.0 Control Measure Selection Tool

To aid in selection of control measures the use of UDFCD's control measure selection tool (*UD-BMP*) is recommended. UD-BMP guides users of this manual through many of the considerations identified above and determines what types of control measures are most appropriate for a site. This tool helps to screen control measures at the planning stages of development and can be used in conjunction with the *BMP-REALCOST* tool described in Section 4. Simplified schematics of the factors considered in the *UD-BMP* tool are provided in Figures 2-1, 2-2, and 2-3, which correspond to highly urbanized settings, conventional developments, and linear construction in urbanized areas. Separate figures are provided because each setting or type of development presents unique constraints. Highly urbanized sites are often lot-line to lot-line developments or redevelopments with greater than 90 percent imperviousness with little room for control measures. Linear construction typically refers to road and rail construction.

3.0 Life Cycle Cost and Control Measure Performance Tool

The importance of cost effective control measure planning and selection is gaining recognition as agencies responsible for stormwater management programs continue to face stricter regulations and leaner budgets. The goal of the *BMP-REALCOST* tool is to help select control measures that meet the project objectives at the lowest unit cost, where the project objectives are quantifiable measures such as reducing pollutant loads or runoff to a receiving water. To do so, UDFCD developed an approach that provides estimates for both the whole life costs and performance of control measures. The approach was developed to be most effective at the large-scale, planning phase. However, it can also be applied to smaller scale projects during the design phase, with only minor loss of accuracy. The *BMP-REALCOST* spreadsheet tool incorporates this approach and requires minimal user inputs in order to enhance its applicability to planning level evaluations. An overview of the general concepts providing the underlying basis of the tool follows.

3.1 Control Measure Whole Life Costs

Whole life costs (also known as life cycle costs) refer to all costs that occur during the economic life of a project. This method of cost estimating has gained popularity in the construction and engineering fields over the past few decades and the American Society of Civil Engineers (ASCE) encourages its use for all civil engineering projects. Generally, the components of the whole life cost for a constructed facility include construction, engineering and permitting, contingency, land acquisition, routine operation and maintenance, and major rehabilitation costs minus salvage value. It is recommended that the cost of administering a stormwater management program also be included as a long-term cost for control measures. Reporting whole life costs in terms of net present value (NPV) is an effective method for comparing mutually exclusive alternatives (Newnan 1996).

To understand the value of using whole life cost estimating, one must first realize how the various costs of projects are generally divided amongst several stakeholders. For example, a developer is typically responsible for paying for the "up front" costs of construction, design, and land acquisition; while a homeowners' association or owner becomes responsible for all costs that occur after construction. Many times, the ratios of these costs are skewed one way or another, with control measures that are less expensive to design and construct having greater long-term costs, and vice versa. This promotes a bias, depending on who is evaluating the control measure cost effectiveness. Whole life cost estimating removes this bias, but successful implementation of the concept requires a cost-sharing approach where the whole life costs are equitably divided amongst all stakeholders.

The methods incorporated into the *BMP-REALCOST* tool for estimating whole life costs are briefly described below. All cost estimates are considered "order-of-magnitude" approximations. This concept must primarily be relied upon at the planning level.

- **Construction Costs:** Construction costs are estimated using a parametric equation that relates costs to a physical parameter of a control measure; total storage volume (for storage-based control measures), peak flow capacity (for flow-based or conveyance control measures) or surface area (for permeable pavements).
- **Contingency/Engineering/Administration Costs:** The additional costs of designing and permitting a new control measure are estimated as a percentage of the total construction costs. A value of 40% is recommended if no other information is available.

- **Land Costs:** The cost of purchasing land for a control measure is estimated using a derived equation that incorporates the number of impervious acres draining to the control measure and the land use designation in which the control measure will be constructed.
- **Maintenance Costs:** Maintenance costs are estimated using a derived equation that relates average annual costs to a physical parameter of the control measure.
- **Administration Costs:** The costs of administering a stormwater management program are estimated as a percentage of the average annual maintenance costs of a control measure. A value of 12% is recommended if no other information is available.
- **Rehabilitation/Replacement Costs:** After some period of time in operation, a control measure will require "major" rehabilitation. The costs of these activities (including any salvage costs or value) are estimated as a percentage of the original construction costs and applied near the end of the facility's design life. The percentages and design lives vary according to the selected control measure.

3.2 Control Measure Performance

The performance of structural control measures can be measured as the reduction in stormwater pollutant loading, runoff volume, and runoff peak flows to the receiving water. It is generally acknowledged that estimating control measure performance on a storm-by-storm basis is unreliable, given the inherent variability of stormwater hydrologic and pollutant build-up/wash off processes. Even if the methods to predict event-based control measure performance were available, the data and computing requirements to do so would likely not be feasible at the planning level. Instead, it is recommended to use an approach that is expected to predict long-term (i.e. average annual) control measure pollutant removal and runoff volume reduction with reasonable accuracy, using control measure performance data reported in the International Stormwater BMP Database (as discussed in Section 1.3).

3.3 Cost Effectiveness

The primary outputs of the *BMP-REALCOST* tool include net present value (NPV) of the whole life costs of the control measure(s) implemented, the average annual mass of pollutant removed (P_R , lbs/year) and the average annual volume of surface runoff reduced (R_R , ft³/year). These reported values can then be used to compute a unit cost per lb of pollutant (C_P) or cubic feet of runoff (C_R) removed over the economic life (n , years) of the control measure using Equations 2-1 and 2-2, respectively.

$$C_P = \frac{NPV}{nP_R} \quad \text{Equation 2-1}$$

$$C_R = \frac{NPV}{nR_R} \quad \text{Equation 2-2}$$

4.0 Conclusion

A variety of factors should be considered when selecting stormwater management approaches for developments. When these factors are considered early in the design process, significant opportunities exist to tailor stormwater management approaches to site conditions. Two worksheets are available at the UDFCD website for the purpose of aiding the owner or engineer in the proper selection of treatment control measures. The *UD-BMP* tool provides a list of control measures for consideration based on site-

specific conditions. *BMP-REALCOST* provides a comparison of whole life cycle costs associated with various control measures based on land use, watershed size, imperviousness, and other factors.

5.0 References

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