Design Guidelines for

Stormwater Bioretention Facilities

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Purpose of This Manual

The purpose of this manual is to provide design guidelines and present a numerical model that can be used for designing bioretention facilities to meet a specified objective, such as maintaining recharge volumes. The following sections discuss design objectives, introduce the components of a bioretention facility, and detail how these components affect facility performance. The numerical model RECARGA is introduced as a tool that can be used in facility analysis and design. A RECARGA user's manual is provided (see Appendix).

Section 1.

What Is a Bioretention Facility?

A bioretention facility is a small-scale stormwater management practice that promotes infiltration of storm water in order to reduce its volume, improve its quality, and increase groundwater recharge. A basic bioretention facility, commonly referred to as a rain garden, is a landscaped garden in a shallow depression that receives storm water from nearby surfaces, commonly impervious.

Additional features, such as an underdrain or a storage zone, can enhance a bioretention facility. An underdrain is a perforated pipe below the root zone that drains water when the facility becomes saturated. Its function is to reduce the duration of ponding. A storage zone is a layer of highly conductive material that is placed below the root zone. It can be used to reduce the amount of water discharged through an underdrain, extend the bottom of the facility to higher permeability soils, and reduce the duration of ponding. Figure 1.1 illustrates the features of basic and enhanced bioretention facilities.
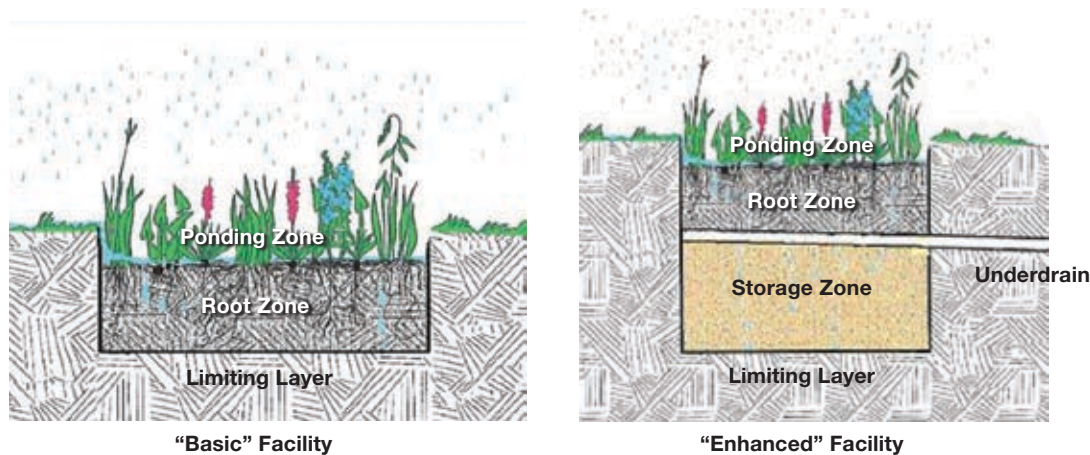
Figure 1.1 "Basic" vs. "Enhanced" Bioretention Facilities

Section 2.

Why Is Bioretention Needed?

This section summarizes impacts on storm water from urban and suburban development and the role of bioretention facilities in mitigating those impacts. It also presents design objectives for bioretention facilities.

2.1 Limitations of Conventional Stormwater Management Practices

Urban and suburban development adversely impacts both surface water and groundwater resources by profoundly altering the hydrologic cycle. The introduction of new impervious surfaces increases the amount of stormwater runoff, while the construction of pipe and channel networks increases the rate at which this excess runoff is delivered to streams and other surface waters. These characteristics of development elevate the risk of downstream flooding. Conventional stormwater management practices rely primarily on temporary storage of storm water in detention facilities (usually ponds) to control peak runoff rates. These facilities are typically designed so that their peak release rates during specified storms (design storms) do not exceed prescribed standards, usually the predevelopment peak rates. This strategy has been relatively successful at reducing local flooding but has failed to address all of the adverse hydrologic impacts of urban and suburban development (Ferguson 1990; Booth and Jackson 1994; Potter 2003).

One such adverse impact is channel erosion. The size of an alluvial channel depends on both the magnitude and duration of flows above a critical erosion threshold. Detention facilities control the magnitude of peak discharges but not the duration of erosive flows. Hence, detention facilities generally do not prevent channel erosion in urbanizing areas. The typical recourse is channel armoring, an expensive and aesthetically unappealing solution.

Detention facilities are also ineffective at controlling peak water levels in downstream ponds and lakes that may drain slowly. During a storm, the level of these water bodies will not drop significantly during the time that detention facilities store water. Thus the increased volume of stormwater runoff associated with the introduction of impervious surfaces will lead to increased peak water levels downstream. The most extreme examples are ponds and lakes that lack surface discharges, such as the kettle ponds that are common in glaciated regions. However, even lakes that discharge to streams or rivers may drain slowly enough to negate the flood-reduction benefits of detention facilities.

Urban and suburban development causes groundwater depletion, an impact that cannot be mitigated by detention facilities. This depletion has two causes. First, the introduction of impervious surfaces decreases the amount of groundwater recharge. Second, urban and suburban development is usually accompanied by increased groundwater withdrawal. The groundwater depletion caused by reduced recharge and increased pumping can threaten the long-term viability of the water source. In addition, this depletion can reduce groundwater discharge to streams, lakes, and wetlands, threatening ecosystems that depend on this source of water.

Human activities in urban watersheds produce a variety of pollutants, such as sediment, nutrients, heavy metals, oil, and bacteria that can impair water bodies. Surface runoff from urban areas is the primary means by which these pollutants are transported to water bodies. Capturing these pollutants is a major goal of stormwater management. While detention facilities promote sedimentation, and hence offer significant water-quality benefits, they are rarely completely effective. Bioretention facilities can enhance water treatment by trapping and in some cases degrading pollutants.

If properly designed, bioretention facilities effectively mitigate urban and suburban stormwater impacts that detention facilities cannot. They control the volume of storm runoff and enhance groundwater recharge. In addition, they enhance overall water treatment. In the following sections, we elaborate on these functions and discuss design objectives.

2.2 Reducing Runoff Volume

Bioretention facilities can significantly reduce the volume of water that runs off a site. In fact, any water that either percolates through the bottom of a facility or is transpired by the plants is a reduction in runoff volume. In these guidelines, the term "stay-on volume" is used to represent the volume of water that is captured by a bioretention facility, plus the volume of precipitation that is retained on the developed site tributary to the facility. The ability of bioretention facilities to reduce runoff volumes stems from the fact that a large proportion of the annual wet-season precipitation is due to relatively small events. For example, about 70 percent of the total wet-season rainfall in Madison, Wis., is delivered by storms that produce less than two inches.

Stormwater regulators are beginning to require volume control in addition to peak flow control and water-quality treatment. Volume-control standards are typically based on retaining a portion of a design storm, or matching average annual stay-on volumes from predeveloped sites. Requirements based on design storms are simple, but they ignore the fact that the performance of a bioretention facility depends on its water content at the onset of a storm (antecedent moisture conditions). Continuous simulation using a hydrologic model such as RECARGA (Atchison and Severson 2004) is the best way to evaluate the performance of a bioretention facility and provides a rigorous basis for designing and implementing volume-control standards.

The Wisconsin Department of Natural Resources (WDNR) has recently instituted a statewide stormwater management requirement for runoff volume control that is based either on a design storm, or on average annual stay-on volumes (Wisconsin Administrative Code 2004). Figure 2.1 summarizes the standard.

NR 151.12(5)(c) *Infiltration*

1. **For residential developments…**
   a. …[match] 90% of the pre–development infiltration volume, [or]…
   b. Infiltrate 25% of the post–development runoff volume from the 2–year, 24–hour design storm with a type II distribution…

2. **For non–residential developments…**
   b. …[match] 60% of the pre–development infiltration volume, [or]…
   c. Infiltrate 10% of the post–development runoff volume from the 2–year, 24–hour design storm with a type II distribution…

Figure 2.1 Wisconsin DNR's Infiltration Standard

2.3 Increasing Groundwater Recharge

Bioretention facilities function by infiltrating runoff from impervious and compacted pervious surfaces. When properly designed, bioretention facilities can match and even exceed predeveloped recharge rates (see Fig. 3.1). Rates in excess of natural rates can result from the fact that focusing infiltration reduces losses to evaporation and transpiration. Modeling results for southern Wisconsin have shown that maximum recharge can be achieved when bioretention areas are equal to about 15 percent of the tributary impervious area (Dussaillant et al. 2004).

Some localities may choose to base stormwater management objectives and requirements on groundwater recharge. Such an approach focuses on the volume of water that is infiltrated through the bottom and sides of the facility and does not credit evaporation losses. Local standards may require that a development match the recharge volume from predeveloped conditions or recharge a particular volume to mitigate another groundwater impact, such as pumping or elimination of other recharge areas.

2.4 Water-Quality Treatment

The term "bioretention" was originally coined to reflect the pollutant retention capabilities of the plants in the facilities. Many research efforts have demonstrated the water-quality treatment performance of bioretention facilities. Table 2.1 summarizes removal rates for typical pollutants.

Table 2.1 Typical Pollutant Removal Rates for Bioretention Facilities

Pollutant	Removal Rate (%)[1]
Total Suspended Solids (TSS)	90[2]
Metals (Cu, Zn, Pb)	>95[3]
Total Phosphorus	80[3]
Total Kjeldahl Nitrogen	65-75[4]
Ammonium	60-80[4]
Organics	90[2]
Bacteria	90[2]

1. Data Compiled by Wisconsin DNR (Bioretention Tech. Note 1004, draft)
2. Prince George's County, Md., Department of Environmental Resources, 1999
3. Davis et al. 2003
4. Davis et al. 2001

Most water-quality performance standards require the removal of a target percentage of a pollutant of concern. As many pollutants are associated with particulates, the most significant pollutant of concern is total suspended solids. Eighty percent removal of total suspended solids is a common treatment requirement. A bioretention facility will remove 100 percent of the total suspended solids that are contained in the portion of the captured storm runoff and most of the suspended solids contained in the overflow due to sedimentation. In the case of dissolved constituents, such as dissolved nutrients, the only discharge to surface water will be by means of overflow and flow from the underdrain, if present.

Therefore, conservative estimates of removal rates can be made by prorating the proportion of overflow and underdrain flow. Note that some pollutants may not be completely removed from the water that discharges from the bottom of a bioretention facility. To prevent groundwater contamination, is it essential that these pollutants be prevented from entering a bioretention facility, unless that facility is designed to provide for their removal.

A simpler approach has been adopted by many jurisdictions. This approach is to treat the entire runoff from either a design event or from a percentage of the average annual volume. In the case of bioretention, the treatment volume is considered to be the volume of runoff that is filtered through the root zone of the facility. Due to the fact that the majority of the annual pollutant loadings occur from more frequent small storms, the design event is commonly equal to the six-month to one-year recurrence interval storm event. When the average volume is considered, the required treatment percentage is typically 80 percent. RECARGA can be used with either approach.

2.5 Reducing Peak Discharge

For a variety of reasons, commonly for reduction of ponding times for plant survival, the ponding depth of bioretention facilities is usually one foot or less. Detention facilities typically pond several feet of water and hence are much more effective at reducing peak discharges. However, bioretention facilities can significantly reduce the required size of downstream detention facilities. Also, detention storage upstream of a bioretention facility, such as provided by rain barrels or cisterns, can greatly increase the latter's efficiency.

Bioretention Facility Components: Design Issues

A basic bioretention facility (rain garden) consists of a shallow depression containing plants; the critical design parameters are the area of the facility and the depth of the ponding zone. A bioretention facility can be enhanced by increasing the ponding depth, adding an underdrain at the base of the root zone, and adding a storage zone below the root zone. The hydraulic conductivity of the limiting layer beneath the facility is critically important for both basic and enhanced facilities. Other secondary considerations are the depth and composition of the root zone soils and the selection of plant species. Table 3.1 summarizes the design issues associated with each component of a bioretention facility. The sections below discuss these issues in greater detail.

Table 3.1 Summary of Bioretention Components/Design Issues

Component	Key Parameter(s)	Main Design Issues	Limitations
3.1 Native Soils	Soil Texture Hydraulic Conductivity (K_n)	• Locate facility in best soils possible • Remove shallow impermeable layers	• Clay loam or finer soils not suitable for infiltration designs
3.2 Facility Area	Area (A_f)	• Land cost/availability • Stay-on increases with facility area	• Decreased recharge benefits above 15-20% of impervious area
3.3 Ponding Zone	Thickness (S_d)	• Balance performance with plant survivability	• Must drain within 24 hours • 18-inch maximum
3.4 Bioretention Plants	Plant Species	• Choose variety of plants for given site conditions per nursery recommendations	• Obligate wetland or upland species generally not suitable
3.5 Root Zone	Thickness (S_r) Soil Composition	• Use soil/compost mix per requirements of plant species	• Minimum thickness necessary for root growth
3.6 Underdrain	Diameter (D_u) Flow Rate (K_u)	• Used to ensure adequate drawdown of ponding zone • Increases treatment volume • Reduces stay-on and recharge	• Must have sufficient topographic relief to enable drainage
3.7 Storage Zone	Thickness (S_t)	• Offsets water loss through underdrain • Extends bottom of facility to permeable soils	• < 4-foot thickness or drain within 5 days

3.1 Native Soils

The saturated hydraulic conductivity of the limiting layer below a bioretention facility is the most important factor affecting feasibility, design, and performance. Soil characteristics vary spatially and with depth. Therefore, it is essential that soils be characterized prior to locating and designing bioretention facilities. Locating facilities in areas with the best soils can greatly improve performance.

Once a bioretention facility has been sited, the key issue is its soil thickness. It may be desirable to remove soil layers that restrict percolation, thus allowing for a facility with a smaller surface area. The tradeoff would be between the benefits of a smaller facility and the costs of excavation and backfilling.

For final design, we recommend performing an approved infiltration test at the depth of the bottom of the facility to determine the saturated hydraulic conductivity of the limiting soil layer. However, for preliminary design and initial site layouts, infiltration tests may not be possible at all potential facility locations. In such cases we recommend that saturated hydraulic conductivity be estimated based on soil texture using Rawls et al. (1998). Soil texture can be determined from soil surveys, site explorations, and/or particle size analysis. Rawls et al. (1998) provides estimates of saturated hydraulic conductivity for various soil textures. These estimates are summarized in Table 3.2, along with recommendations for facility design.

Compaction can drastically reduce the permeability of soils; therefore, efforts should be made to prevent compaction from occurring in the vicinity of planned infiltration facilities, due, for example, to heavy equipment. If such compaction does occur, the soils should be loosened by deep tilling or ripping with the incorporation of compost.

Table 3.2 Soil Texture Effects on Bioretention Facility Design

Soil Texture	Sat. Hydraulic Conductivity (in/hr)[1]	Typical Design
Sand	3.60	Basic Bioretention
Loamy Sand	1.63	Basic Bioretention
Sandy Loam	0.50	Basic Bioretention
Loam	0.24	Underdrain Recommended[2]
Silt Loam	0.13	Underdrain Required
Sandy Clay Loam	0.11	Underdrain Required
Clay Loam	0.03	Not Recommended for Infiltration[3]
Silty Clay Loam	0.19	Underdrain Required
Sandy Clay	0.04	Not Recommended for Infiltration[3]
Silty Clay	0.07	Not Recommended for Infiltration[3]
Clay	0.07	Not Recommended for Infiltration[3]

1. Rawls et al. (1998).
2. Underdrain system recommended but may be capped initially; see section 3.6 for details
3. Generally not feasible to meet infiltration goals; however, may be used for water-quality treatment if designed with an underdrain

3.2 Facility Area

The area of the facility is the most important design parameter, as it directly affects the storage volume in the facility and the area available for infiltration. The performance of a facility depends on the ratio of the area of the facility to the area of the surfaces contributing runoff (facility area ratio). Figure 3.1 illustrates this relationship for a hypothetical facility that receives runoff from an impervious surface, based on model simulations using wet-season rainfall from Madison, Wis., for the period 1992-97. Note that the amount of runoff spilling from the facility decreases with increasing facility area ratio, although the rate of decrease diminishes sharply at a ratio of about 0.15. More importantly, the recharge induced by the facility attains a maximum at a facility area ratio of 0.15. Therefore, for the conditions shown, a facility with an area equal to 15 percent of the area of the contributing impervious surface would provide maximum recharge benefits, exceeding the regional recharge rate. Increased losses to evaporation explain the drop-off in recharge with larger facility areas. Simulations with other soil conditions and design parameters show similar results.

The pronounced nonlinearity of the facility performance with area ratio means that it is critical to size each bioretention facility properly, using the tools provided in this manual or comparable tools. It also means that if the facility area ratio of a set of bioretention facilities varies significantly, the aggregate performance of the set will be less than the performance estimated using the average facility area ratio. (See Section 4.2.1 for further discussion.) This is important to keep in mind during plat-level design.

Rain Garden Simulation

Madison Rainfall: April–September, 1992–1997
Ponding depth = 6 inches
Storage zone thickness = 3 feet
Subsoil conductivity = 0.4 inches/hour

Figure 3.1 Bioretention Performances vs. Facility Area Ratio
All rates are expressed as depths over the area of the facility and contributing surfaces.

3.3 Ponding Depth

The ponding depth of the facility provides an initial storage volume to capture stormwater runoff to the facility, allowing the water to spread and infiltrate over the entire facility area. The primary consideration for determining the ponding depth of a facility is the time required to drain the surface of the facility after an event (drawdown time). As a rule of thumb, the duration of ponding after a storm event has passed should be less than 24 hours to ensure survival of the plants, although the exact duration required will depend on the plants selected. (RECARGA provides quantitative information on the duration of soil saturation. This information can be used to refine the design of the ponding depth.) Excessive ponding times can suffocate many plants and cause root rot. Loss of plants provides an early indication of facility failure.

The effective drawdown rate when the facility is ponded is approximately equivalent to the sum of the hydraulic conductivity of the limiting soil layer (K_n) and the maximum flow through the underdrain (K_u), if applicable. The drawdown time can be estimated as the ratio of the ponding depth to the effective drawdown rate.

Practically, a minimum of four to six inches in depth should be provided in the ponding zone. Shallower depths typically result in localized ponds, due to insufficient depth to spread the water over the entire area. This may reduce facility effectiveness and result in sedimentation in the low areas. A maximum of 18 inches is typical, due to aesthetics, safety, drain times and plant survival concerns. In these guidelines, a default pond depth of six inches is recommended. (Remember that 70 percent of rainfall comes from storms of less than two inches.) Greater ponding depths result in an increase in the initial available volume for capturing storm water within the facility (reducing the volume that will eventually overflow) and should be considered if warranted by drawdown times.

3.4 Bioretention Plants

The plants in a bioretention facility maintain the soil structure of the root zone. The plant roots throughout the root zone continually loosen the soil and create macropores, which maintain infiltration capacity over time. The plants also facilitate the removal of pollutants.

When a facility fails, most commonly from failing to drain, one of the first indicators is damage to the plants. Additionally, due to the poor aesthetics of dead plants, the health of the plants themselves is a key component of a landowner's perception of success. Many of the remaining facility parameters (e.g., ponding depth, underdrain flow rates, soil composition and thickness of the root zone) are designed to ensure plant survival.

Due to the high variability of local climate conditions, the best resource for plant selection is normally a local nursery. In general, the key parameters to consider for selecting plants are the frequency and duration of inundation, the drainage of the soils, aesthetics, and the amount of sun or shade expected at the site. Obligate wetland species are not recommended if the soils used in the root zone are sandy. Upland species are also not recommended, due to frequent periods of inundation. We suggest planting a variety of species at first, allowing conditions to "proof" the choice of plant selection. Plan to replace some species after the first growing season.

3.5 Root Zone

The primary purpose of the root zone is to provide a growing medium for the plants. The main design objectives are to provide adequate depth, nutrients, and drainage conditions for the plant roots. In general, a default root zone thickness of 24 inches is recommended; however, it may be prudent to provide additional thickness for deep-rooted plant species (e.g., shrubs, trees, and prairie species). Arid regions may require additional root-zone thickness to enhance the moisture retention of the facility to protect against drought conditions.

Most bioretention and rain garden design references recommend a mix of topsoil, sand, and compost to provide adequate nutrients and drainage conditions that allow plants to thrive. From a water-quality perspective, the root zone is the primary site of pollutant removal. In some cases, soil amendments, such as compost or peat moss, may be added to enhance the ability of this layer to remove specific pollutants. Although different mixes could be used, the hydraulic conductivity of the root zone is rarely the limiting layer for percolation of water through the facility. Hence we do not consider root-zone hydraulic conductivity as a design parameter and use 3.94 inches per hour as a default value.

As in the case of the ponding zone, adding thickness to the root zone does provide some additional water retention capacity in the facility. However, the increase in storage per unit increase in thickness is less in the root zone because of the presence of soil material and water remaining from previous rainfalls. Figure 3.2 demonstrates water retention benefits from additional storage in the ponding zone, root zone, or storage zone.

Retention Benefits from Additional Storage in Facility Zones
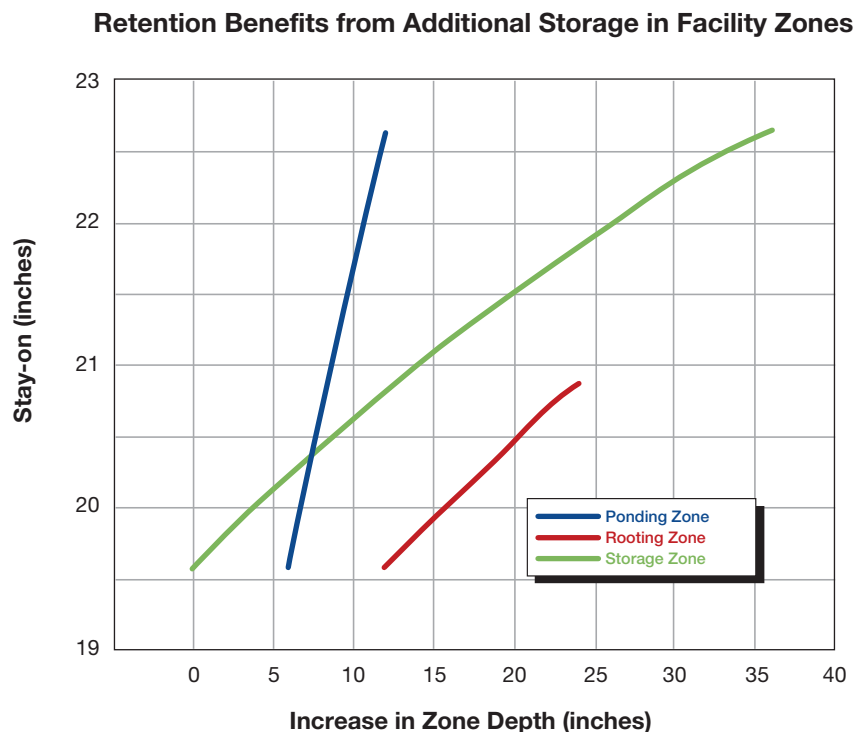
Figure 3.2 Comparison of Water Retention Benefits from Additional Storage in Ponding, Root, and Storage Zones *Results are based on a subsurface hydraulic conductivity of 0.24 inches per hour. Note from the slopes that increasing the ponding thickness provides the greatest increase in stay-on. However, the drainage time also increases, providing an upper limit on ponding depth.*

3.6 Underdrain

The primary purpose of the underdrain is to decrease the duration of ponding in facilities with less permeable native soils. We advocate using an underdrain as an adaptive feature of a bioretention facility. By designing an underdrain so that an accessible orifice or cap is the controlling feature, rather than the underdrain pipe size or perforations, the underdrain discharge rate can be adjusted if actual drainage conditions vary from those predicted during design or as a temporary measure during extended wet periods. Therefore, if excessive ponding is observed in the facility or plant damage is observed, the orifice control can be enlarged to increase the drawdown rate without excavating and reconstructing the facility. To provide the capacity for increased release rates for such adjustments, it is recommended that the remainder of the underdrain system (underdrain pipe size and perforations) be designed to drain the ponding zone within six hours.

Adding an underdrain increases the volume of water that can be captured and filtered through the root zone of the facility (an advantage for water-quality designs). However, the resulting flow through the underdrain still contributes to the volume discharged to downstream surface waters, reducing the retention (or stay-on) and recharge capacity of the facility. The volume of water discharged through the underdrain can be easily approximated by comparing the flow rate through the underdrain with the observed drawdown rate when the facility is completely saturated. Over the long term, the relative volumes associated with each of these rates are also approximately proportional to the design flow rates. For example, if the maximum underdrain flow rate is equal to half of the drawdown rate, just less than half of the storm water infiltrating the surface of the facility will be discharged through the underdrain.

3.7 Storage Zone

The main purpose of the storage zone is to compensate for water discharged through the underdrain. This is achieved by reducing the frequency and overall duration of saturated and ponded conditions above the underdrain (when underdrain flow occurs). By providing additional storage capacity within the facility beneath the underdrain, any additional water captured within this zone during a storm event will not contribute to underdrain flow.

Even without an underdrain, a storage layer can increase the volume of water captured by the facility. However, there are three factors that reduce the effectiveness in this layer. First, the available pore space for storing additional water is typically only 25 to 35 percent of the total soil volume. Second, storm events that produce inflow rates in excess of the infiltration capacity of the upper soil layers may not utilize this available volume, as the storm volume may overflow prior to infiltrating down to this storage layer. Finally, the time to drain the available pore space in this layer may be too long to allow for the full storage zone to be available for consecutive storm events. For these reasons, a large storage zone may not be a good strategy for reducing the facility area in low-permeability soils. Also, without an underdrain, a storage zone is not an effective strategy for reducing the maximum duration of ponded conditions.

Finally, it may be desirable to expand the storage zone to eliminate low-permeability soil or subsoil layers. As a rule of thumb, the thickness of the storage zone should be limited to approximately four feet or a thickness that drains the storage zone in less than five days (storage zone thickness divided by the hydraulic conductivity of the limiting layer). These guidelines use a default hydraulic conductivity of 5.91 inches per hour for this soil zone, which is typical for a gravelly sand mixture.

Section 4.

Bioretention Facility Design and Analysis Using RECARGA

This section introduces the designer to RECARGA (Atchison and Severson 2004). Detailed instructions for installing and using RECARGA are provided in the "RECARGA User's Manual" included in the appendix. We begin this section by discussing how RECARGA can be used to simulate the performance of, and to design, a bioretention facility. We then use a hypothetical development to illustrate important design issues.

4.1 RECARGA Analysis: Facility Performance Simulation

RECARGA is a model developed to simulate the performance of bioretention designs. RECARGA allows the user to simulate a design using one of three rainfall options: (1) continuous rainfall, using a user-specified precipitation/ evaporation file, (2) event rainfall using the Soil Conservation Service (SCS) Type I, IA, II, or III distributions, or (3) user-specified runon. The user designs a facility, and RECARGA simulates the movement of water throughout the facility, records the soil moisture and volume of water in each water budget term, and summarizes the results, including hours ponded, runon, runoff, recharge, evaporation, underdrain flow, soil moisture, and overall stay-on.

RECARGA uses the Green-Ampt (Green and Ampt 1911) infiltration model for initial infiltration into the soil surface and the Van Genuchten relationship for drainage between soil layers (Van Genuchten 1980). Surface inflow to the facility from impervious surfaces is calculated using a simple initial abstraction. For pervious surfaces, surface inflow is calculated using the SCS TR-55 methodology (SCS 1986), based on user-supplied curve numbers. Underdrain flow is calculated using an orifice equation. The model also tracks continuous soil moisture and evapotranspiration between storm events.

The user enters the following: facility area; ponding, root, and storage zone thickness; root, storage, and limiting layer hydraulic conductivity; and underdrain flow rate, tributary area, curve number for contributing pervious area, and percentage of contributing area that is impervious.

RECARGA can also be used to determine, for a given facility design, the facility area ratio required to meet a specified stay-on requirement. The facility area ratio (FAR) is the ratio of the area of the bioretention facility to the area draining to the facility (excluding the facility area). RECARGA will solve for the FAR required to meet a target stay-on objective. RECARGA calculates the FAR by interpolation, with a relative error that is always less than three percent and generally less than one percent for larger facilities. RECARGA also graphs the stay-on for values of FAR ranging from 0.01 to 0.25. Figure 4.1 displays the user interface for RECARGA.
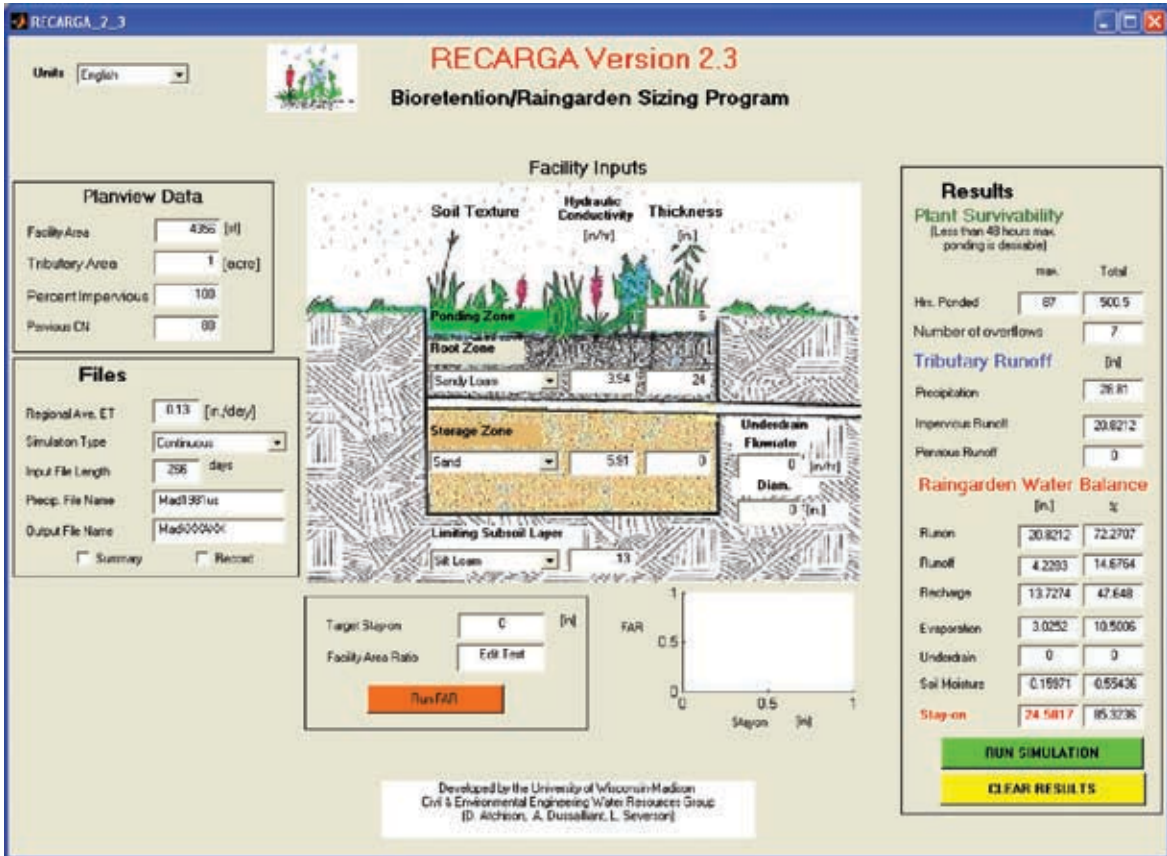
Figure 4.1 RECARGA User Interface

4.2 Illustration of Design Issues

To illustrate design issues, we present results from the application of RECARGA to a hypothetical development under a variety of site conditions and design configurations using daily 1981 wet-season rainfall for Madison, Wis. (which totaled 28.81 inches). We assume that the site is initially in agricultural row crops and is to be developed to accommodate a single-family residence. Figure 4.2 shows a schematic of the site and a summary of the pre- and post-development conditions for alternative soil textures.

| | | Curve Number (CN) | | |
| | | Annual Runoff (in.) | | |
Existing	Area (sf)	Loamy Sand	Loam	Silt Loam
Agriculture	6,534	56	70	79
		0.1	1.1	2.7
Developed				
Roof	2,200	98	98	98
		19.5	19.5	19.5
Driveway	520	98	98	98
		19.5	19.5	19.5
Lawn, Poor Condition	3,814	68	79	86
		0.8	2.7	5.3
Total	6,534	n/a	n/a	n/a
		8.6	9.7	11.2

Figure 4.2 Hypothetical Site

Table 4.1 gives the runoff and stay-on volumes for the hypothetical single-family residence with a bioretention facility that receives runoff from the entire site and has a limiting soil texture of loam, which has a hydraulic conductivity of 0.24 inches per hour. Note that with a FAR of only 0.04, 86 percent of the precipitation for that year is either evaporated or infiltrated. This number can be calculated by dividing the stay-on value by the sum of the stay-on and runoff; i.e., 13,548 / (13,548+2,139).

Table 4.1 Baseline Bioretention Facility Analysis

Facility Area, A_r (sf)	FAR	Impervious Area, A_i (sf)	Pervious Area, A_p (sf)	Ponding Depth, S_d (in)	Root Thickness (in)	Storage Thickness, S_t (in)	Natural Infiltration Rate, K_n (in/hr)	Underdrain Rate, K_u (in/hr)	Runoff Vol., V_{rf} (ft^3)	Stay-on Vol., V_s (ft^3)
272	0.04	2,720	3,542	6	18	0	0.24	0	**2,139**	**13,548**

4.2.1 Effects of Varying Facility and Tributary Area

Table 4.2 gives the results of the case in which the runoff from the pervious areas is not treated, but the facility area remains the same. Row 4.2a shows runoff and stay-on volume associated with the impervious runoff routed through the facility. Row 4.2b below shows the runoff and stay-on from the pervious areas not routed through the facility. Comparison of the total stay-on with the stay-on in Table 4.1 indicates that diversion of the pervious area runoff results in only a 1.0 percent reduction in stay-on. Clearly it is relatively ineffective to treat pervious areas with bioretention facilities, and focus should be directed to treating impervious surfaces.

Table 4.2 Treating Impervious Area Only

	Facility Area, A_r	FAR	Impervious Area, A_i	Pervious Area, A_p	Ponding Depth, S_d	Root Thickness	Storage Thickness, S_t	Nat. Infiltration Rate, K_n	Underdrain Rate, K_u	Runoff Vol., V_{rf}	Stay-on Vol., V_s
4.2a	272	0.10	2,720	0	6	18	0	0.24	0	974	6,209
4.2b	n/a	n/a	n/a	3,542	n/a	n/a	n/a	n/a	n/a	1,307	7,197
Total										**2,281**	**13,406**

Table 4.3 gives the results of the case in which the impervious areas are routed to a facility and the pervious areas are enhanced to match the predevelopment curve number (79 to 70) (e.g., through compaction reduction and vegetation). Row 4.3a shows the runoff and stay-on from the impervious areas routed through the facility. Row 4.3b shows the runoff and stay-on from the enhanced pervious areas. As compared with routing both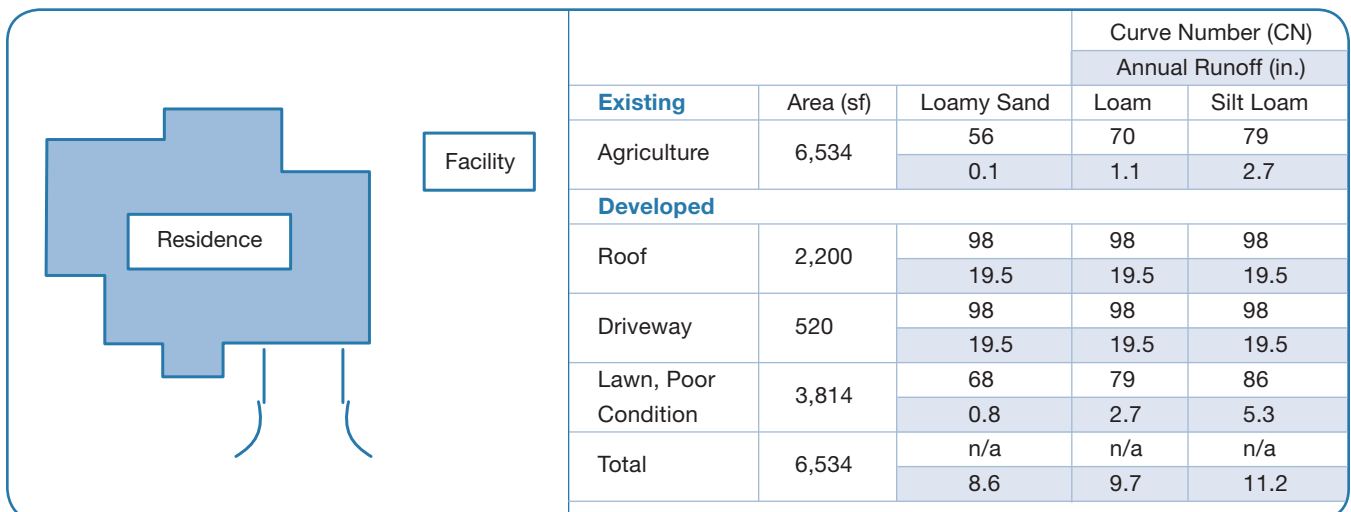 impervious and pervious runoff through a facility (Table 4.1), treating the impervious runoff and enhancing the pervious areas (Table 4.3) *increases* the stay-on by 3.9 percent and *decreases* the runoff by 25 percent.

Table 4.3 Enhanced Pervious Areas

	Facility Area, A_r	FAR	Impervious Area, A_i	Pervious Area, A_p	Ponding Depth, S_d	Root Thickness	Storage Thickness, S_t	Nat. Infiltration Rate, K_n	Underdrain Rate, K_u	Runoff Vol., V_{rf}	Stay-on Vol., V_s
4.3a	272	0.10	2,720	0	6	18	0	0.24	0	974	6,209
4.3b	n/a		n/a	3,542	n/a	n/a	n/a	n/a	n/a	634	7,870
Total	272									**1,608**	**14,079**

Table 4.4 gives the results of treating only the driveway runoff with a facility of the same size as the previous cases. The total runoff volume is 6,590 cubic feet, about three times the runoff for the case in which all impervious areas are routed through the same facility. This demonstrates the importance of treating all impervious surfaces.

Table 4.4 Effects of Bypassing Some Impervious Areas

#	Facility Area, A_r	FAR	Impervious Area, A_i	Pervious Area, A_p	Ponding Depth, S_d	Root Depth	Storage Thickness, S_t	Nat. Infiltration Rate, K_n	Underdrain Rate, K_u	Runoff Vol., V_{rf}	Stay-on Vol., V_s
4.4a	272	0.52	520	0	6	18	0	0.24	0	0	1,901
4.4b	n/a	n/a	2,200	3,542	n/a	n/a	n/a	n/a	n/a	5,283	0
4.4b	n/a	n/a	n/a	3,542	n/a	n/a	n/a	n/a	n/a	1,307	7,197
Total										**6,590**	**9,098**

In the case of Table 4.5, the two facilities have different area ratios, but the total facility area is the same (272 square feet). In this case, the performance of the two facilities is significantly poorer than that of the single facility (Table 4.2).

Table 4.5 Varying Facility Area Ratios

#	Facility Area, A_r	FAR	Impervious Area, A_i	Pervious Area, A_p	Ponding Depth, S_d	Root Thickness	Storage Thickness, S_t	Nat. Infiltration Rate, K_n	Underdrain Rate, K_u	Runoff Vol., V_{rf}	Stay-on Vol., V_s
4.5a	136	0.06	2,200	0	6	18	0	0.24	0	1,406	4,203
4.5b	136	0.26	520	0	6	18	0	0.24	0	5	1,569
Total										**1,411**	**5,772**

Table 4.6 gives the results of using two separate facilities to treat the roof and driveway, where the facility area ratios are the same (0.10). Lines 4.6a (roof) and 4.6b (driveway) give the resulting runoff and stay-on volumes. The next line gives the totals. Line 4.6c gives the results for a single facility treating both impervious areas, where the facility area is equal to the sum of the areas of the two facilities (and hence the FAR is also 0.1). Note that the runoff and stay-on volumes are the same for the single and dual facilities. This illustrates that the performance of multiple facilities can be simulated by the performance of a single facility of the same total area and receiving the same runoff, as long as the facility area ratios of the multiple facilities are the same.

Table 4.6 Constant Facility Ratio

#	Facility Area, A_r	FAR	Impervious Area, A_i	Pervious Area, A_p	Ponding Depth, S_d	Root Thickness	Storage Thickness, S_t	Nat. Infiltration Rate, K_n	Underdrain Rate, K_u	Runoff Vol., V_{rf}	Stay-on Vol., V_s
4.6a	220	0.10	2,200	0	6	18	0	0.24	0	788	5,022
4.6b	52	0.10	520	0	6	18	0	0.24	0	186	1,187
Total	272									**974**	**6,209**
4.6c	272	0.1	2,720	0	6	18	0	0.24	0	**974**	**6,209**

4.3 Surface and Subsurface Soils

Soil and subsoil conditions at the site are the most important control on the design and performance of a bioretention facility. The principal factor is the infiltration capacity of the limiting layer underneath the facility. In addition, the post-development soil texture determines the runoff from pervious surfaces, while the predevelopment texture generally determines the runoff and/or stay-on target.

Figures 4.3 and 4.4 illustrate the role of the hydraulic conductivity of the limiting layer below the facility. Figure 4.3 is a plot of runoff from the facility vs. the limiting infiltration rate for facility area ratios of 0.05 and 0.10. For both facility area ratios, runoff declines sharply as the hydraulic capacity increases from zero to about 0.5 inches per hour, and then flattens considerably. Figure 4.4 illustrates that the limiting hydraulic conductivity has an even greater effect on the maximum duration of ponding in the facility, based on 1981 wet-season rainfalls in Madison, Wis. Excessive ponding durations can severely damage plants and give the impression of facility failure.
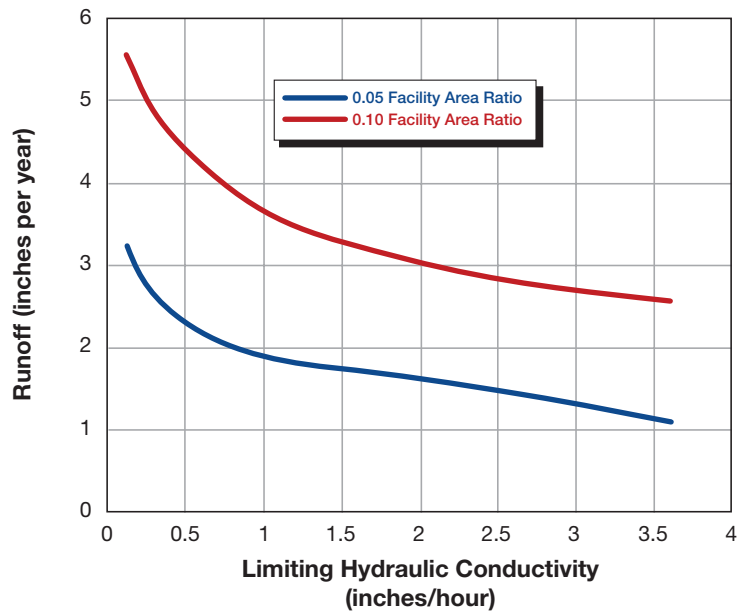
Figure 4.3 Runoff Reduction and Limiting Layer Hydraulic Conductivity
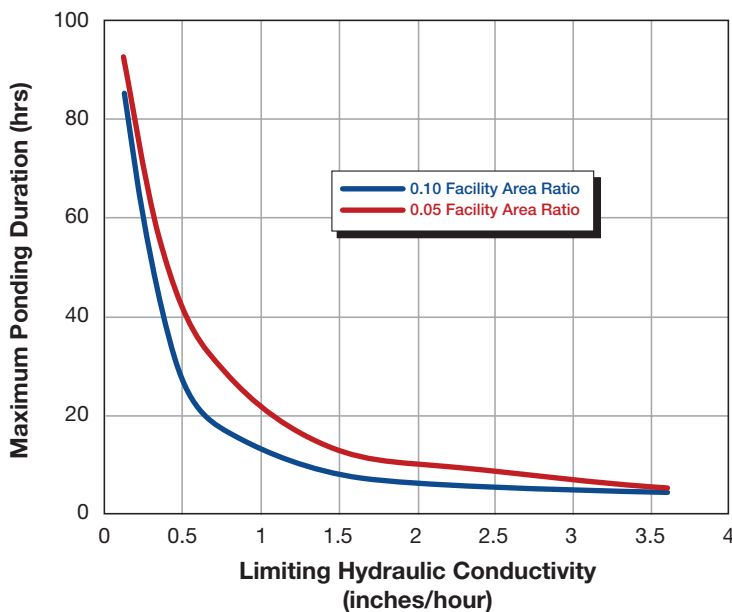
Figure 4.4 Surface Ponding Duration and Limiting Layer Hydraulic Conductivity

Table 4.7 illustrates the combined effects of the pervious soil textures and the texture of the limiting layer below the facility. The table gives the facility size required to control runoff at 90 percent of the predevelopment amount for various soil textures (under the assumption that the pervious soils are not disturbed during the development process), relative to base case of loam soils for both the pervious soils and the limiting subsurface layer at the facility (100 percent). Note that the relative sizes range from 37 percent for silt loam/sand, to 292 percent for loamy sand/silt loam textures.

Table 4.7 Relative Facility Size as Determined by Site vs. Facility Soils

		Soils in Pervious Contributing Areas		
		Silt Loam	Loam	Loamy Sand
Curve Number ⟹		79	68	58
Redeveloped Runoff ⟹		2.7	1.1	0.1
Allowable Runoff ⟹		5.3	3.9	3.0
Texture of Limiting Layer	Silt Loam[1]	177%	215%	292%
	Loam	95%	100%	100%
	Sandy Loam	78%	82%	82%
	Loamy Sand	51%	55%	56%
	Sand	37%	39%	44%

1. Silt loam facilities include an underdrain and six-inch storage zone.
2. All sizes relative to loam site soils with loam facility soils designed for the demonstration site (195 sf).

4.4 Underdrain and Storage Zone

An underdrain can reduce ponding times and increase the amount of water filtered. The former is illustrated in Table 4.8, which gives simulation results for our hypothetical development. Line 4.8a gives the baseline results. Line 4.8b gives the effects of adding an underdrain. Note that the addition of an underdrain allows an additional volume of water to infiltrate through the root zone, reducing the maximum ponding time from 71.75 hours to 29 hours. From a water-quality perspective this is a favorable outcome, as it increases the volume of runoff treated by the facility. However, since water exiting through the underdrain flows to the surface water, it is still considered runoff. Therefore, the addition of an underdrain reduces ponding time but increases stormwater runoff. The addition of a 30-inch storage layer below the level of the underdrain to this case recaptures this loss, as is shown on line 4.8c.

The results in line 4.8d are for a modified base case with silt loam soils and an underdrain that yields the same drawdown rate as a silt loam without an underdrain. The results indicate that the volume of water that infiltrates through the root zone is almost the same as the baseline case. This implies that designs with equivalent drawdown rates treat a similar volume of water, regardless of the limiting layer hydraulic conductivity.

Table 4.8 Effects of Underdrains on Facility Performance

Example	Facility Area, A_r	FAR	Impervious Area, A_i	Pervious Area, A_p	Ponding Depth, S_d	Root Thickness, S_r	Storage Thickness, S_t	Nat. Infil. Rate, K_n	Underdrain Rate, K_u	Runoff Vol., V_{rf}	Stay-on Vol., V_s	Max Hours Ponded
Loam without Underdrain												
4.8a	272	0.1	2,720	3,542	6	18	0	0.24	0	2,139	13,548	71.75
Loam with Underdrain												
4.8b	272	0.1	2,720	3,542	6	18	0	0.24	0.26	3,098	12,589	29
Loam with Underdrain and Additional Storage												
4.8c	272	0.1	2,720	3,542	6	18	30	0.24	0.26	2,129	13,558	n/a
Silt Loam with Underdrain												
4.8d	272	0.1	2,720	3,542	6	18	0	0.13	0.11	2,153	12,398	n/a

4.5 Conclusions

Based on the case study and on results presented earlier in this manual, we reiterate the following findings and recommendations:

- It is inefficient to treat pervious areas with bioretention facilities.

- It is ineffective to leave portions of the impervious surfaces untreated and overcompensate by constructing a larger facility. Instead, the focus should be on treating all of the impervious surfaces and enhancing the infiltration capacity of the pervious surfaces. You cannot compensate for bypassed impervious surfaces by increasing the facility area ratio for areas treated.

- The benefits of multiple bioretention facilities with the same facility area ratios can be determined by simulating the performance of a single facility receiving all of the runoff and having an area equal to the sum of the areas of the multiple facilities. If the facility area ratios are not the same, the results based on a single facility will overestimate the aggregate benefits.

- Increasing the depth of the ponding zone provides the greatest increase in stay-on volume per inch of increase, followed by the root zone and then storage zone. However, increasing the depth of the ponding zone increases the drainage time, providing an upper limit on ponding depth.

- Adding an underdrain decreases ponding time, but at the expense of stay-on.

- Adding a storage zone increases stay-on by increasing the amount of water that infiltrates through the root zone and decreasing the amount of water that flows out the underdrain.

Appendix

RECARGA User's Manual, Version 2.3

Section A.

Introduction

*The RECARGA model and this publication may be downloaded free of charge from the University of Wisconsin Aquatic Sciences Center's online "Publications Store" (*aqua.wisc.edu/publications/default.aspx*). The RECARGA model and user's manual are also available from the Wisconsin Department of Natural Resources' Runoff Management Models website* (www.dnr.state.wi.us/org/water/wm/nps/models).

The RECARGA model (Atchison and Severson 2004) is a design tool for evaluating the performance of bioretention facilities, rain garden facilities, and infiltration basins. Individual facilities with surface ponding, up to three distinct soil layers, and optional underdrains can be modeled under user-specified precipitation and evaporation conditions. The model continuously simulates the movement of water throughout the facility (ponding zone, soil layers, and underdrains), records the soil moisture and volume of water in each water budget term (infiltration, recharge, over-flow, underdrain flow, evapotranspiration, etc.), and summarizes the results. The results of this model can be used to size facilities to meet specific performance objectives, such as reducing runoff volume or increasing recharge, and to analyze sensitivity to design parameters.

The model uses the Green-Ampt infiltration model for initial infiltration into the soil surface and the Van Genuchten relationship for drainage between soil layers. Surface inflow to the facility from impervious surfaces is calculated using a simple initial abstraction. For pervious surfaces, surface inflow is calculated using the SCS TR-55 methodology, based on user-supplied curve numbers. Underdrain flow is calculated using the orifice equation. The model tracks continuous soil moisture and evapotranspiration between storm events. More detail on the model methodology is included in the documentation section of this manual (Section B).

A-1 Installation

To install RECARGA on your computer, copy the "RECARGA" folder to the folder of your choice. To activate the program, double-click the "RECARGA_2_3.exe" file. The program will display a DOS window in addition to the RECARGA interface. Error messages will be displayed in the DOS window.

A-2 Precipitation Input Files

The model needs a user-provided precipitation text file for calculating the input to the facility. The precipitation file should contain relevant rainfall and evapotranspiration data for the region for which the facility is being analyzed (Figure A-1). The precipitation text file needs to be saved in a tab-separated format ("*filename*.txt") with three columns, and the first row should be reserved for labeling the data columns. In many cases, the required precipitation input file may be provided with the model. In such a case, the files should be stored in the same folder as the model. **Note:** The value in row 1 for rainfall needs to be zero.

Figure A-1 Example Precipitation Input File

Hr	Rain(mm)	Evap(mm)
0	0	0.095327486
1	0	0.095327486
2	0.508	0
3	0.508	0
4	0.254	0
5	0	0.095327486
6	0	0.095327486
7	0	0.095327486
...		

Column 1 (Time): Column 1 is used to provide the interval for the input file. Beginning with time equal to 0, the column should list the time at an hourly interval throughout the length of the precipitation record provided.

Column 2 (Precipitation): Column 2 is used to record the incremental precipitation at each hourly time-step. The RECARGA model runs the calculation procedures in metric or English units; therefore, the precipitation data needs to be recorded in millimeters or inches. NOAA data are available from its website at *www.noaa. gov/climate.html*.

Column 3 (Potential Evaporation): Column 3 is used to record the incremental potential hourly evaporation (in millimeters). The program assumes that pan data are being used and applies a coefficient of 0.75 to all data. If other data are used that do not require corrections, they must be divided by 0.75 prior to entry.

A-3 Running the RECARGA Model

Double-click the "RECARGA_2_3.exe" shortcut to begin the program. The program should display a user interface (Figure A-2). Begin by entering the input/output file data and the facility inputs.

Figure A-2 RECARGA User Interface
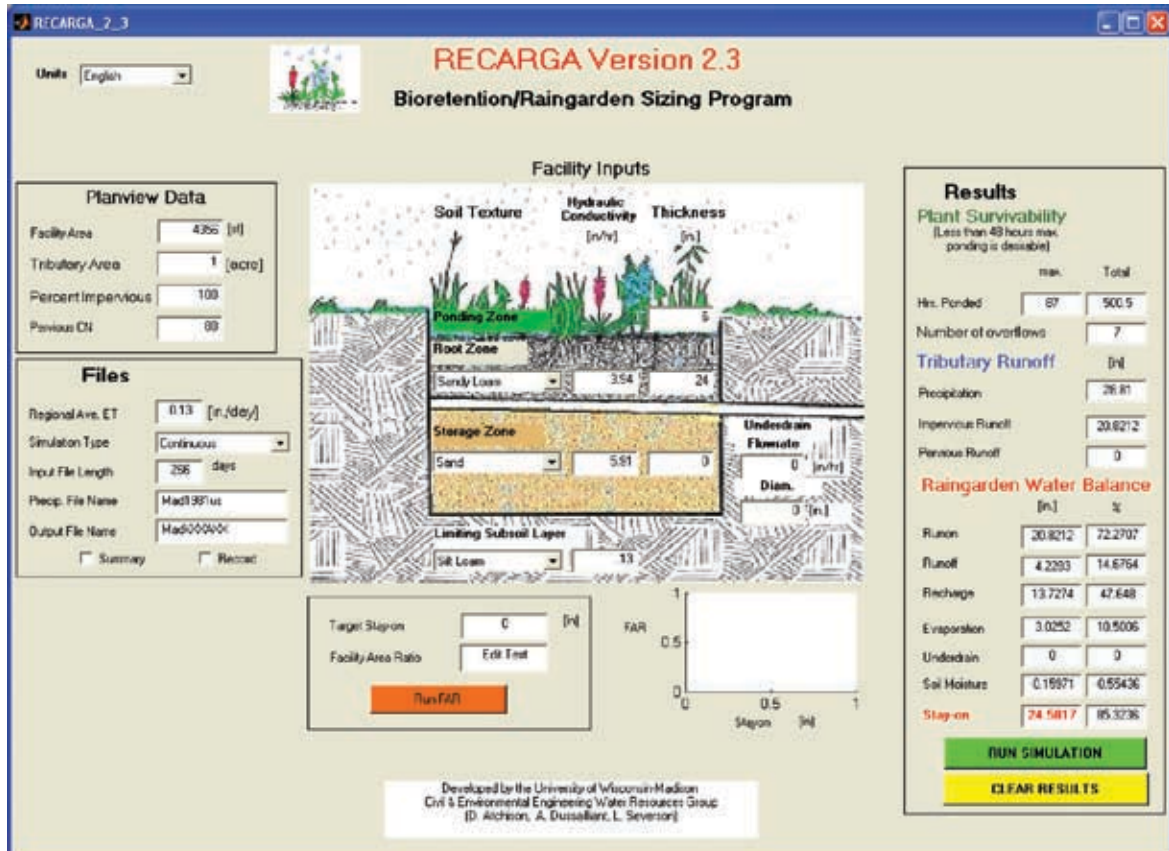
A-3.1 Simulation Type

Begin by selecting one of three **simulation types**—continuous, single-event, or user input. The continuous runoff simulation provides a continuous simulation of hydrologic processes using the precipitation/evaporation input file. The user input option may be used to bypass the model's runoff calculation with a user input file of hourly runon (depth) to the facility obtained from another model. Both simulation types have the following inputs:

Input File Length: Enter the number of days for the calculation. If a number less than the total number of data lines is entered, the program will calculate only that number of days from the beginning date.

Precip. Input File: Enter the name of the precipitation file to use. (Exclude the ".txt" extension.)
Note: This file needs to be stored in the "…\RECARGA\" folder.

The single event option allows the user to simulate the runoff from a single storm event. This option has the following inputs:

Rainfall Distribution: Select the appropriate SCS hyetograph—Type I, IA, II, or III.

Rainfall Depth: Enter the 24-hour rainfall depth for the simulation.

The following inputs are common to all three simulation types:

Regional Ave. ET: Enter the average hourly evapotranspiration for the region (the daily average divided by 24 hours). This is used to calculate the available initial abstraction from impervious areas tributary to the facility.

Output File Name: Enter the file name for the output files. Exclude the ".txt" extension; the model will add the extension and save these files to the "…\RECARGA\" folder. Check the "Summary" and/or "Record" boxes to include output files of those types. These files are described in detail in the results section of this guide.

Summary: This file provides an overall summary of the inputs and results over the span of the calculation.

Record: This file provides an hourly record of the performance of the facility during the calculation period.

A-3.2 Facility Inputs

Soil Texture: Enter the soil texture for each of the soil layers. The default values for the rooting zone and storage zone are "Loamy Sand" and "Sand," respectively. Native soil refers to the limiting layer below the facility.

Hydraulic Conductivity: Enter the saturated hydraulic conductivity for each soil layer. The default values for the rooting zone and storage zone are 3.94 inches per hour (10 cm/hr) and 5.91 inches per hour (15 cm/hr), respectively. Determine the native soil hydraulic conductivity from the texture class (see Table A-1 or an approved infiltration test conducted at the depth of the facility bottom.

USDA Soil Texture Class	Low Bulk Density Geometric Mean (25th-75th Percentile) [cm/hr]	High Bulk Density Geometric Mean (25th-75th Percentile) [cm/hr]
Sand	18.19 (26.68-9.65)	9.14 (21.85-6.40)
Fine Sand	14.13 (23.61-11.81)	10.00 (21.98-6.81)
Loamy Sand	12.30 (19.55-8.38)	4.14 (7.76-3.05)
Loamy Fine Sand	6.22 (12.20-3.56)	1.28 (11.60-0.68)
Sandy Loam	5.58 (12.96-3.05)	1.28 (3.13-0.51)
Fine Sandy Loam	2.24 (3.56-0.98)	0.82 (1.70-0.34)
Loam	0.39 (2.84-0.16)	0.62 (1.65-0.28)
Silt Loam	1.44 (3.71-0.76)	0.34 (0.99-0.10)
Sandy Clay Loam	0.77 (5.05-0.20)	0.28 (1.09-0.10)
Clay Loam	0.42 (1.31-0.22)	0.07 (0.38-0.02)
Silty Clay Loam	0.37 (1.04-0.23)	0.49 (1.40-0.23)
Sandy Clay		0.09 (0.25-0.03)
Silty Clay		0.18 (0.75-0.05)
Clay	0.20 (0.60-0.09)	0.18 (0.69-0.03)

Table A-1 Saturated Hydraulic Conductivity Based on USDA Soil Texture Class
(Rawls et al. 1998)

Depth: Enter the depth of the ponding zone and the soil layers. The default ponding depth is six inches.

Underdrain: Enter the maximum underdrain flow. To find the necessary underdrain flow to drain the facility within 24 hours after an event, divide the ponding depth by 24 hours and subtract the native soil hydraulic conductivity. The program will calculate the required diameter of the underdrain or control orifice to meet this flow rate.

Facility Area: Enter the facility area (in square feet).

Basin Area: Enter the area (in acres) of the basin tributary to the facility.

Percent Impervious: Enter the percentage of the basin area that is impervious (e.g., roofs, driveways, parking lots, paved walkways).

Pervious CN: Enter the representative curve number for the pervious areas tributary to the facility based on the tables provided in Technical Release 55 (TR-55).

A-3.3 Run Simulation

Run the simulation by clicking the "Run Simulation" button.

A-4 Model Output

A-4.1 On-Screen Output

Plant Survival Terms

Ponding Times: The maximum and total duration of time during which the facility is ponded are crucial to the survival of the plants. In general, the ponding duration should be less than 24 hours after a storm event has ended. (Note that the maximum ponding duration may exceed this by a few hours if ponding occurred during the storm.)

Number of Overflows: This is the number of times during the simulation that the facility overflowed, which may be an important design consideration. Note that facilities with a large number of overflows may require greater erosion protection along the overflow route.

Tributary Runoff

The results reported in this section are the total depth of precipitation and runoff from the tributary pervious and impervious areas.

Rain Garden Water Balance

The water balance terms in the facility are summarized in terms of depth (over the entire basin) and percentage (of the runon).

Runon: Water flowing into the facility over the simulation period (includes direct rainfall on the facility).

Runoff: Water overflowing the facility.

Recharge: Water percolating through the bottom of the facility.

Evaporation: Water evaporated and transpired from the facility.

Underdrain: Water flowing through the underdrain.

Soil Moisture: Water retained in the facility soils at the end of the simulation.

Stay-on: Water retained on the site. The depth of stay-on is equal to the depth of the precipitation minus the runoff depth and the underdrain depth. The percentage reported is the percentage of the overall precipitation depth.

A-4.2 Summary Output File

The summary output file option creates a text file in the "…\RECARGA\" folder with the name entered in the "Output File Name" box (*"outputfilename*.txt"). This file summarizes the input parameters, facility inputs, date/time of the simulation, input/output file names, and final results of the simulation (Figure A-3). The final results are summarized in two parts:

Water Balance Terms: The depth and volume of each water balance term is summed throughout the simulation. The summary file also includes some mass balance checks to verify the final results.

Plant Survivability Terms: These provide individual and aggregate statistics on the occurrence of conditions critical to plant survival, including ponding, root zone saturation, and moisture stress.

RECARGA 2.3

Date:	12-Jan-2004 10:51:45
Output File:	Example.txt
Input File:	Mad1981.txt
Number of time steps=	25537
CPU elapsed time (s)=	46

INPUT TERMS

% Impervious=	60
Pervious CN=	80
Facility Area (m2)=	100
Trib. Area (m2)=	1000
RATIOimp2rg=	6
RATIOperv2rg=	4

LAYER	DEPTH (cm)	Ksat (cm/hr)	TEXTURE
Depression	15	---	---
Root Zone	45	10.00	2
Storage	30	15.00	1
Native	---	0.34	5

Init. Cond.: suction head (cm)=	-100
Max. Underdrain flow (cm/hr)=	0.31
Underdrain diam (mm)=	7

WATER BALANCE TERMS

	Volume(m3)	Depth (cm)	% of Inflow
Inflow	400.52	36.41	100.00
Runoff	23.66	2.15	5.91
Recharge	208.58	18.96	52.08
Evaporation	79.38	7.22	19.82
Underdrain	95.73	8.70	23.90
Storage	-6.83	-0.62	-1.71
Infiltrated	376.86		
Precip.		73.18	
Imp. Inflow	317.31	52.89	79.23
Perv.Inflow	30.32	7.58	7.57
Basin Stay-on(cm)		38.41	

Mass Balance Checks:

Vinsoil=	input-roff-dvh
Vinsoil (m3)=	3.768642e+002
Vinf difference (%)=	-0.0
Vrecharg1=	inf-et-dsws
Vrecharg1 (m3)=	2.085808e+002
Vrech difference (%)=	0.0
dVsoil=	inf-rech-et
dVsoil=	8.889862e+001
dVsfce (m3)=	0.000000e+000
dVs2=	input-roff-inf

PLANT SURVIVABILITY TERMS

total time ponded (h)=	129.8
max time ponded (h)=	27.5
total time RZ saturated (h)=	146.5
total time RZ at wilting point (h)=	1851.3
total time TZ saturated (h)=	252.3
max time RZ saturated (h)=	28.8
max time RZ at wilting point (h)=	648.5
max time TZ saturated (h)=	45.8
near saturated times for simulation=	11

727.8	9.5
2319.8	28.8
2946.0	0.5
2981.3	27.0
3764.0	28.8
4043.8	4.5
4058.8	12.5
4073.0	8.5
4172.3	22.3
4310.0	0.8
5276.3	3.5

wilting point times for simulation= 11

554.3	145.3
652.3	25.3
1132.0	75.5
1884.8	648.5
2128.5	141.8
2233.0	11.5
2918.0	187.5
3727.3	67.3
4012.5	34.3
4643.8	54.5
6068.0	460.0

ponded times for simulation= 10

726.3	8.0
2318.5	27.5
2945.8	0.3
2979.8	25.3
3762.5	27.3
4042.3	2.3
4057.3	10.8
4071.8	7.0
4170.8	20.8
5274.8	0.8

overflow times for simulation= 3

2294.3	2.8
2956.0	0.3
3738.5	1.3

Figure A-3 Example of Summary File Results

A-4.3 Record File Output

The summary output file option creates a text file in the "…\RECARGA\" folder with the name entered in the "Output File Name" box with "_WB" added to the end of the name (*"outputfilename_*WB.txt"). This file records the depth of water for each water budget term occurring at hourly time steps throughout the simulation period (Figure A-4). The water depth for each term is reported as the depth relative to the facility area (volume/facility area). The file also records the relative water content in each layer expressed as a fraction of the overall soil volume occupied by water (ThetaRZ [rooting zone], ThetaSZ [storage zone], and ThetaCZ [native soil layer]). This file can be imported into a spreadsheet file to graph the water movement through the facility.

Time(hr)	Runon(cm)	Ponding(cm)	Infil(cm)	Runoff(cm)	Drain(cm)	Recharge(cm)	ET(cm)	ThetaRZ	ThetaSZ	ThetaCZ
653	0.817	0	0.817	0	0	0.002	0	0.134	0.194	0.39
654	1.978	0	1.978	0	0	0.002	0	0.204	0.194	0.39
655	4.385	0	4.385	0	0.028	0.002	0	0.292	0.194	0.39
656	2.559	0	2.559	0	0.201	0.002	0	0.327	0.199	0.39
657	0.6	0	0.6	0	0.239	0.002	0	0.322	0.209	0.39
658	0	0	0	0	0.236	0.002	0.017	0.312	0.216	0.39
659	0	0	0	0	0.232	0.002	0.017	0.304	0.219	0.39
660	0	0	0	0	0.228	0.002	0.017	0.297	0.221	0.391
661	0	0	0	0	0.225	0.002	0.017	0.292	0.221	0.391
662	0	0	0	0	0.206	0.002	0.017	0.287	0.221	0.391
663	0	0	0	0	0.18	0.002	0.017	0.283	0.221	0.391
664	0	0	0	0	0.159	0.002	0.004	0.279	0.221	0.392
665	0	0	0	0	0.143	0.002	0	0.276	0.221	0.392
666	0.422	0	0.422	0	0.132	0.002	0	0.289	0.221	0.392
667	1.778	0	1.778	0	0.203	0.002	0	0.33	0.224	0.393
668	2.2	0	2.2	0	0.241	0.002	0	0.353	0.244	0.393
669	0.956	0	0.956	0	0.249	0.002	0	0.343	0.27	0.395
670	0.111	0	0.111	0	0.245	0.002	0	0.328	0.286	0.398
671	0	0	0	0	0.239	0.003	0.017	0.317	0.293	0.403
672	0	0	0	0	0.234	0.004	0.017	0.308	0.296	0.41

Figure A-4 Example of Record File Output

A-5 Facility Area Ratio

As mentioned above, RECARGA has the potential to calculate the facility-to-tributary area ratio (FAR) needed to meet a target stay-on objective. As before, the user should enter the following rain garden design parameters with one additional entry, the target stay-on:

- Tributary Area
- Percent Impervious
- Pervious Curve Number
- Precipitation Files
- Depression Depth
- Root Layer Depth
- Root Layer Infiltration Rate
- Storage Layer Depth
- Storage Layer Infiltration Rate
- Native Soil Infiltration Rate
- Underdrain Flow Rate
- Underdrain Diameter
- Target Stay-on

Once the above parameters are entered, press the **Run FAR** button. The user no longer has to enter the facility area. (*Note:* If you do, the program will **not** use it for this function.) RECARGA will run the rain garden design for a facility-to-tributary area ratio of 1, 5, 10, 15, and 25 percent. Through iteration of stay-on results matching target stay-on, the program will output the required facility area ratio in the **FAR(%)** box.

Section B.

Model Documentation

B-1 MATLAB Computer Model

RECARGA is a numerical model that was developed in 2002 by Alejandro Dussaillant as a tool for evaluating bio-retention facilities. A flow schematic of the RECARGA model is presented in Figure B-1. We have subsequently updated the model several times as described below.

Tributary Basin   **Facility**   **Downstream**

Precipitation

Pervious Areas TR-55

Impervious Areas Initial Abstraction

Runon

Basin Stay-on

Evapo-Transpiration

Ponding Zone

Green-Ampt

Rooting Zone

Van Genuchten

Storage Zone

Van Genuchten

Native Soils

Van Genuchten
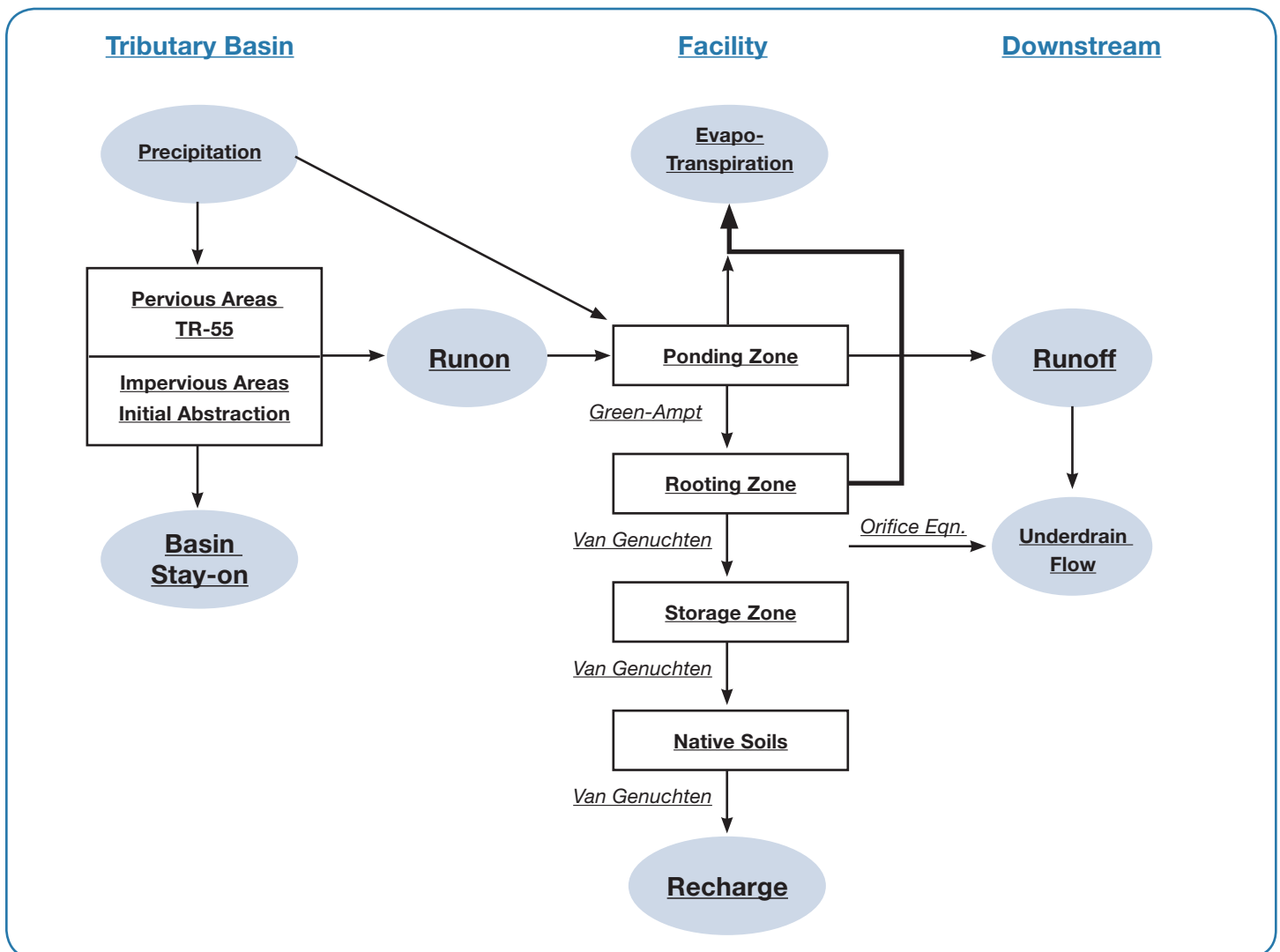
Recharge

Runoff

Orifice Eqn.

Underdrain Flow

Figure B-1 RECARGA Model Flow Schematic

B-2 RECARGA Model Updates

Version 1.0

- Continuously models water flow in all compartments of the bioretention facility—the ponding, root, and storage zones—as well as into the native subsoil.

- Uses a specified hourly precipitation record, which is uniformly disaggregated into 15-minute time steps, to continuously model rainfall.

- Allows only two water sources—direct precipitation on the facility and runoff from impervious surfaces; the latter is characterized by the Facility Area Ratio (FAR), the ratio of the impervious area to the surface area of the rain garden facility.

- Uses Green-Ampt equation to model infiltration into the facility (Green and Ampt 1911).

- Calculates drainage from user-supplied saturated hydraulic conductivity, which is converted to unsaturated hydraulic conductivity for a given soil water content calculated using the Van Genuchten Relationship (Van Genuchten 1980).

- Makes impervious abstraction available after 12 hours without rainfall.

- Programmed in MATLAB computing software and language.

- Uses metric units only.

Version 2.0

- Allows for tributary pervious surfaces. Runoff from these surfaces is calculated using the SCS runoff equation.

- Includes an underdrain function that calculates discharge using the orifice equation based on the diameter of the underdrain and the depth of water above the outlet.

- Calculates evapotranspiration between storm events from a continuous evapotranspiration record (e.g., pan evapotranspiration data) included in the input precipitation file.

- Reports a continuous output record and summary output record of water budget terms for the facility on an hourly time scale.

- Makes impervious abstraction available after six hours without rainfall.

- Allows the user to enter the facility area and tributary area instead of ratios.

- Incorporates a graphical user interface.

Version 2.1

- Allows for use of SCS design storm events.

- Allows user to specify runon using a continuous record developed outside of the model.

- Uses English units in addition to metric.

Version 2.2

- Makes initial abstraction for pervious SCS runoff calculations available after 24 hours without rainfall for metric mode.

- Incorporates additional graphics to the user interface, including a rain garden profile.

Version 2.3

- Includes a design module that enables the model to calculate the facility area ratios required to meet a target stay-on.

- Corrects for spurious differences in results between the metric version and the English version when a storage zone depth of zero is run.

- Makes initial abstraction for pervious SCS runoff calculations available after 24 hours without rainfall for English mode.

Section C.

Governing Equations

C-1 Runoff

Runoff is obtained from either direct unit runon files, user input, or input precipitation files that use the SCS Curve-Number Method and initial abstraction methods.

C-1.1 Pervious Areas

The curve-number approach uses the SCS methodology to determine the watershed storage capacity, $S_{d,perv}$, from curve numbers (CN). The model then calculates the effective runoff depth (w_i) from the pervious areas from the difference of the cumulative effective runoff between time steps from the SCS runoff equation below.

$$W_i = \frac{\left(P_i - 0.2 * S_{d,perv}\right)^2}{P_i + 0.8 * S_{d,perv}},$$

$$S_{d,perv} = \frac{100}{CN} - 10,$$

$$w_i = W_i - W_{i-1},$$

where P_i is the cumulative precipitation at time i, W_i is the cumulative effective runoff at time i, and w_i is the effective runoff during time-step i.

C-1.2 Impervious Areas

The runoff from impervious areas is calculated using a simple initial abstraction routine. The model tracks the available surface depression depth ($S_{d,imp}$), which is restored between events by the average evapotranspiration rate (ET_{ave}) entered by the user.

$$\frac{\partial S_{d,imp}}{\partial t} = ET_{ave},$$

$$S_{d,imp} = min(\int ET_{ave}, S_{max,imp}),$$

$$W_j = max(P_j - S_{d,imp}, 0)$$

$$w_j = W_j - W_{j-1},$$

where P_j is the cumulative precipitation at time j, W_j is the cumulative effective runoff at time j, and w_j is the effective runoff during time-step j.

C-2 Evapotranspiration

Evapotranspiration from the rooting zone is expressed as:

$$Q_{et} = E_{max} \cdot \left(1 - \left[1 + A_w\right]^{1/m}\right)$$

with

$$A_w = \frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}}$$

where E_{max} is the evaporation value in the input file and θ, θ_{fc}, and θ_{pwp} are the water contents at current conditions, field capacity, and the permanent wilting point, respectively.

C-3 Green-Ampt Equation

The RECARGA model is based on the Green-Ampt infiltration equation (Green and Ampt 1911):

$$\frac{dF(t)}{dt} = i \qquad\qquad 0 \le t \le t_p$$

$$\frac{dF(t)}{dt} = K_{sat} \cdot \left(1 + \frac{B}{F(t)}\right) \qquad\qquad t_p \le t \le t_r$$

with

$$B = \left(h_{wf} + h_s(t)\right)\left(\theta_{sat} - \theta_{ini}\right)$$

where i is water supply intensity ([L]/[T]), K_{sat} is the saturated hydraulic conductivity ([L]/[T]), h_{wf} is the average capillary suction head at the wetting front ([L]), $h_s(t)$ is the ponded depth at the soil surface at time t, θ_{sat} is the saturated volumetric water content, and θ_{ini} is the (uniform) initial soil moisture at the beginning of the water input event ($t = 0$). Thus, $(\theta_{sat} - \theta_{ini})$ represents the initial soil water deficit, and B is the overall driving force for infiltration. The formulation assumes one-dimensional, vertical flow and total saturation behind the wetting front.

In RECARGA, h_{wf} is approximated by the air-entry soil water potential (bubbling pressure) of the root zone (i.e., $h_{wf} \cong h_b$). Additionally, i is the rainfall intensity at ponding time, and the ponding depth, h_s, is updated in the rain garden surface water budget.

C-4 Surface Water Balance

The water balance in the rain garden surface depression can be expressed as:

$$A\frac{dh_s}{dt} = Q_{RAIN} + Q_{RUNON} - Q_{INFILTRATION} - Q_{RUNOFF}$$

where A is the rain garden area ([L]^2), and the flows Q are the inputs and outputs to the rain garden depression ([L]^3/[T]). We assume that rain and runon are uniformly distributed over the rain garden area. Runoff from the rain garden occurs once the maximum depression depth, h_d, is surpassed.

If we assume that the concentration and conveyance time for the runon is negligible — which for the case of a roof is reasonable, as times of concentration are in the order of only a few minutes — and that runon is distributed homogeneously in the garden surface, the total amount of water entering the garden can be approximated by:

$$Q_{IN} = Q_{RAIN} + Q_{RUNON} = Q_{RAIN} \cdot \left(1 + \frac{1}{L}\right)$$

where L denotes the rain garden to connected impervious area ratio. Q_{IN} assumes an abstraction due to roof depression storage, ST, which is approximated as 2.5 mm, and assumed to evaporate completely.

C-5 Soil Layering, Drainage, and Hydraulic Properties

The soil is modeled as three homogeneous layers, and the percolation between them is assumed to be only gravity driven; i.e., the hydraulic gradient is equal to unity. Therefore, we approximated the drainage, $d(t)$, from a top layer to the one below as the unsaturated hydraulic conductivity, $K(\theta)$, as given by the Van Genuchten relationship (Van Genuchten 1980):

$$d(t) = K(\Theta) = K_{sat} \cdot \Theta^{1/2} \left[1 - \left(1 - \Theta^{1/m}\right)^m\right]^2$$

where Θ is the soil layer dimensionless water content $(\theta - \theta_{res})/(\theta_{sat} - \theta_{res})$, and m is the Van Genuchten parameter.

For restricted flow due to control by a lower layer in saturated conditions, the model corrects for the infiltration and drainages according to the limiting hydraulic conductivity.

C-6 Underdrain Flow

$$U(t) = C_o A H_u^{3/2}$$

Underdrain flow was modeled according to the orifice flow equation:

where H_u is the head above the underdrain elevation, defined as the ponding depth plus root zone thickness when ponding occurs. Where ponding depth is zero, the underdrain head is defined as root zone dimensionless water content (Θ) times the root zone thickness.

For restricted flow due to control by a lower layer in saturated conditions, the model corrects for the infiltration and drainages according to the limiting hydraulic conductivity plus the underdrain flow.

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