

RECARGA User's Manual

Version 2.3
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University of Wisconsin – Madison
Civil & Environmental Engineering Department
Water Resources Group

Dustin Atchison
Linda Severson

INTRODUCTION

The RECARGA model was developed to provide a design tool for evaluating the performance of bioretention facilities, raingarden facilities, and infiltration basins. Individual facilities with surface ponding, up to 3 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, overflow, underdrain flow, evapotranspiration, etc.) at each time step 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 for analyzing the potential impacts of varying the 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. Input to the facility is calculated from user specified land cover data (percent impervious area, pervious area curve numbers and the area of the facility and tributary basin) using an initial abstraction equation (for impervious areas) or the TR-55 methodology for pervious areas. Underdrain flow is calculated using the orifice equation. The model also tracks continuous soil moisture and evapotranspiration between storm events. More detail on the model methodology is included in the documentation chapter of this manual.

UPDATES FOR VERSION 2.1

Version 2.1 is updated to include the ability to run the model in English or Metric units. Also the model now allows for the user choose between three options for calculating runoff to the facility:

1. Continuous rainfall, using a user-specified precipitation/evaporation file.
2. Event rainfall, using SCS Type I, IA, II or III distributions.
3. User-specified runoff.

UPDATES FOR VERSION 2.2

Version 2.2 has added raingarden graphics that allows the user to visualize what each input parameter represents

UPDATES FOR VERSION 2.3

Version 2.3 had added a feature allowing the user to design a raingarden and enter a desired target “stayon” value and RECARGA outputs the facility to tributary area ratio that would be needed to achieve the target stayon. It also graphs “stayon” vs. facility area ratios of 1,5,10,15 and 25% to allow the user interpret maximum benefits of the facility.

NOTE TO WISCONSIN USERS

DNR conservation practice standards for infiltration basins (DNR Conservation Practice Standard 1003) and bioretention (DNR Conservation Practice Standard 1004) limit some design parameters for infiltration devices built in Wisconsin. Common limitations affect allowable tributary area, native soil infiltration rates, design pond depth, design pond draw down, and storage layer depth (bioretention only). These limitations are intended to limit the incidence of device failures and to provide adequate pollutant control. When choosing input variables for RECARGA, these limitations should be recognized. Although RECARGA may accept and process variables outside these ranges, the resulting facility design may not be acceptable for installation in Wisconsin. DNR conservation practices may be downloaded from the DNR Internet site:

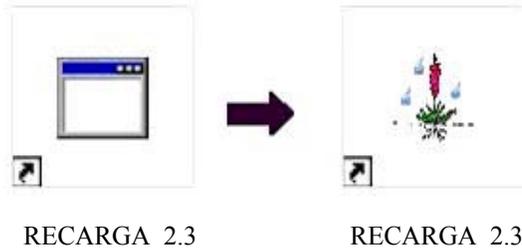
<http://dnr.wi.gov/runoff/stormwater/techstds.htm#Post>

In addition, design infiltration rates for the native soil must be determined in accordance with DNR Conservation Practice Standard 1002: Site Evaluation for Stormwater Infiltration. The RECARGA default infiltration rate for silty clay loam soils is .19 inches/hour. However, DNR Conservation Practice Standard 1002 requires that this value be set at .04 inches/hour when determined by soil texture alone. This change from .19 to .04 inches/hour for silty clay loam soils can be made manually on the RECARGA input data sheet. The default infiltration rates for other soil textural classes in RECARGA match those in DNR Conservation Practice Standard 1002.

INSTALLATION

To install RECARGA on your PC, copy the “RECARGA” folder file to the folder of your choice. To activate the program, double-click the RECARGA_2_3.exe file. The program will display a C-prompt in addition to the RECARGA interface. The C-prompt will display any error messages that occur.

In most Windows environments the RECARGA_2_3 shortcut will display the default application icon. To change this icon to a unique one, shown below, created for RECARGA, right-click the shortcut and select “Properties”. Then click “Change Icon” and “OK” on the next pop-up message. Then browse to the RECARGA folder and select “RGico.ico” to change the display icon for this shortcut. However, the program will still run with the original icon.



PRECIPITATION INPUT FILES

The model uses 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. The text file needs to be saved in a tab-separated format (*filename.txt*) with three columns and the first row 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.

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
...		

Figure 1. Example Precipitation Input File

Column 1 (Time)

Column 1 is used to provide the time step for the input file. Beginning with time equal to 0, the column should list the time at an hourly time step 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, therefore the precipitation data needs to be recorded in millimeters or inches. Generally, precipitation data can be obtained from available local raingage data or from the NOAA website at www.noaa.gov/climate.html.

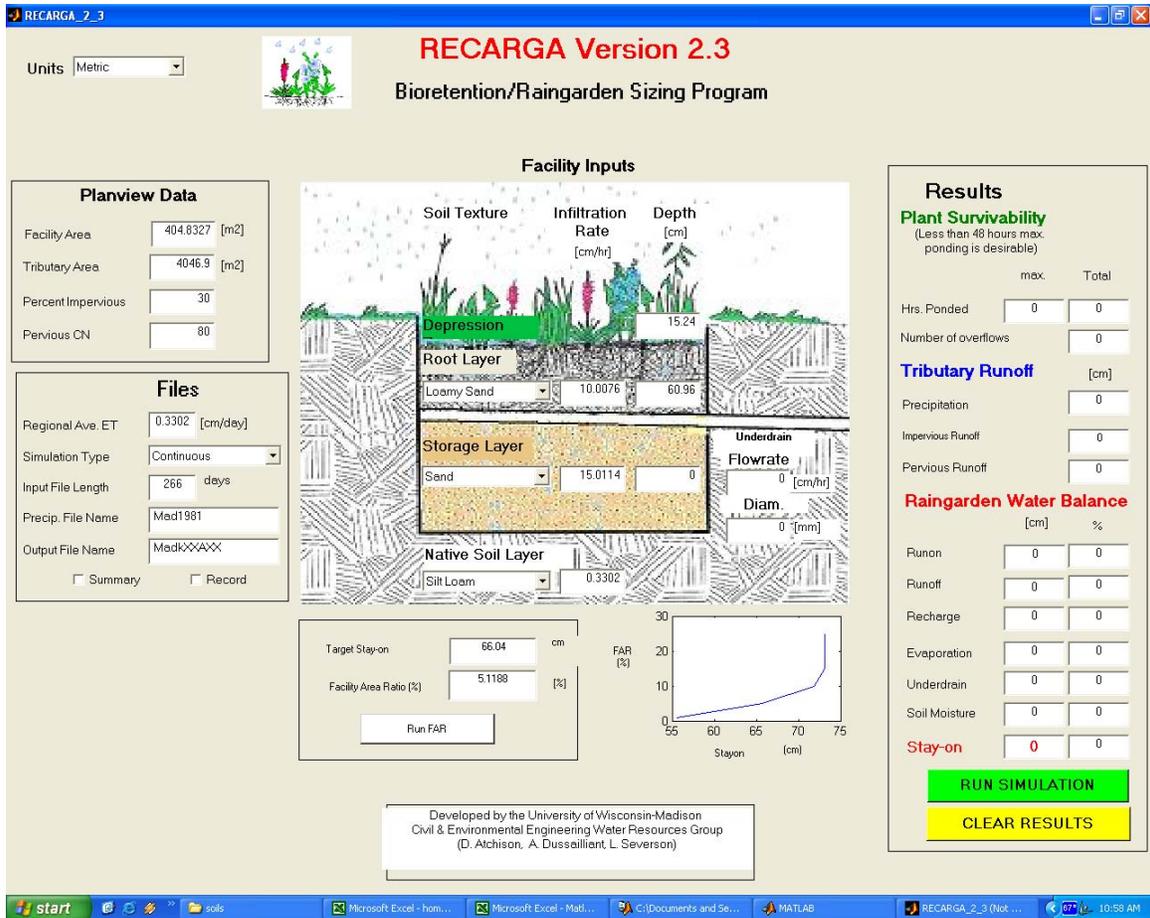
Column 3 (Potential Evaporation)

Column 3 is used to record the incremental potential hourly evaporation (in millimeters). Often potential evaporation data is available as daily pan evaporation data. Translate the daily pan evaporation data by distributing the daily value evenly over the non-precipitation hours of the corresponding day. Although evaporation generally occurs only during daylight hours, the RECARGA model calculates evaporation as occurring during the non-precipitation hours throughout the day, simplifying the data input (this does not produce a significantly different result). The RECARGA model assumes that pan evaporation is the default data type and applies a pan coefficient of 0.75 to all input data.

Another method to calculate the potential evaporation is to use Lamoreux's Equation, which uses the average monthly temperature, relative humidity, solar radiation and wind speed to calculate the average daily average evaporation. This is also a useful equation to fill in missing pan evaporation data when needed. Values obtained from this equation need to be scaled by dividing by the 0.75 pan coefficient to correct for that scaling within the RECARGA model.

RUNNING THE RECARGA MODEL

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



Simulation Type

Begin by selecting one of three **simulation types**: continuous, single-event or user input. The “continuous” runoff simulation is used to simulate a continuous precipitation/evaporation input file using the model’s tributary runoff methods (SCS curve number method for pervious areas and initial abstraction for impervious areas). The “user input” option may be used to bypass the model’s runoff calculation with a user input file of hourly runoff (depth) to the facility obtained from another model. Both methods have the following inputs:

Input File Length: Enter the number of days for the calculation. If a number less than the total file length 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 (Note: this file needs to be stored in the ...\RECARGA\ folder). Exclude the “.txt” extension.

The “single event” option allows the user to calculate 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 type provides an overall summary of the inputs and results over the span of the calculation.

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

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. Select the native soil layer texture based either on the soil description from explorations or available soils maps or the USDA textural triangle from a particle size analysis on a sample of the native soils. The native soils are the anticipated soils at the bottom of the facility.

Hyd. Conductivity: Enter the saturated hydraulic conductivity for each soil layer. The default values for the rooting zone and storage zone are 3.94 in/hr (10 cm/hr) and 5.91 in/hr (15 cm/hr), respectively. Determine the native soil hydraulic conductivity from the texture class (see Table 1, the model uses the geometric means for high bulk density for default values for each soil texture) or an approved infiltration test conducted at the depth of the facility bottom.

USDA Soil Texture Class	Low Bulk Density Geometric Mean (25 th -75 th Percentile) [cm/hr]	High Bulk Density Geometric Mean (25 th -75 th 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 1. Saturated Hydraulic Conductivity Based on USDA Soil Texture Class (Rawls et. al, 1998)

Depth: Enter the depth of the ponding zone (default 6 inches) and the soil layers.

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.

Basin Area: Enter the area of the basin tributary to the facility.

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

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).

Run Simulation

Run the simulation by clicking the “Run Simulation” button.

MODEL OUTPUT

On-Screen Output

Plant Survivability Terms

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

Number of overflows: This result gives the number of times during the simulation at which the facility overflowed, this can be important for establishing the expectation of the success of a facility (if measured in the frequency of overflows observed versus expected). Also, facilities with a large number of overflows may require greater erosion protection along the overflow route.

Tributary Runoff

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

Raingarden Water Balance

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

Runon: Depth of water flowing into the facility over the simulation period.

Runoff: Depth of water overflowing the facility.

Recharge: Depth of water infiltrating into the soils beneath the facility.

Evaporation: Depth of water evaporated from the facility surface and through root uptake.

Underdrain: Depth of water flowing through the underdrain.

Soil Moisture: Depth of water retained in the facility soils at the end of the simulation versus the initial conditions.

Stay-on: Total depth of water retained on the site. This 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.

“Summary” 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 (“*outputfilename.txt*”). This file summarizes the input parameters; facility inputs, the date/time of the simulation and the input/output file names; and the final results of the simulation. 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: The total duration, total occurrences and time/duration of each occurrence that the facility is under various conditions is recorded. These conditions are: times that the facility is ponded, times that the water content in the rooting zone are near saturation and near the wilting point of the plants and times that the facility is in overflow.

<p>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</p>				<p>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</p>			
<p>INPUT TERMS %Impervious= 60 Pervious CN= 80 Facility Area (m2)= 100 Trib. Area (m2)= 1000 RATIOimp2rg= 6 RATIOperv2rg= 4</p>							
LAYER	DEPTH (cm)	Ksat (cm/hr)	TEXTURE				
Depression	15	---	---				
Root Zone	45	10.00	2				
Storage	30	15.00	1				
Native	---	0.34	5				
<p>Init. Cond.: suction head (cm)= -100 Max. Underdrain flow (cm/hr)= 0.31 Underdrain diam (mm)= 7</p>							
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 Stayon(cm)		38.41					
<p>Mass Balance Checks: Vsoil=input-roff-dvh Vsoil (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</p>							

Figure 2. Example Summary File Results

“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. 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 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 3. Example Record File Output

Facility Area Ratio

As mentioned above, RECARGA has the potential to calculate the facility to tributary area ratio needed to meet a target stayon objective. As before, the user should enter the following raingarden design parameters with one addition entry, the Target Stayon:

- Tributary Area
- Percent Impervious
- Pervious CN
- 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 Stayon**

Once the above parameters are entered hit 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 raingarden design for a facility to tributary area ratio of 1,5,10,15, and 25%. Through iteration of stayon results matching target stayon the program will output the required facility area ratio in the **Facility Area Ratio (%)** box.

MODEL DOCUMENTATION

MATLAB Computer Model

The RECARGA model was developed using the MATLAB computing software and language. MATLAB is a high-powered programming platform, which is ideally suited for matrix and array calculations. The platform contains a vast mathematical function library, which can be accessed by using called up modules (.mat files) from the main program file. This methodology allows for easy program development and modifications by piecing the required functions together using the various modules, without adding the code to the main executable file. The RECARGA model was developed using a graphical user interface to allow users to easily change design values without modifying the actual code contained within the program. The MATLAB version of the program was then exported to a C-language program with supporting libraries for user's without the MATLAB software.

The model disaggregates hourly precipitation into 15 minute time steps for calculating the runoff from tributary areas, water flow to the various water budget terms (evapotranspiration, infiltration, recharge, underdrain flow and overflow), ponding depth and water content in each of the soil layers. The program solves for each of these terms at the 15-minute time step and records the results for final output, summarized as either total or hourly data.

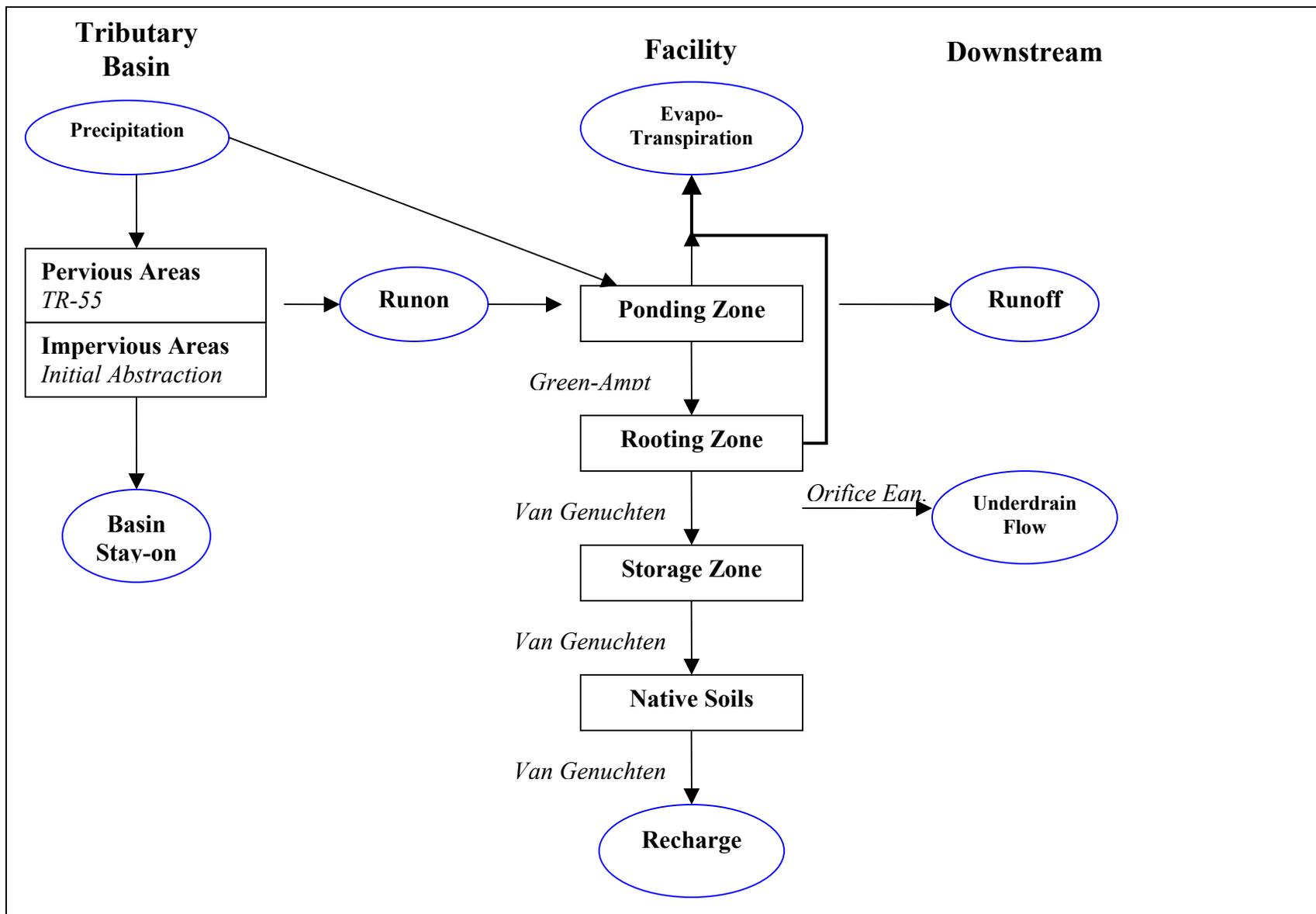


Figure 4. RECARGA Model Flow Schematic

Governing Equations

Model Hydrology

Hydrology is modeled from either direct unit runoff files, from user input, or using input precipitation files and utilizing the SCS Curve-Number Method and initial abstraction methods.

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.

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

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

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

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 .

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 .

Evapotranspiration

Evapotranspiration from the rooting zone is expressed as:

$$Q_{et} = E_{\max} \cdot \left(1 - [1 + A_w]^{1/m}\right) \quad (C.7)$$

$$\text{with } A_w = \frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}} \quad (C.7a)$$

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

Green & Ampt Equation

The RECARGA model is based on the Green-Ampt infiltration equation (Mein and Larson 1973):

$$\frac{dF(t)}{dt} = i \quad 0 \leq t \leq t_p \quad (C.1a)$$

$$\frac{dF(t)}{dt} = K_{sat} \cdot \left(1 + \frac{B}{F(t)}\right) \quad t_p \leq t \leq t_r \quad (C.1b)$$

with

$$B = (h_{wf} + h_s(t))(\theta_{sat} - \theta_{ini}) \quad (C.2)$$

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 $t=0$ (beginning of water input event). 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.

Surface water balance

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

$$A \frac{dh_s}{dt} = Q_{RAIN} + Q_{RUNON} - Q_{INFILTRATION} - Q_{RUNOFF} \quad (C.3)$$

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 raingarden 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 (Hollis and Ovenden 1988) – and that runon is distributed homogeneously in the garden surface, the total amount of water entering the garden can be approximated by:

$$Q_{IN} = Q_{RAIN} + Q_{RUNON} = Q_{RAIN} \cdot \left(1 + \frac{1}{L}\right) \quad (C.4)$$

where L denotes the rain garden to connected impervious area ratio. Q_{IN} considers an abstraction due to roof depression storage ST , which is approximated as 2.5 mm (Hollis and Ovenden 1988), and assumed to evaporate completely.

Soil Layering, Drainage and Hydraulic Properties

The soil is modeled as three homogeneous layers where 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; Rawls, Ahuja et al. 1993):

$$d(t) = K(\Theta) = K_{sat} \cdot \Theta^{1/2} \left[1 - \left(1 - \Theta^{1/m} \right)^m \right]^2 \quad (C.5)$$

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.

Underdrain Flow

Underdrain flow was modeled according to the orifice flow equation:

$$U(t) = C_o A H_u^{3/2} \quad (C.6)$$

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.