Green–Ampt model of a rain garden and comparison to Richards equation model

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Abstract

Traditional stormwater management, which relies heavily on detention storage, does not mitigate groundwater depletion resulting from groundwater pumping and loss of groundwater recharge. There has been an increasing interest in the use of alternative practices, such as rain gardens, that enhance infiltration of stormwater. A rain garden is a landscaped garden in a shallow depression of relatively small area that receives the stormwater from an impervious surface. We developed a simple numerical model that can be applied in the design and evaluation of rain gardens. Water flow through the rain garden soil is modelled over three layers: a root zone, a middle storage layer of high conductivity, and a lower layer that represents the subsoil at the site. To continuously simulate recharge, runoff and evapotranspiration, a Green–Ampt equation coupled with a surface water balance is used. For the climate of southern Wisconsin, simulation results show that the model yields similar results to a model based on the Richards equation: very high recharge rates are possible in the rainy season (twice the natural annual rates). A rain garden with an area of 10 to 20% of the contributing impervious area maximizes groundwater recharge. Increasing the depression depth increases recharge, but also increases ponding times, potentially affecting plant survival. The feasibility of a rain garden depends heavily on the saturated hydraulic conductivity of the underlying soil. These preliminary results show promise as a screening model and applicable tool for rain garden design.

1 Introduction

Urbanization has well-known adverse hydrologic effects [1, 2]. The main management focus has been the increase in the peak rate of stormwater runoff
due to the introduction of impervious area and to improved drainage systems [3, 4]. But another neglected impact of urban development is groundwater depletion due to increased pumping and diminished recharge.

Traditional stormwater management, which relies heavily on detention, does not mitigate groundwater depletion resulting from groundwater pumping and loss of groundwater recharge [3]. In recent years there has been increasing interest in the use of alternative practices, such as rain gardens, that encourage infiltration of stormwater as a means of mitigating groundwater impacts. These practices can be particularly effective when infiltration is focused in order to maximize recharge.

A rain garden for stormwater infiltration is a landscaped garden in a shallow depression (10-30 cm depth) of relatively small area that receives the stormwater from a roof, parking lot or other impervious surface. The garden plants provide a biologically active root zone that maintains soil infiltrability and porosity. Additionally, plant evapotranspiration during inter-storm periods provides a higher available soil water storage capacity for the next rainfall event.

We have developed a simple numerical model of focused groundwater recharge (RECARGA) to compare with our more complex model RECHARGE [5], to be applied in the design and evaluation of rain gardens. Three homogeneous layers of soil represent the rain garden soil profile (Figure 1). The upper layer represents the root zone, designed to be coarse textured and rich in organic matter. The middle layer, the storage zone, is a high conductivity layer that transmits infiltrated water readily and provides water storage. The lower layer represents the urban subsoil, which may restrict flow.

The purpose of this simpler model is to provide a tool of wider use while capturing the essential behavior of a rain garden. The objective of the model application is to explore how rain garden dimensions affect the amount of recharge and the duration of saturated conditions in the root zone. The model can be used to design the critical dimensions of a rain garden, including its surface area, surface depression depth and thickness of the storage zone layer.

The RECARGA model, based on the Green-Ampt Equation, includes the major relevant processes of interception and depression storage, runon from an impervious area, ponding and infiltration through a layered soil, and evapotranspiration, in a continuous simulation mode where the surface water and soil water flow are coupled.

We compare RECARGA to results of RECHARGE for climatic conditions of southern Wisconsin during the non-snowfall season (April-September) of the period 1992-1997.

2 Methods

2.1 Green–Ampt equation

The RECARGA model is based on the Green-Ampt infiltration equation [6]:

\[
\frac{dF(t)}{dt} = i, \quad 0 \leq t \leq t_p, \tag{1a}
\]
\[
\frac{dF(t)}{dt} = \frac{K_{sat} \left(1 + \frac{B}{F(t)}\right)}{t_p \leq t \leq t_r},
\]  
(1b)

with
\[
B = \left(h_{s} + h_{s}(t)\right)(\theta_{sat} - \theta_{ini}),
\]  
(2)

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

In RECARGA, \( h_{s} \) is approximated by the air entry soil water potential (bubbling pressure) of the root zone using \( h_{s} \approx 0.76 \ h_{b} \) [7, 8]. Additionally, \( i \) is the rainfall intensity at ponding time, and the ponding depth \( h_{i} \) is updated in the rain garden surface water budget.

### 2.2 Surface water balance

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

\[
A \frac{dh_{s}}{dt} = Q_{RAIN} + Q_{RUNON} - Q_{INFILTRATION} - Q_{RUNOFF},
\]  
(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]/[T]). We assume that rain and runon are uniformly distributed over the rain garden area. Runoff from the raingarden occurs once \( h_{s} \) surpasses the maximum depression depth \( h_{p} \).

If we assume that the concentration and conveyance time for the runon is negligible – which for the case of a roof is reasonable [9] – and that runon is distributed homogeneously, the total amount of water entering the garden can be approximated by:

\[
Q_{IN} = Q_{RAIN} + Q_{RUNON} = Q_{RAIN} \cdot \left(1 + \frac{1}{L}\right),
\]  
(4)

where \( L \) denotes the rain garden to connected impervious area ratio. \( Q_{IN} \) considers an abstraction due to roof depression storage, and assumed to evaporate completely.
2.3 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. Then the drainage $d(t)$ from a top layer to the one below is approximated as the unsaturated hydraulic conductivity $K(\Theta)$, as given by the van Genuchten relationship [10, 11]:

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

where $\Theta$ is the soil layer dimensionless water content given by $\Theta = (\Theta_{\text{sat}} - \Theta_{\text{rev}})/(\Theta_{\text{sat}} - \Theta_{\text{rev}})$, and $m$ is calculated from $m = 1 - 1/n$ ($n$ is the van Genuchten parameter). We assume there is no hysteresis.

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. Evapotranspiration was assumed constant.

2.4 Numerical solution of the model

The model RECARGA was implemented in Matlab, using the same input files as RECHARGE. For mass balance, the water budget of each soil layer was checked and corrected during each time step.

3 Results and discussion

Continuous simulations were conducted using hourly rainfall data for Madison, Wisconsin, for the months of April through September of the period 1992-1997.

The soil profile characteristics used are presented in Table 1. For RECHARGE, we used a spatial step of 2 cm and variable time stepping. RECARGA was run with a fixed $\Delta t$ of 15 minutes. The initial condition for each year was assumed as the water content at -100 cm of soil suction in the whole profile, approximately equal to field capacity. The interception and depression storage used were 2 mm, and evapotranspiration was fixed at 3.3 mm/day.

Table 1. Mualem-van Genuchten parameters of the rain garden soil layers

<table>
<thead>
<tr>
<th>Soil Characteristic</th>
<th>Root Zone Layer</th>
<th>Storage Zone Layer</th>
<th>Confining Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture</td>
<td>Loam</td>
<td>Sand</td>
<td>Clayey Silt</td>
</tr>
<tr>
<td>Depth (cm)</td>
<td>30</td>
<td>{30, 90}</td>
<td>10</td>
</tr>
<tr>
<td>$\alpha$ (cm$^{-1}$)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$n$</td>
<td>1.600</td>
<td>1.378</td>
<td>1.242</td>
</tr>
<tr>
<td>$\Theta_{\text{sat}}$ (m$^3$/m$^3$)</td>
<td>0.02</td>
<td>0.041</td>
<td>0.075</td>
</tr>
<tr>
<td>$\Theta_{\text{rev}}$ (m$^3$/m$^3$)</td>
<td>0.41</td>
<td>0.41</td>
<td>0.39</td>
</tr>
<tr>
<td>$K_{\text{sat}}$ (cm/h)</td>
<td>10.16</td>
<td>15.00</td>
<td>{0.25, 1.00}</td>
</tr>
</tbody>
</table>
3.1 Area ratio $L$

Figure 2 illustrates the models' results for the case where $ST = 90$ cm, $h_d = 15$ cm, and $K_{so} = 1$ cm/h for the period 1992-1997. (The depths reported here represent the total volume divided by the sum of the areas)

As the rain garden area ratio increases, the runoff decreases to zero for both models, with no significant difference. The recharge amounts reach a maximum between about 10 and 20% in a similar manner (Figure 2). (The reason for the peak in recharge is that at greater area ratios evapotranspiration starts to become a progressively larger term in the soil column water budget, as the water infiltrates less deeply when it is spread over a larger area.). The maximum recharge depth is 45 cm, or about 80% of the average rainfall for April through September. This is over twice the typical recharge rate for the silt loam soils in this region. Note that both models do not include recharge due to snowmelt, which is a large component of recharge in rural areas in this region.

RECARGA and RECHARGE have almost identical infiltration and evapotranspiration (not shown), while RECARGA shows slightly lower runoff (about 2 cm). Recharge values differ slightly for the highest ratio tested, $L=50\%$ (Figure 2); given that infiltration and ET are the same, and as soil water storage loss was higher for RECARGA, it seems that eqn (5) could be overestimating the downward soil water movement for this larger area ratio, drier case.

3.2 Storage depth $ST$

Deep percolation seems to be fairly insensitive to even tripling of $ST$ from 30 to 90 cm. Results indicate practically no difference in potential recharge between both models (not shown).

Results for ponding times for $ST = 90$ cm (Table 2) show that the longest continuous ponding time estimated by RECARGA is within 5% of the result given by RECHARGE for intermediate ratios $L$. For very low or very high values of $L$, however, RECARGA tends to underestimate the ponding time considerably (by 30% approximately). The total time that the rain garden is ponded in the period is also underestimated by RECARGA, in comparison to RECHARGE. Further study is needed so as to elucidate if this observation is related to RECARGA not capturing the details of flow in a layered soil profile.

<table>
<thead>
<tr>
<th>$L$ (%)</th>
<th>RECHARGE</th>
<th>RECARGA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum ponding time (h) / Total time ponded (h)</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>69 / 3983</td>
<td>53 / 3247</td>
</tr>
<tr>
<td>5</td>
<td>51 / 2475</td>
<td>49 / 1789</td>
</tr>
<tr>
<td>10</td>
<td>41 / 1196</td>
<td>37 / 653</td>
</tr>
<tr>
<td>20</td>
<td>37 / 407</td>
<td>35 / 183</td>
</tr>
<tr>
<td>50</td>
<td>15 / 56</td>
<td>5 / 11</td>
</tr>
</tbody>
</table>

Table 2. Rain garden ponded times for $ST=90$ cm ($h_d=15$ cm, $K_{so}=1.0$ cm/h)
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Table 3 shows a comparison of ponded times for both models using 1995 data, $L=10\%$, $K_s=1$ cm/h and $h_d=15$ cm. RECARGA predicts a similar maximum continuous ponded time as RECHARGE, although considerable smaller total ponded times (by 50% on average approximately).

Table 3. Rain garden ponded times for 1995, $L=10\%$ ($h_d=15$ cm, $K_s=1.0$ cm/h)

<table>
<thead>
<tr>
<th>$ST$ (cm)</th>
<th>Maximum ponding time (h) / Total time ponded (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RECHARGE</td>
</tr>
<tr>
<td>30</td>
<td>32 / 285</td>
</tr>
<tr>
<td>90</td>
<td>32 / 190</td>
</tr>
<tr>
<td>300</td>
<td>17 / 34</td>
</tr>
<tr>
<td>600</td>
<td>4 / 23</td>
</tr>
</tbody>
</table>

It is worth noting that for the case of $ST=600$ cm, it is the only simulation where RECARGA underestimates recharge compared to RECHARGE (by 15%). This may be a clue towards understanding why RECARGA slightly overestimates recharge for all other cases modeled. As percolation from a layer is a function of average water content in the layer – eqn (5) – then when the storage zone is very thick as in this case, RECARGA underestimates percolation from it, compared to RECHARGE, where a more detailed accounting of the water content along the soil profile possible accumulates more water at the bottom of the storage zone.

3.3 Rain garden surface depression depth $h_d$

RECARGA yields very similar recharge results compared to RECHARGE, except for the highest area ratio of 50% (not shown). Table 4 compares ponding time output: Both models yield similar results, except at area ratios above 20%.

Table 4. Rain garden ponded times ($h_d=45$ cm, $K_s=1.0$ cm/h, $ST=90$ cm)

<table>
<thead>
<tr>
<th>$L$ (%)</th>
<th>Maximum ponding time (h) / Total time ponded (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RECHARGE</td>
</tr>
<tr>
<td>2.5</td>
<td>192 / 6935</td>
</tr>
<tr>
<td>5</td>
<td>113 / 3836</td>
</tr>
<tr>
<td>10</td>
<td>71 / 1603</td>
</tr>
<tr>
<td>20</td>
<td>58 / 463</td>
</tr>
<tr>
<td>50</td>
<td>14 / 52</td>
</tr>
</tbody>
</table>

3.4 Lower layer saturated conductivity $K_{ss}$

For a lower saturated conductivity of the bottom constraining layer, results for 1995 (Figure 3) show that as $K_{ss}$ is lowered from 1.0 to 0.25 cm/h RECARGA starts to overestimate recharge by approximately 4 cm. The reason for this could be the fact that RECARGA estimates percolation as a function of the average water content of the whole layer; in this case, a lower $K_{ss}$ probably would make
the bottom layer to be saturated more time than estimated by RECHARGE, and therefore yield a higher recharge estimate. This can be further investigated.

Table 5 compares the continuous ponding times for the 1995 season for both models, for the case of $K_a=0.25$ cm/h. RECARGA and RECHARGE yield almost identical maximum ponding times except for area ratios of 50%, while RECARGA computes significantly less total time ponded for the year, especially for $L$ values higher than 10%.

<table>
<thead>
<tr>
<th>$L$ (%)</th>
<th>Maximum ponding time (h) / Total time ponded (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>RECHARGE</strong> / <strong>RECARGA</strong></td>
</tr>
<tr>
<td>2.5</td>
<td>259 / 1827 / 259 / 1662</td>
</tr>
<tr>
<td>5</td>
<td>183 / 1531 / 182 / 1286</td>
</tr>
<tr>
<td>10</td>
<td>128 / 995 / 127 / 478</td>
</tr>
<tr>
<td>20</td>
<td>116 / 362 / 109 / 109</td>
</tr>
<tr>
<td>50</td>
<td>35 / 35 / 1 / 1</td>
</tr>
</tbody>
</table>

4 Conclusions

For the data used (hourly rainfall for Madison, WI, 1992-1997), RECARGA compares well to RECHARGE. Thus, it shows promise as a simpler model that can be used as a screening tool for narrowing the design parameter space for RECHARGE, or as more readily available tool for design engineers.

RECARGA mimics RECHARGE results regarding the effects on recharge of the following design parameters: the rain garden area ratio to the contributing impervious area; depression depth; storage zone thickness; and subsoil saturated hydraulic conductivity. In particular, RECARGA yields identical qualitative trends and very similar quantitative results for recharge and runoff, as well as maximum continuous ponding time (variable related to anoxic conditions in the root zone, critical for plant survival).

Caution is advised though, as the results for low $K_a$ show: although RECARGA shows a similar trend, it overestimates recharge depth slightly. This could be related to how RECARGA estimates percolation from one layer to the next, based in average soil layer water content – further detailed study may elucidate why. More simulations are needed to verify that RECARGA and RECHARGE are comparable, with wider range of parameter values (especially $K_a$), and in particular for different climates and soil situations.
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Figure 1: Conceptual diagram of a rain garden.

Figure 2: Simulation results for Madison 1992-1997 rainy seasons ($ST=90$ cm, $h_d=15$ cm, $K_{so}=1$ cm/h), for models RECHARGE and RECARGA.
Figure 3: Potential groundwater recharge results for RECHARGE (RE) and RECARGA (GA) models, for Madison, WI, for 1995 ($ST=90$ cm and $h_s=15$ cm) for: a) $K_{ss}=1\text{ cm/h}$; b) $K_{ss}=0.25\text{ cm/h}$.

References


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