International Congress on Environmental Modelling and Software

2nd International Congress on Environmental Modelling and Software - Osnabrück, Germany - June 2004

Jul 1st, 12:00 AM

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Abstract: Traditional stormwater management does not mitigate groundwater depletion resulting from groundwater pumping and reduction in recharge. Infiltration practices, such as rain gardens, offer a potentially effective approach for addressing groundwater depletion. A rain garden is a landscaped garden in a shallow depression that receives the stormwater from nearby impervious surfaces, focusing recharge. We have developed a numerical model that can be applied in rain garden design and evaluation. Water flow through the rain garden soil is modeled over three layers- a root zone, a middle storage layer of high conductivity, and a subsoil lower layer. To continuously simulate recharge, runoff and evapotranspiration, the model couples the Richards Equation with a surface water balance. The model was applied to the climate of southern Wisconsin. Simulation results show that very high recharge rates are possible during the non-snowfall season. A rain garden with an area of approximately 10-20% of the contributing impervious area maximizes groundwater recharge. An experimental rain garden was installed to gather quantitative data on the water budget terms in a continuous fashion. Sensors were installed to measure the water input, garden ponding, soil moisture and bottom drainage. To validate the Richards Equation model, we used data from three experiments resembling typical recharge events. The model results agree well with soil moisture data, but predicts a higher recharge than measured (15 to 37% more). This could be due to intermediate storage in the system, insufficient characterization of initial conditions, or limitations of the 1-D model.

***Keywords**:* rain garden; infiltration; Richards; recharge; urbanization.

1. INTRODUCTION

In recent years there has been increasing interest in the use of alternative practices, such as rain gardens, that encourage infiltration of stormwater to mitigate 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 topographic depression of small area that receives stormwater from a roof or other connected impervious surface. The garden plants, usually native species with aesthetic attributes, provide a biologically active root zone that helps maintain soil infiltrability through macropores (Beven and Germann 1982).

For modeling unsaturated flow, tools are available in the literature that model the coupling of a surface and subsurface flow (Esteves et al. 2000; Gandolfi and Savi 2000) and others that use Richards Equation (Richards 1931) to model infiltration and redistribution into layered soils (Fayer 2000; Simunek et al. 1998; van Dam and Feddes 2000), but not both capabilities, which are required for rain garden modeling.

Therefore, we developed a numerical model of focused groundwater recharge, RECHARGE, based on the Richards Equation to be applied in the design and evaluation of rain gardens. The model includes the major relevant processes in a continuous simulation mode where the surface water balance and soil water flow are coupled.

Three homogeneous layers of soil represent the rain garden soil profile. The upper layer represents the root zone, which would typically be designed to be coarse-textured and rich in organic matter. The middle layer is of high conductivity and water storage capacity. The lower layer represents the urban subsoil, which may restrict flow.

Simulation results presented in Dussaillant et al. (2002, 2004) for Madison, Wisconsin, show that very high recharge rates are possible and that a rain garden with an area of 10 to 20% of the contributing impervious area maximizes recharge.

However, there is a lack of data on rain garden performance in general, and in particular on their water balance. To gather quantitative data in a continuous fashion, we have installed an experimental rain garden, to validate our numerical models for rain garden design. Here we take the first steps towards validating the numerical model, with experiments in the field rain garden setup.

2 METHODS

2.1. Recharge numerical model

RECHARGE is a model based on Richards Equation (Richards 1931) that couples surface ponding and soil water flow in a rain garden with layered soil (Dussaillant et al. 2004), with plant transpiration as a sink:

$$\frac{\partial\theta(h,z)}{\partial t}=\frac{\partial\theta}{\partial h}\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left[K(h,z)\left\{\frac{\partial h}{\partial z}+1\right\}\right]-S(h,z), \quad (1)$$

where θ is the soil volumetric moisture content ($[L]^3/[L]^3$), h is the suction head ([L]), z is the vertical position ([L]), t is time ([T]), K is the unsaturated hydraulic conductivity ([L]/[T]) and S is the plant transpiration rate (1/[T]). $\partial\theta/\partial h$ is the soil moisture capacity function. The formulation used assumes one-phase, vertical matrix flow, with isothermal conditions and no air effects.

For the soil hydraulic properties we used the van Genuchten-Mualem functions (Mualem 1976; van Genuchten 1980):

$$\theta(h)=\frac{\theta_{sat}-\theta_{res}}{\left[1+\left(\alpha|h|\right)^{n}\right]^{m}}+\theta_{res}$$

(2a)

$$K(h)=K_{sat}\frac{\left\{1-\left(\alpha|h|\right)^{n-1}\left[1+\left(\alpha|h|\right)^{n}\right]^{-m}\right\}^{2}}{\left[1+\left(\alpha|h|\right)^{n}\right]^{m/2}}$$

(2b)

$$\frac{d\theta}{dh}=\frac{\alpha m\left(\theta_{sat}-\theta_{res}\right)}{1-m}\frac{\left\{1-\left[1+\left(\alpha|h|\right)^{n}\right]^{-1}\right\}^{m}}{\left[1+\left(\alpha|h|\right)^{n}\right]^{m}}$$

(2c)

where $|h|$ is the absolute value of the pressure head [cm], θ_{sat} is the saturated soil water content [m^3/m^3], θ_{res} is the residual soil water content [m^3/m^3], K_{sat} is the saturated hydraulic conductivity [cm/h], α is the van Genuchten parameter [cm^{-1}] (with $\alpha=h_b^{-1}$, where h_b is the air-entry or 'bubbling' pressure), and m=1-1/n.

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 ($[L]^2$), h_s is the surface water ponded depth ([L]) and the flows Q are the inputs and outputs to the depression ($[L]^3/[T]$). Runoff from the rain garden occurs once h_s surpasses the depression depth h_d (Figure 1).

Assuming that the concentration time for the runon is negligible and that runon is distributed homogeneously in the garden surface, the total amount of water entering the garden is:

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

(4)

where L denotes the ratio of the area of the rain garden to the area of the connected impervious surfaces. Q_{IN} also accounts for an abstraction due to roof depression storage. $Q_{INFILTRATION}$ is computed using Darcy's law.

Richards Equation is discretized using a Crank-Nicholson finite difference scheme. Given the top boundary condition (surface water balance), and the soil hydraulic properties, plus the bottom boundary condition (unit gradient), the system is unique. The coupling is solved iteratively.

This system was solved using the Thomas algorithm, with a modified Picard iteration for mass balance (Celia et al. 1990). We used an adaptive time stepping scheme (Kavetski et al. 2001), with a fixed spatial step Δx.

RECHARGE was validated using literature results, to test situations common to a rain garden context: layered soil profiles, sharp wetting fronts, and ponding (Dussaillant et al. 2004).

2.2 Experimental setup

The rain garden was installed in Madison, Wisconsin. The rain garden area is 5.4 m^2, and is connected to two downspouts draining approximately 50-60 m^2 of roof each. Valves allow one or both to be connected, to achieve an area ratio L of approximately 5% or 10%.

The rain garden is essentially a lysimeter containing 6.5 m^3 of soil (3 m long, 1.8 m wide and 1.2 m deep) enclosed within a polyethylene liner. This liner hydraulically isolates the garden soil, allowing the measurement of water that percolates through the raingarden and exits by a bottom drain (Khire 1995). The rain garden root zone is 50 cm deep, consisting of 60% mason's sand and 40% organic matter The 70 cm sandy storage zone is underlain by a permeable geomembrane consisting of textile (Figure 1). Two 3 cm wide rings of benthonite clay were placed to minimize sidewall preferential flow (Corwin 2000).

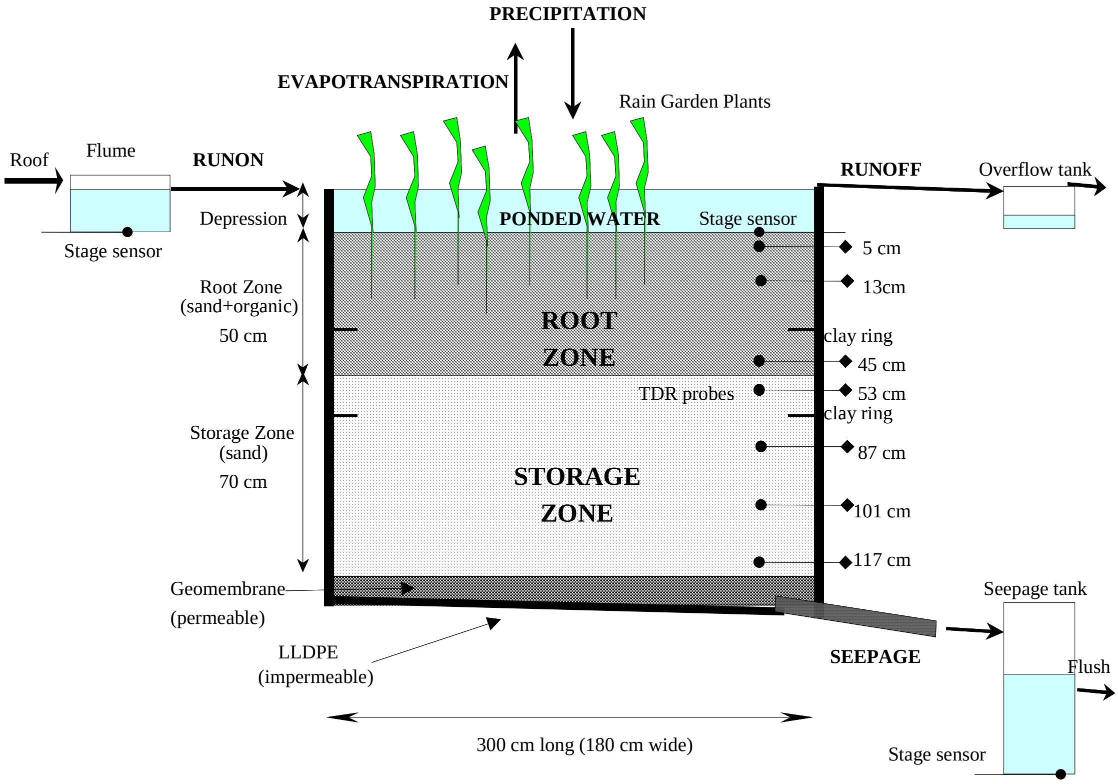

Figure 1. Cross section diagram of experimental rain garden lysimeter (Madison, Wisconsin).

2.3 Measurement

Site rainfall is measured by a tipping bucket. Runon from the roof to the garden flows through a trapezoidal flume, which was equipped with a pressure transducer in its stilling basin (Figure 1).

To estimate the soil water storage term, time domain reflectometry (TDR) probes were placed at 7 depths to monitor soil water content (Figure 1) and connected to a SDMX50 multiplexer, a Tektronix 1502B TDR cable tester and a CR-10 datalogger (Campbell Scientific). The TDR programming uses a Topp calibration to estimate volumetric soil water content (Topp et al. 1980).

The seepage through the soil is directed to a drain at the bottom of the lysimeter, connected to a 100 m long PVC pipe that empties to the seepage collection tank. This setup provides a measure of recharge, critical variable in this application.

2.4. Estimation of soil hydraulic properties

Soil cores were taken from the rain garden soil layers approximately 6 months after construction, so that soil had settled down. Specimens were prepared in the laboratory by compacting soil samples to the average dry unit density measured from undisturbed core samples.

Soil water characteristic curves, $\theta(h)$, were measured in a hanging column setup (Khire 1995). Only desorption curves were measured. The data from the laboratory measurements and field data was fitted to the van Genuchten-Mualem equations (Mualem 1976; van Genuchten 1980), assuming there is no hysteresis, using a spreadsheet solver and confirmed using the software RETC. Saturated hydraulic conductivity, K_{sat}, was determined using falling head permeameters (Dingman 1994).

The functions for unsaturated hydraulic conductivity, $K(h)$, and soil moisture capacity, $M(h)$, were determined using the parameters from the soil water characteristic function fit.

2.5. Field experimental runs

Three controlled experiments were performed, where the water input was maintained until the rain garden ponded to 15 cm and then shut-off (there was no spillover to the overflow tank).

First, the rain garden was initially very wet due to water ponding done the day before (VW Experiment). This was followed by another controlled ponding, with moderately wet initial conditions given that 2 days had passed without any water input (MW Experiment). Finally, we did not input any water to the rain garden for 3 days up to the last run, assuming this would bring the soil to field capacity (FC Experiment).

Average flow was 7 gallons per minute, which corresponds to a 2.58 cm/h steady rain (for an area ratio *L* of 10% in this case). Note that 90% of the water volume in the 50-year period 1948-1998 for Madison, Wisconsin, is accounted for by rains of this hourly intensity or less.

3 RESULTS AND DISCUSSION

3.1. Soil hydraulic parameters

Saturated hydraulic conductivity, K_{sat}

The densities and hydraulic conductivities measured are within the range common for sands. The storage zone is denser than the root zone, which may partly explain the lower resulting K_{sat}. The average value for each layer was used in the simulations (Table 1).

Soil water retention curves, $\theta(h)$

Table 1 contains the fitted parameters for the laboratory data. Additionally, another fit was done with field measurement data for θ_{res} and θ_{sat}. There is a slight difference, though not significant. The second set of parameters was used in RECHARGE modeling.

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

Soil Characteristic	Root Zone Layer	Storage Zone Layer
α (cm^{-1})	0.033	0.032
n	3.594 (3.637)	3.250 (2.146)
θ_{res} (m^3/m^3)	0.03	0.15 (0.10)
θ_{sat} (m^3/m^3)	0.40	0.37
K_{sat} (cm/h)	83.1	36.9

3.2 Controlled experiment runs and model simulations

Table 2 summarizes the characteristics of each of the three experiments: VW (Very Wet), MW (Moderately Wet) and FC (Field Capacity). No overspill was allowed: the inflow was shut off as soon as the ponding depth reached 15 cm. After ponding, the infiltration of water was monitored and found to vary between 5 and 7 cm/h.

Model simulation input contained the same initial condition as given by the TDR data. Soil moisture data was interpolated between probes. The spatial step used was 1 cm. We assumed a subsoil saturated hydraulic conductivity of 5 cm/h.

Table 3 compares experimental parameters with the results obtained by model simulations. The model mimics the ponding times reasonably well (within a few minutes), and if any runoff is simulated, it is fairly negligible (6% of the water input for the worst case, Experiment FC).

Taking Experiment FC as an illustration, RECHARGE reproduces the data results qualitatively quite well for both the root zone and storage zone probe data (Figure 2). The model follows the data closely during the onset and the end of saturation for both soil layers. The seepage tank cumulative measurement was 0.94 m^3 after 5.9 hours, compared to 1.36 m^3 estimated.

For all experiments, overestimation of recharge volume by the model is rather large. Nevertheless, extending the time range shows that the model estimate and collection tank measurement tend to converge slightly, especially for the wetter experiments VW and MW (results not shown).

Table 2. Experiment characteristics

Characteristic	Experiment VW	Experiment MW	Experiment FC
Root Zone initial soil moisture (m^3/m^3)	0.10	0.10	0.13
Storage Zone initial soil moisture (m^3/m^3)	0.20-0.32	0.10-0.26	0.22
Average inflow (m^3/h)	1.54	1.50	1.59
Equivalent intensity at L=10% (cm/h)	2.51	2.44	2.54
Start time of application	16:00	15:00	12:17
End time of application	17:10	16:52	13:57
Water application duration (h)	1.17	1.87	1.67
Total water applied (m^3)	1.81	2.80	2.65

Table 3. Experimental data compared to RECHARGE model results (in parenthesis)

Parameters	Experiment VW	Experiment MW	Experiment FC
Start time of ponding	16:53 (16:59)	16:08 (16:11)	13:20 (13:12)
End time of ponding	19:02 (18:59)	20:08 (19:54)	16:42 (16:58)
Ponded infiltration (cm/h)	5-6 (5.0)	5-7 (5.0)	5-7 (5.0)
Maximum ponding depth (cm)	15 (9.0)	15 (15.0)	15 (15.0)
Recharge collected (m^3)	0.42 (0.78)	1.19 (2.04)	0.94 (1.36)

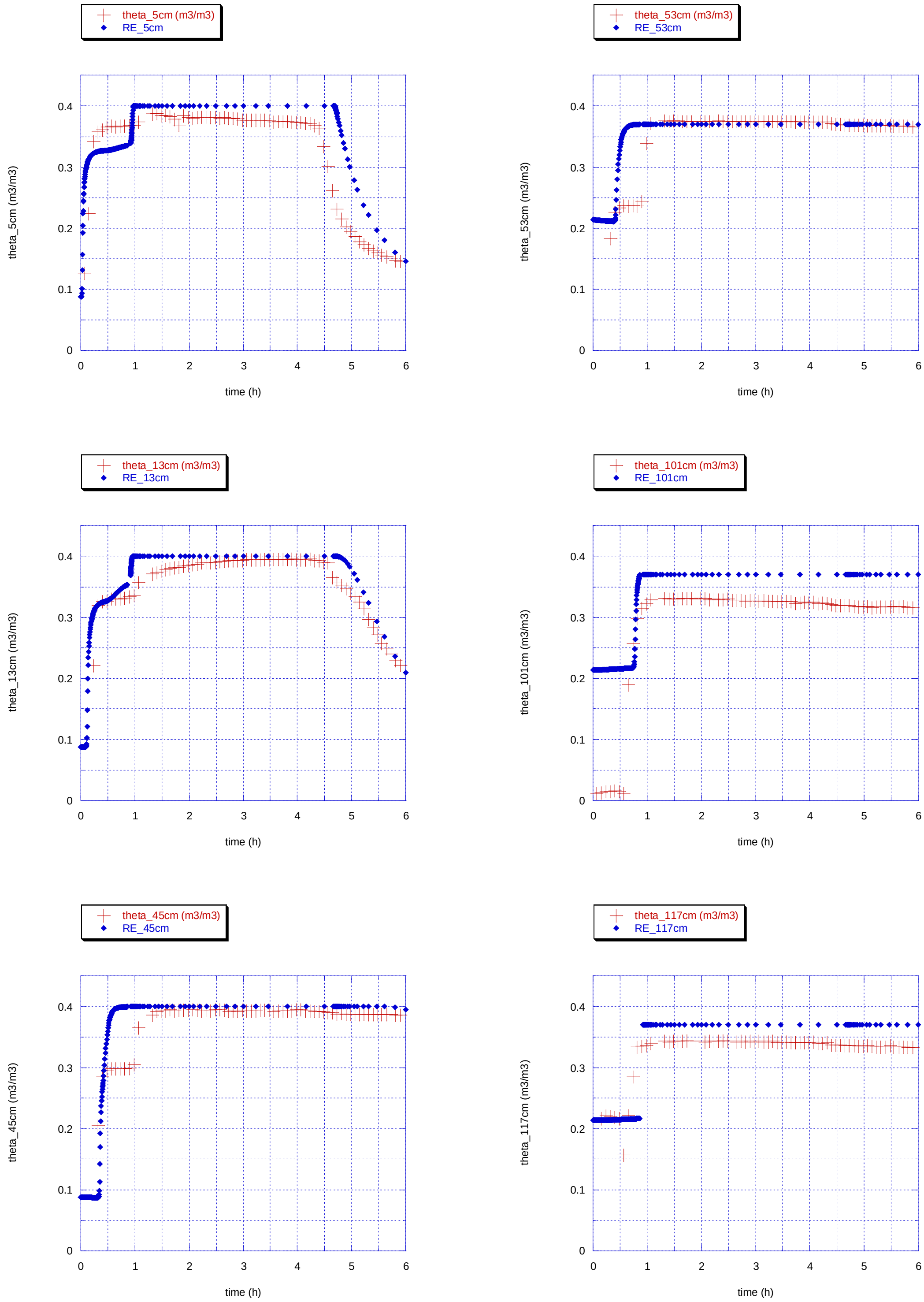

Figure 2. Experiment FC (09/01/02) TDR field measurements of volumetric water content (+) compared to RECHARGE output (♦), for probes in the root zone (left column plots: 5, 13 and 45 cm deep) and in the storage zone (right column plots: 53, 101 and 117 cm deep).

Using the rain garden water budget we can have another estimate of seepage. For each experiment, we know the water inflow, the overspill was zero, and we assume evapotranspiration is negligible. Thus, the difference between soil water storage and inflow will yield the percolation from the bottom of the soil profile. The computed seepage values are 0.77, 2.13 and 1.64 m^3, respectively, very similar to RECHARGE predictions (Table 3). This suggests that there may be a delay in the arrival of water to the seepage tank, either due to the lysimeter drain constriction or the 100 m long drain pipe, which could explain the discrepancies with the model results. Alternatively, there could be experimental leaks or a lack of representativeness of TDR data, or ultimately it is possible that the 1D model cannot capture the complexities of the 3D flow, or adequately represent the boundary condition sufficiently well.

4. CONCLUSIONS AND RECOMMENDATIONS

The model simulates the three experiment sets used reasonably well, yielding very similar soil moisture evolution in time as the seven TDR probes installed in the soil profile. Since three short-term experiments are insufficient to validate the RECHARGE model with certain confidence, future work will include more run tests. Even so, it can be argued that the three tests presented here resemble typical recharge events, which in the aggregate will probably dominate the long-term cumulative recharge depth.

Simulation results for cumulative recharge volumes overestimate the collection tank measurements by over 30% for two of the experiments. Longer-term data needs to be collected to test if this tendency continues and if it can be explained by storage or lag times in the draining system (as suggested by a mass balance calculation) or by insufficient characterization of initial (or boundary) conditions which probably dominate the short term results. Also, the lysimeter drainage may affect the flow in a way the 1-D model cannot capture on an event basis.

Ongoing work includes improvements in the model and experimental conditions so as to permit more precise conclusions. Nevertheless, RECHARGE and the field experiment are viewed as a valuable contribution towards the study and design of rain gardens for stormwater infiltration.

5. ACKNOWLEDGEMENTS

Funding for this project was provided by U.S.E.P.A. Water and Watersheds grant R-82801001, the University of Wisconsin System, P. Universidad Católica de Chile, and the Chilean Ministry of Planning..

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