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FIELD EVALUATION OF RAIN GARDENS AS A METHOD FOR ENHANCING GROUNDWATER RECHARGE

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FINAL REPORT

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PROJECT SUMMARY

Title: Field Evaluation of Rain Gardens as a Method for Enhancing Groundwater Recharge

Project I.D.: R/UW-BMP-002

Investigator: Kenneth W. Potter, Professor, Department of Civil & Environmental Engineering

Period of Contract: July 1, 2000-June 30, 2002

Background/Need: In urbanized areas of Wisconsin that rely on groundwater as the primary source of water, groundwater withdrawals significantly exceed groundwater recharge rates. This can lead to environmental degradation, as it reduces the discharge of groundwater to springs, wetlands, streams, and lakes and their associated ecosystems. Rain gardens, sunken gardens that receive stormwater runoff, appear to offer a solution to groundwater loss. In a previous research project, the PI has used a numerical model to demonstrate that a rain garden with area equal to 10% of the connected pervious area can double the local groundwater recharge rate. The explanation of this surprising result is that focusing of runoff to a small, highly pervious area greatly reduces losses to evapotranspiration.

Objectives: Before rain gardens can be widely implemented, they should be tested through carefully designed demonstration projects. The purpose of the proposed project was to construct an experimental rain garden for use in evaluating rain garden performance.

Methods: We have constructed an experimental rain garden, at the Dane County Parks Lussier Family Heritage Center in Madison. The rain garden is essentially a lysimeter, in that it is lined so that the drainage can be collected and measured. The rain garden has an area of 5.4 m^2 and is connected to two downspouts, each draining about 55 m^2 of roof. Valves allow one or both roof areas to be connected, yielding area ratios of 0.05 and 0.10. Roof runoff is measured by means of a prerated trapezoidal flume in which a pressure transducer has been installed. Another transducer monitors the ponded depth in the rain garden. Runoff from overspill is collected in an overflow tank. To estimate soil moisture storage, Time Domain Reflectometry (TDR) probes were placed at seven depths and connected to a multiplexer, cable tester, and data logger. Seepage through the rain garden (which we take to be recharge) flows through a bottom drain to a pipe that discharges into a seepage collection tank. The tank contains a siphon that empties and triggers a switch when it accumulates 112 liters. The tank also contains a pressure transducer for monitoring changing water levels.

Three controlled experiments were performed during the period August 26 to September 1, 2002. In these experiments water was artificially supplied to the rain garden at a rate of seven gallons per minute until the ponding level reached 15 cm. (This supply rate corresponds to a rainfall rate of about one inch per hour when both roofs are contributing.) During the experiments soil water measurements were made with the TDR system, for comparison with model results.

Results and Discussion: The modeled and experimental results match well with respect to ponding times and overflow volumes. The model also does a reasonably good job of predicting the temporal pattern of soil moisture in the rain garden. However, the modeled volume of subsurface discharge from the rain garden was significantly larger than observed. It is believed that the discrepancy is due to leakage of water through the TDR access holes. This problem has subsequently been corrected.

Conclusions: An experimental rain garden has been constructed that allows measurement of all water budget terns except evapotranspiration. Experiments to date have demonstrated that a previously developed numerical model of rain gardens provides useful predictions of rain garden performance.

Related Publications: None.

Key Words: Rain gardens; artificial groundwater recharge

Funding: University of Wisconsin System

INTRODUCTION

For about half of Wisconsin, groundwater is the primary water source for human activities. In urbanized area, groundwater withdrawals significantly exceed groundwater recharge rates. For example, unit area groundwater withdrawals in the Madison area equal about 40 cm, an amount that is over twice the recharge rate. This does not generally pose a water supply problem, because groundwater readily migrates from the adjacent undeveloped area. However, groundwater pumping does cause environmental degradation.

Under undeveloped conditions, springs, wetlands, streams, and lakes and their associated ecosystems depend on a constant supply of water discharged from groundwater. This water has important advantages over storm runoff. Its flow rate and temperature are nearly constant and its quality is generally excellent. Storm runoff, on the other hand is episodic, causes thermal pollution, and contains sediment, nutrients, and other contaminants. Urban development greatly reduces the discharge of groundwater to water bodies and aquatic ecosystems and at the same time increases the discharge of storm runoff. The net result is severe environmental degradation, even at relatively low levels of urbanization. This has been observed in southern Wisconsin as well as in other parts of the United States (Booth and Jackson, 1997).

One potential strategy for mitigating the depletion of groundwater is to direct runoff from impervious surfaces to highly pervious ones. This has been done for many years on Long Island through the use of infiltration basins (Aronson and Seaburn, 1974). However, infiltration basins are often not successful in Wisconsin, partly because of the difficulty in constructing effective basins in a landscape with complex glacial stratigraphy and predominantly silty soils.

Rain gardens, sunken gardens that receive stormwater runoff, appear to be a viable alternative to infiltration basins. While the latter are generally sited low in a watershed, where infiltration can be hard to achieve, rain gardens are constructed adjacent to impervious surfaces and hence are dispersed throughout the watershed. Furthermore, the use of many rain gardens rather than one infiltration pond makes it possible to account for site-specific hydrologic, stratagraphic, and water quality conditions.

In a previous research project, we developed a numerical model (RECHARGE) for use in the evaluation and design of rain gardens (Dussailant *et al.*, in press). RECHARGE models a three-layered rain garden, consisting of a rooting zone, a high conductivity storage layer, and a lower layer representing the *in situ* soil. The model is based on the Richards Equation, and 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. Application of the model using hourly rainfall data from Madison for the period 1992 to 1997 indicates that a rain garden can recharge groundwater during the rainfall season at a rate equal to about twice the average annual groundwater recharge for undeveloped portions of southern. Furthermore, this can be achieved with a rain garden with area equal to 10-20% of the area of the contributing impervious surface.

These preliminary results are very encouraging. In the case of new developments it is certainly feasible to construct rain gardens with area equal to 10% of the connected impervious area. In many developed areas it is should be possible to add rain gardens. Even a rain garden with area equal to five percent of the impervious area provides substantial groundwater recharge. However before rain gardens can be widely implemented, they should be tested through carefully designed demonstration projects. The purpose of the proposed project was to construct an experimental rain garden for use in evaluating rain garden performance.

PROCEDURES AND METHODS

Construction of Experimental Rain Garden

The experimental rain garden was installed in the Dane County Parks Lussier Family Heritage Center in Madison, Wisconsin. It is essentially a lysimeter with a surface area of 5.4 m^2 and containing 6.5 m3 of soil enclosed within a polyethylene liner (Figure 1). This liner hydraulically isolates the garden soil from the surroundings, permitting direct measurement of deep percolation. The liner consists of 40 mil LDPE, shaped to conform to the excavation.

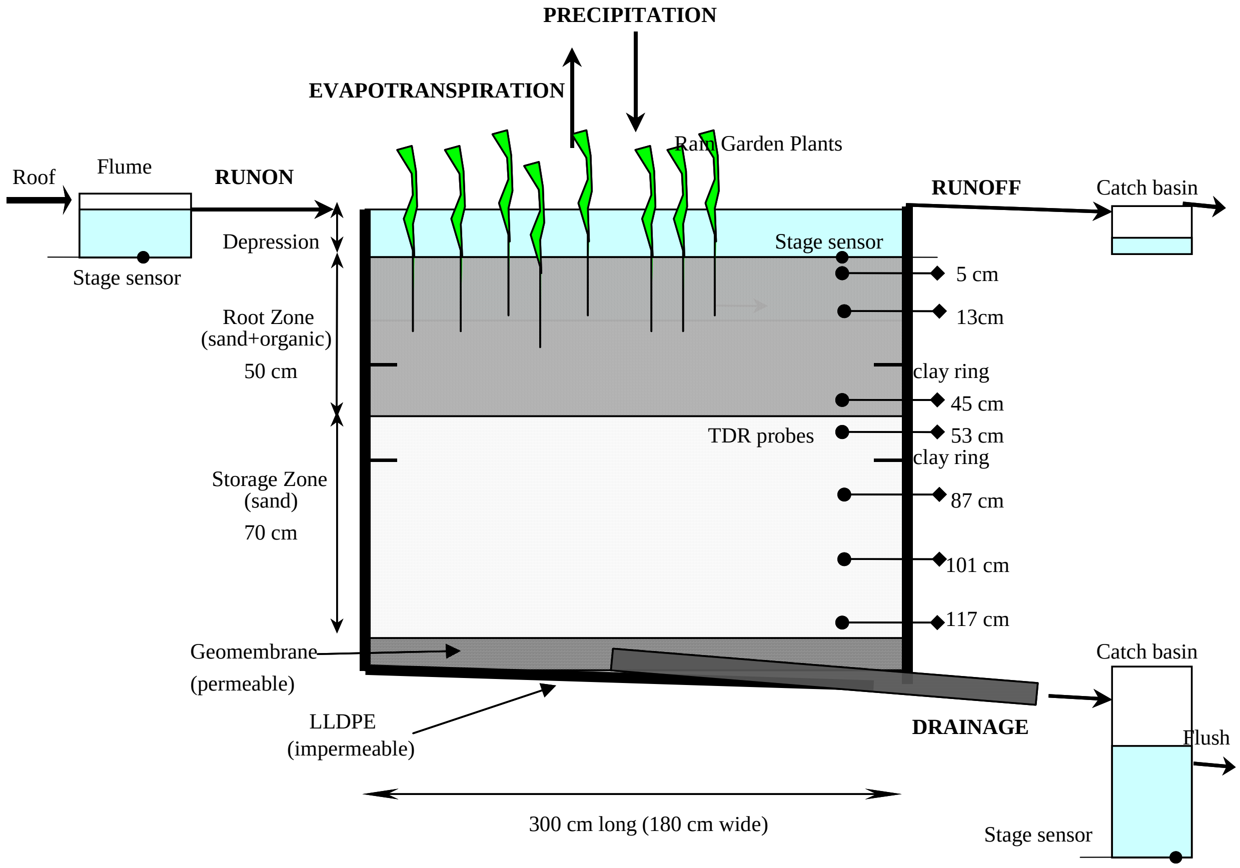

Figure 1. Conceptual diagram of experimental rain garden.

The root zone of the experimental rain garden is 50 cm deep, consisting of 60% sandy material and 40% peat moss, the latter providing moisture retention. A 70 cm storage zone underlies the root zone, consisting entirely of sand. The sandy storage zone is underlain by a permeable geomembrane consisting of a textile over plastic web. This allows for drainage without loss of sand. The storage zone soil was manually compacted using tampers, and two 3 cm-wide rings of benthonite clay were placed at depths of 30 and 70 cm to minimize sidewall preferential flow (Corwin, 2000).

Figure 2 shows a plan view of the rain garden and the flow distribution system. The rain garden is connected to two downspouts draining 50 m^2 of roof each. Valves allow for connection of one or both downspouts; hence the ratio of roof to rain garden area can be either five percent or 10%. Both downspouts are piped into a stilling basin filled with gravel so as to reduce turbulence and provide more favorable conditions for downstream flow measurement. Water entering the rain garden is distributed through a manifold of perforated pipes.

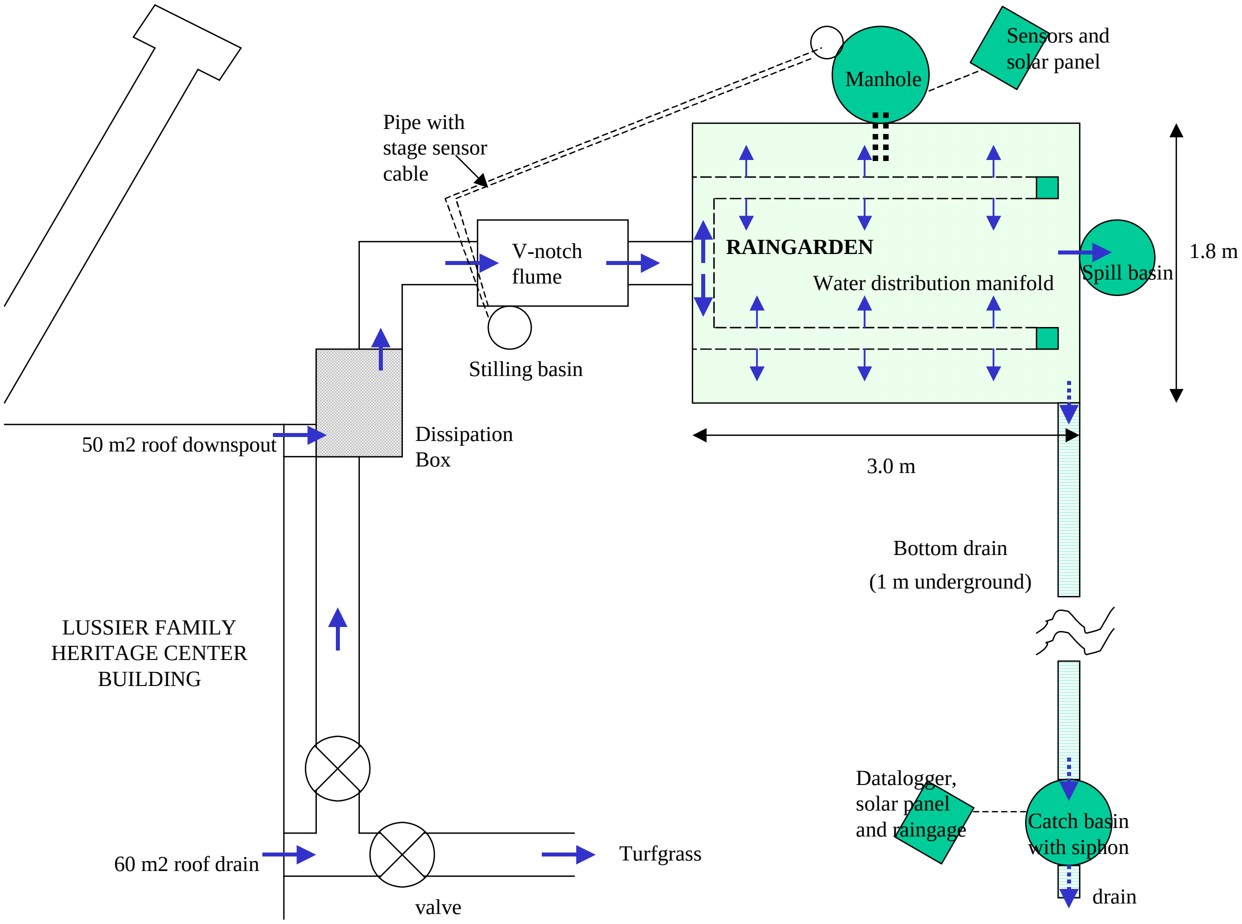

Figure 2. Conceptual plan view diagram of experimental rain garden.

Several sensor systems are used to measure terms of the water budget. Site rainfall is measured by a tipping bucket rain gauge located at the site. Flow from the roof downspouts to the rain garden passes through a prerated trapezoidal flume. A pressure transducer in the stilling well measures water levels in the flume. Another transducer monitors the depth of ponding in the rain garden so as to allow for measurements of changes in surface storage. Spillage from the rain garden is collected in a runoff catch basin, where it can be manually collected and quantified.

Time Domain Reflectometry (Benson and Bosscher 1999) is used to measure water storage in the rooting and storage zones of the rain garden. TDR probes were placed at seven depths (Figure 2) and connected to a SDM multiplexer, a Tektronix 1502B Time Domain Reflectometry (TDR) cable tester, and a CR-10 datalogger. The specific depths were selected so as to provide data spaced more densely close to interfaces and more sparsely in the bulk of the homogeneous layers. A manhole was installed on one side of the rain garden to provide access to the TDR probes.

Drainage from the rain garden flows through a drain to a PVC pipe that empties to a catch basin. This basin contains a siphon that empties when the basin accumulates 100 liters, triggering a switch, and a pressure transducer that monitors the changing head in the basin. These three sensors are connected to a CSI CR-10 datalogger powered by a solar panel and two rechargeable batteries.

The CR-10 dataloggers were programmed so as to read and store data as a function of water input frequency. Volumetric water content is computed assuming a Topp calibration (Topp, *et al.* 1980; Benson and Bosscher 1999).

Plant Selection

The plants chosen for the rain garden needed to be aesthetically pleasing and be able to withstand ponding times of one to two days. Plants meeting the second criteria were obtained from Kercher and Zedler (2001), which reports research on the tolerance of Wisconsin native plants to various hydrologic regimes. Table 1 provides a list of plants used in the rain garden.

Table 1. Experimental rain garden plants

Species name	Common name
Aquilegia canadensis	Columbine
Aster laevis	Smooth blue aster
Baptisia alba	White wild indigo
Baptisia bracteata	Cream wild indigo
Bolboschoenus fluvatilis	River bulrush
Caltha palustris	Marsh marigold
Iris versicolor	Wild iris
Liatris pycnostanchya	Prairie blazing star
Lobelia siphilitica	Great blue lobelia
Pycnanthemum virginianum	Mountain mint
Rosa blanda	Early fall rose
Silphium laciniatum	Compass plant
Zizia aurea	Golden alexanders

Calibration of Soil Water Characteristic Curves

About six months after the rain garden was constructed, soil cores were collected for estimation of soil water characteristic curves. Soil cores from the root and storage zones were prepared in the laboratory by compacting soil samples to the average dry unit density measured from undisturbed core samples. Porosity was estimated from bulk density laboratory determination. The soil properties were estimated using procedures described below.

Soil water characteristic curves, $\theta(h)$, were measured in a hanging column setup equipped with a Buchner funnel, specifically recommended for sandy soils (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 no hysteresis.

Falling head permeameters were used to estimate saturated hydraulic conductivity, K_{sat}, using soil samples compacted to the same dry density as the undisturbed soil cores. The functions for unsaturated hydraulic conductivity, $K(h)$, and soil moisture capacity, $M(h)$, were determined using the parameters obtained from the curve fit for the soil water characteristic function.

Rain Garden Experiments

Three controlled experiments were performed during the period August 26 to September 1, 2002. In these experiments water was artificially supplied to the rain garden at a rate of seven gallons per minute until the ponding level reached 15 cm. (This supply rate corresponds to a rainfall rate of about one inch per hour when both roofs are contributing.) During the experiments soil water measurements were made with the TDR system, for comparison with model results.

Table 2 summarizes the conditions associated with each of the three experiments. No overspill was allowed - the inflow was shut off as soon as the ponding depth got to 15 cm. Water application rates were very similar (6.6-7.0 gal/min), but much less water was required in experiment 1 because the initial soil moisture was much higher.

Table 2. Experimental conditions

Condition	Experiment 1	Experiment 2	Experiment 3
Date	08/27/02	08/29/02	09/01/02
Initial condition	very wet	moderately wet	field capacity
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
Inflow (gal/min)	6.8	6.6	7.0
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 time (h)	1.17	1.87	1.67
Total water applied (gal)	477.4	740.5	701.4

Model simulation input files were programmed so as to have the same initial condition as that given by the TDR data: soil moisture data was interpolated between probe nodes so as to provide a complete initial profile for RECHARGE runs. The spatial step used was 1 cm. We assumed a limiting bottom K_{sat}^3 of 5 cm/h for the rain garden during saturated conditions.

RESULTS AND DISCUSSION

Soil hydraulic parameters

Estimated densities and saturated hydraulic conductivities for the rain garden soils are given in Table 3. The estimated values are within the range common for sands. The storage zone is denser, which may partly explain the lower saturated hydraulic conductivity. The average value for each layer was used in the model simulations. Table 4 gives the parameters estimated based on the laboratory data and parameters based on both laboratory and field data.

Table 3. Soil parameters

Soil Characteristic	Root Zone Layer	Storage Zone Layer
Texture	60% sand, 40% peat moss	Mason's sand
Dry density (g/cm^3)	1.4	1.8
K_{sat} (cm/h)	80.4-85.9	26.9-47.0

Table 4. Mualem-van Genuchten parameters of the rain garden soil layers from laboratory data.

Soil Characteristic	Root Zone Layer	Storage Zone Layer
Texture	Sand with peat moss	Sand
α (cm^{-1})	0.033	0.032
n	3.594 (3.637)	3.250 (2.146)
$\theta_{residual}$	0.03	0.15 (0.10)
$\theta_{saturated}$	0.40	0.37
K_{sat} (cm/h)	83.1	36.9

Table 5 compares experimental parameters with the results obtained by model simulations. The model mimics the ponding times reasonably well (within a few minutes. In experiments 2 and 3, the model predicted that six percent and four percent of the input water would spill, while no spill occurred in the experimental rain garden.

Table 5. Experimental data vs. model parameters (values in parenthesis are the result of model simulations).

Parameters	Experiment 1	Experiment 2	Experiment 3
Start time of application	16:00	15:00	12:17
End time of application	17:10	16:52	13:57
Water application time (h)	1.17	1.87	1.67
Total water applied (gal)	477.36	740.52	701.40
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)
Total ponding time (h)	2.15 (2.0)	4.00 (3.7)	3.37 (3.7)
Ponded infiltration (cm/h)	5-6 (5.0)	5-7 (5.0)	5-7 (5.0)
Overspill runoff	no (no)	no (6% input)	no (4% input)
Max. ponding depth (cm)	15 (9.0)	15 (15.0)	15 (15.0)

Experiment 1 – August 27

Initial conditions were very wet - soil moisture in the root zone was around 0.1 m^3/m^3, while in the storage zone it was between 0.2 and 0.32 m^3/m^3. Figure 3 shows the TDR measurements compared with the RECHARGE model simulations. RECHARGE results follow the general data trends, particularly for the storage zone nodes. It does a poorer job with the more surficial nodes in the root zone, where it overestimates the time length of saturation by approximately half an hour, by prolonging the end time. For all the nodes, RECHARGE tends to react more rapidly to the wetting, reaching θ_{sat} approximately half an hour sooner than the data shows. This is likely due to uneven spreading in the rain garden.

The catch basin measured 0.66 m^3 at the end of the experiment, as compared to a model simulation of 0.87 m^3. This discrepancy is believed to be due in part to leakage through the TDR access holes.

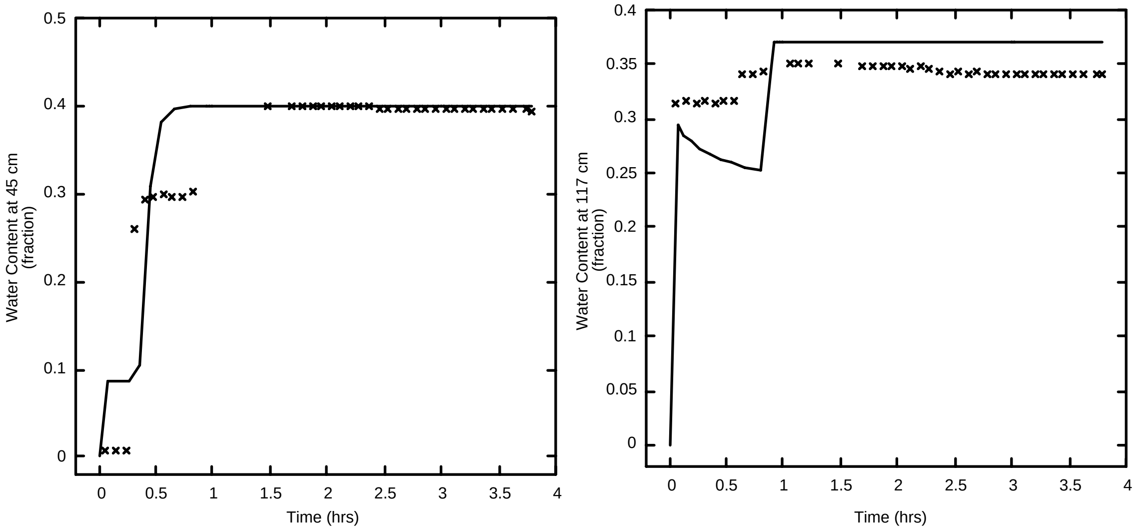

Figure 3. August 27 experiment: TDR field measurements of volumetric water content (X) compared to RECHARGE output, for probes in the root zone (45 cm) and the storage zone (117 cm).

Experiment 2 – August 29

Initial conditions were wet, since a ponding event had occurred two days before. RECHARGE results resemble data measurements very closely (Figure 4) for all probes. The model predicts the onset of saturation very accurately, and also the root zone desaturation, while underestimating the length of the saturation times in the storage zone.

The catch basin measured 1.05 m^3 at the end of the experiment, as compared to model simulation of 2.00 m^3.

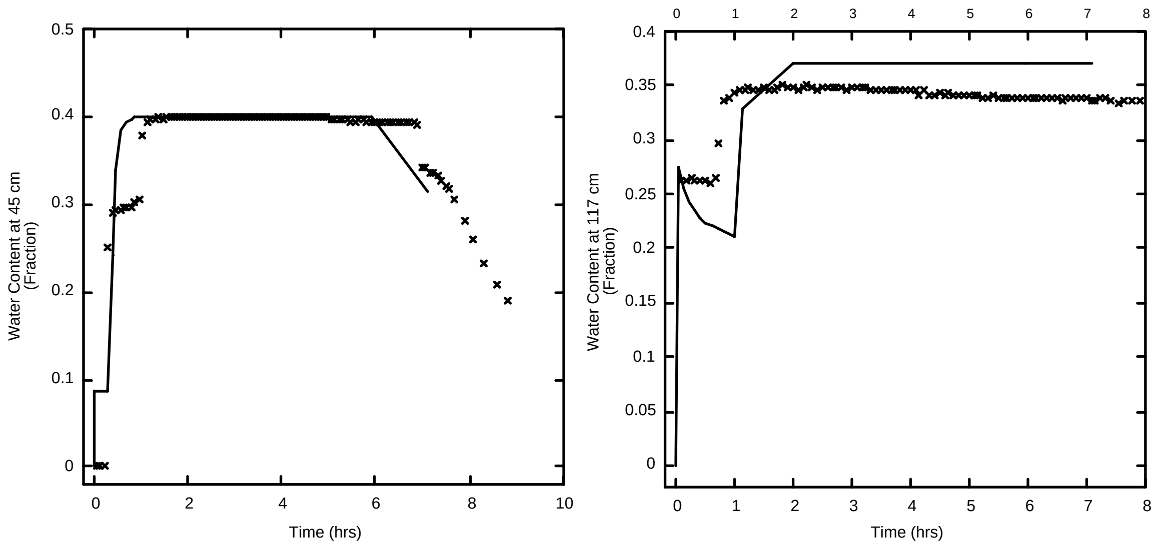

Figure 4. August 28 experiment: TDR field measurements of volumetric water content (X) compared to RECHARGE output, for probes in the root zone (45 cm) and the storage zone (117 cm).

Experiment 3 – September 1

Initial soil conditions for this experiment were approximately field capacity. RECHARGE matches the observed data well (Figure 5) for both the root zone and storage zone probe data. The model follows the data closely during the onset and the end of saturation for both soil layers.

The catch basin measured 1.03 m^3 at the end of the experiment, as compared to model simulation of 1.40 m^3.

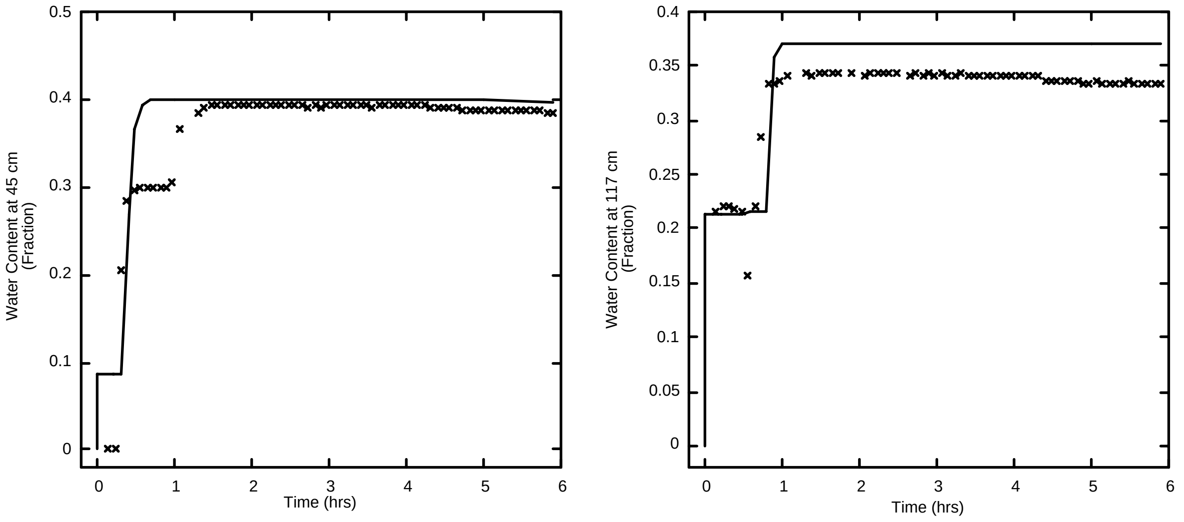

Figure 5**.** September 1 experiment: TDR field measurements of volumetric water content (X) compared to RECHARGE output, for probes in the root zone (45 cm) and the storage zone (117 cm).

CONCLUSIONS

An experimental rain garden has been constructed that allows for measurements of all water budget terms except evapotranspiration, which can be estimated by mass balance. Soil water measurements made during three experiments compare well to modeled values. However, the measured quantity of water draining the experimental rain garden was significantly less than the predicted amount, due mainly to leakage of water through the measurment ports. Once this problem has been corrected the experimental rain garden will be an excellent tool for understanding rain garden behavior and for testing numerical models.

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