Methodology for Determining Effects of Extent and Geometry of Impervious Surface on Hydrologic Balance

Elizabeth Warnemuende, William Shuster, Doug Smith, James Bonta

Abstract

Urbanization of watersheds previously managed for agricultural uses results in hydrologic changes associated with increased flooding, erosion, and surface water degradation. Few studies have been conducted to quantify these effects under controlled conditions and standard rainfall simulation methodologies have not been established. In this project, the feasibility of rainfall simulation methods to evaluate hydrologic and erosional responses to various impervious treatments is examined. In addition, a modular segmented soil box design is developed in order to quantify the hydrologic, erosional, and water quality impacts of specific urban land use configurations, including the impacts of land uses of areas hydrologically connected to impervious areas.
Hydrologic, nutrient, and pesticide data from runoff under rainfall simulation will be collected and analyzed. Treatments will include the following distributions of imperviousness at the 20%, 30%, and 40% total impervious area level: effective impervious elements each 1.25%, 5%, and 20% of total hydrologic area, non effective impervious elements each 1.25%, 5%, and 20% of total hydrologic area. In addition, potential urban and turf best management practices of will be evaluated. In conjunction with this study, a field study will be conducted at the North Appalachian Experimental Watershed near Coshocton, OH by members of the USDA-ARS and U.S. EPA. The field study will investigate impervious surface effects at the small watershed scale.

Keywords: urbanization, impervious surfaces, urban runoff, rainfall simulation

Introduction

The current socioeconomic climate favors the conversion of land previously in agricultural management for urban and suburban uses. As agricultural watersheds are urbanized, the resultant increase in impervious rooftops and transportation surfaces becomes a major controlling factor of the new urban watershed hydrology. Precipitation that falls on rooftops and pavement quickly runs off, instead of infiltrating into the soil as it would generally do in a natural or farmed landscape. This often results in increased runoff volume, peak flow rates, soil erosion, and contaminant transport, and decreased time of concentration. The economic and environmental impacts of the resulting damage to property and ecosystems are significant.

Hydrology of urban watersheds is often characterized by the extent and type of impervious areas, but impacts of the spatial and size distributions of impervious elements is not well understood (Shuster et al. 2003). The Soil Conservation Service curve number procedure is commonly used to estimate runoff. Different methods that have been previously

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used to estimate curve numbers for impervious areas and their host watersheds yield highly inconsistent estimates (Pandit and Regan 1998). These methods do not explicitly account for spatial and size and distributions of impervious surfaces. Rainfall simulations have been used to estimate curve numbers (Hawkins 1979, Pierson et al. 1995), but methods are needed to adapt these methods for urbanized settings.

The primary objectives of this study are to develop laboratory rainfall simulation methods sensitive to the spatial and size distributions of impervious surfaces, and to use these to evaluate the hydrologic, erosional, and water quality impacts of various impervious surface configurations and to guide field work in this area. This project is intended as a supporting project to a U.S. EPA/USDA-ARS joint pilot project investigating urbanization by utilizing existing experimental watersheds at the North Appalachian Experimental Watershed near Coshocton, Ohio, having the overall objective of determining the impacts of increasing urbanization on hydrology and water quality. This paper describes initial efforts to detect runoff and sediment loss differences between impervious surface configurations under laboratory rainfall simulation, and proposes a modular soil box design for this purpose.

Methods

Rainfall simulation

A programmable variable – intensity oscillating nozzle rainfall simulator (Foster et al. 1979) was used for all trials. Vertical distance between the nozzles and the soil surface was approximately 2.5 m, and nozzle pressure was 41.4 kPa. The water source was deionized.

Prior to each rainfall event, the soil bed was initially prepared by draining and drying under a large fan. Soil clods were then broken to 2-3 cm, and the surface was graded by hand or with a rake to achieve the desired slope. Impervious elements were installed as prescribed. Three layers of 17 mesh 0.011 aluminum screen were suspended above and parallel to the soil surface to help prevent soil crusting and sealing and maintain infiltration on the pervious portions of the soil box. A prewetting rain of 60 minutes at 10 mm/hr was applied and the soil box was then left to drain and dry for 24 hours. Runoff samples were collected every 2 minutes during rainfall simulation and immediately weighed to the nearest 0.01g. These weights were adjusted to account for the tare weight of each container. Then 10 – 20 mL of saturated alum solution ($AlK(SO_4)_2$) was added to each sample to flocculate suspended sediment and allowed to settle at room temperature for 12-18 hours.

After settling, the runoff water was poured out. Sediment was transferred to 1-L bottles and placed in ovens at 105^{O}C for at least 24 hours, or until dry. Dry weights were recorded to the 0.01g. Runoff volumes were determined for each sample according to (1), and runoff and sedimentation rates were determined for each sample interval according to (2) and (3), respectively.

(1) Runoff Sample Volume = (Sample Wt – Container
Tare Wt – Sediment Wt) × 1mL/g

(2) Runoff Rate = Runoff Volume / Sample Duration

(3) Sediment Rate = Sediment Mass / Sample Duration

Two-dimensional slope rainfall simulation trials

In the first trial set of rainfall simulations, impervious elements were installed on a 4×4-m soil box having a two-dimensional slope and a soil depth of 5-8 cm (Figure 1).

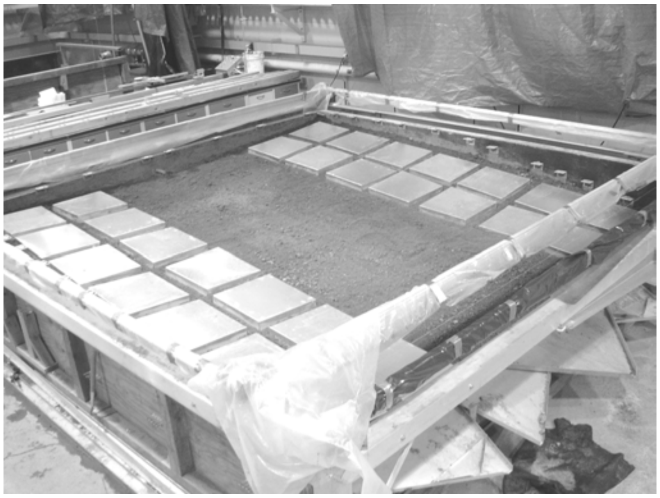

Figure 3. Two-dimensional slope soil box with impervious elements.

The soil bed had 4% side slopes and a 3% channel grade. Side slopes were 1.5 meters in length and 4 meters in width, and the main channel was 4 meters in length and 1 meter in width. The lower edge was connected to a flume for sample collection. Subsurface drainage was allowed to flow freely from the box through drainage tubes installed in a sand layer underlying the soil bed. This drainage was not collected. Rainfall simulations were performed on impervious configurations representing 0% impervious cover, and 35% impervious cover at the periphery and adjacent to the main channel. Twenty-eight impervious elements each representing 1.25% of total area were used. The 35% impervious configurations are shown in Figures 2 and 3.

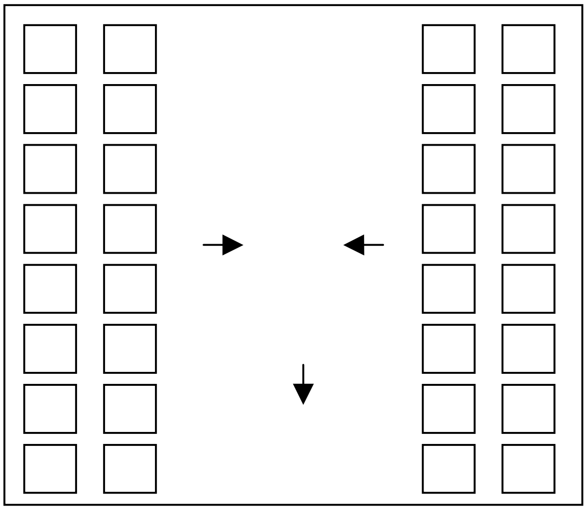

Figure 2. Configuration of impervious elements within 4×4-m soil box, representing peripheral development in two-dimensional slope trials. Arrows indicate slope direction.

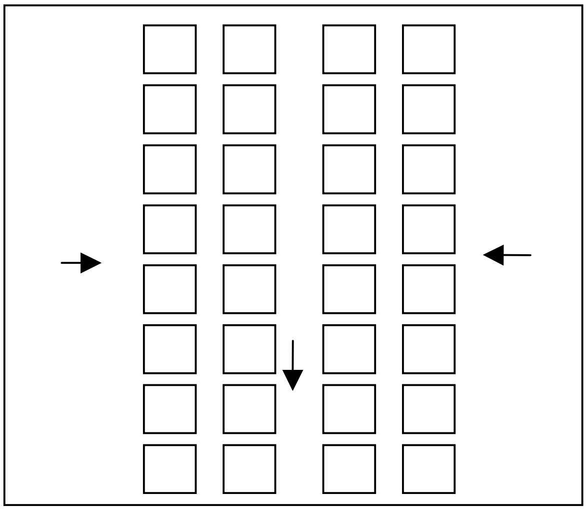

Figure 3. Configuration of impervious elements within 4×4-m soil box, representing channel development in two-dimensional slope trials. Arrows indicate slope direction.

Impervious elements were five-sided boxes constructed of sheet metal and installed by pressing the open edges of the box into the soil so that 4 cm of each edge was below the soil surface, and 4 cm remained above the soil surface. This simulated a rooftop-type impervious surface.

A rainfall sequence of 60 minutes at 20 mm/hr, followed by 10 minutes at 30 mm/hr, and then 10 minutes at 40 mm/hr was used for each rainfall simulation. For the 0% impervious treatment, the 40 mm/hr intensity segment was carried out for 40 minutes, to account for the longer time to reach steady state discharge. Rainfall interval times were based upon observed time to achieve steady state.

One-dimensional slope rainfall simulation trials

In the second trial set of rainfall simulations, impervious elements were installed on a divided 5×1.6-m soil box having a uniform lengthwise 5% slope, such that each impervious treatment was applied to a 5×0.6-m area (Figure 4).

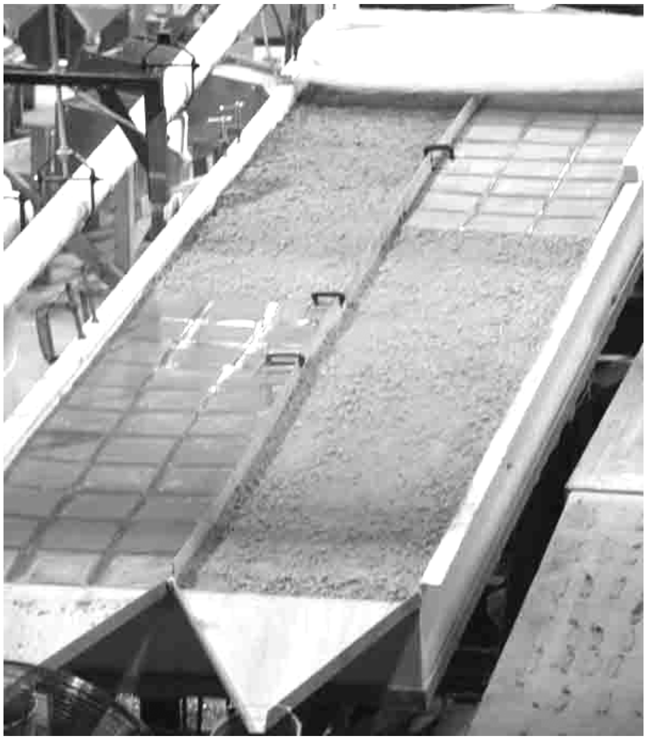

Figure 4. One-dimensional slope soil box with impervious elements.

Runoff samples were again collected through flumes at the plot ends, and water drained freely into an underlying sand layer and out of the box through drainage tubes.

Rainfall simulations were performed on 40% impervious configurations simulating urban development at the periphery and adjacent to the main channel, along a one dimensional watershed section, as shown in Figure 5.

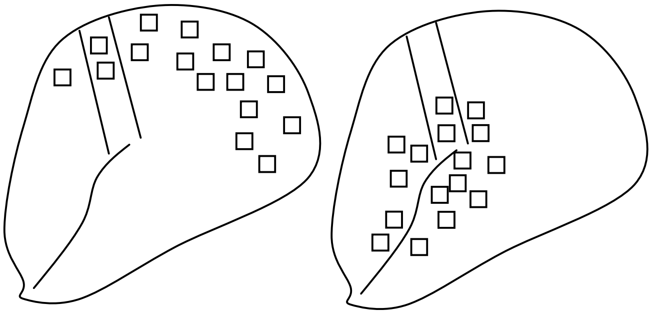

Figure 5. One-dimensional watershed flow path represented in rainfall simulation trials.

Impervious elements consisted of unglazed residential clay tile, with dimensions 20×20×0.6 cm. Because a raised impervious element would block flow in one-dimension, these were installed flush with the soil surface, representative of a transportation surface. Silicone caulk was used to seal between tiles, so that the upper 40% of the soil box was entirely impervious in one case, and the lower 40% of the box was entirely impervious in the other case.

A rainfall sequence of 50 minutes at 25 mm/hr followed by 16 minutes at 75 mm/hr was used. Rainfall interval times were based upon observed time to achieve steady state.

Results and Discussion

Two-dimensional slope rainfall simulation trials

Hydrographs from two-dimensional slope rainfall simulations are shown in Figure 6. Onset of runoff was significantly earlier where impervious elements were present. Onset of runoff was slightly earlier where impervious elements existed at the periphery, verses adjacent to the channel. However, this difference is more likely attributed to subtle differences in the soil surface shape than to treatment differences. Sediment loss rates (Figure 7) were similar between impervious treatments. As for runoff, sediment loss was lower and delayed in the 0% impervious treatment, as compared to the impervious treatments.

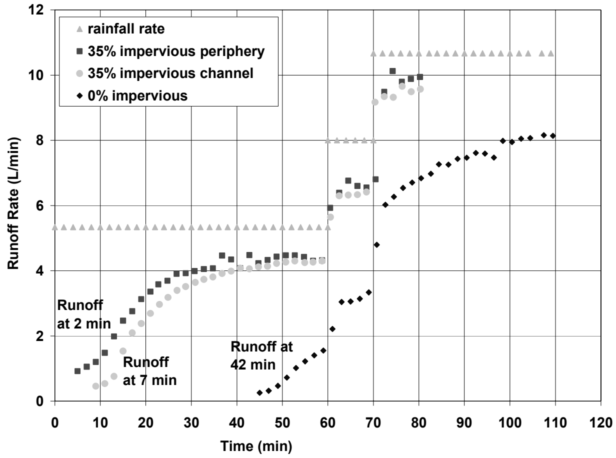

Figure 6. Rainfall and hydrographs from two-dimensional slope rainfall simulations with impervious surfaces.

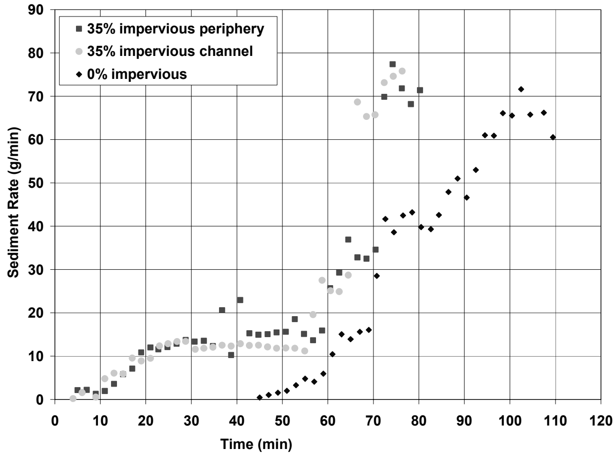

Figure 7. Sediment loss rates from two-dimensional slope rainfall simulations with impervious surfaces.

The soil surface shape was difficult to reproduce precisely for all runs, and it is believed that these inconsistencies were sufficient to impact runoff and sediment losses. In addition, treatments were geometrically very similar, since differences were implemented on the relatively short side slopes of the soil box. These difficulties led to the development of the one-dimensional flow system.

One-dimensional slope rainfall simulation trials

Hydrographs and sediment losses from the one-dimensional slope simulations are shown in Figures 8 and 9, respectively.

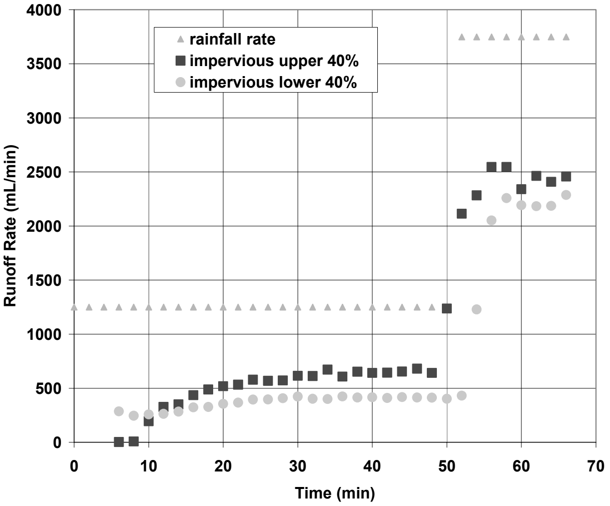

Figure 8. Rainfall and hydrographs from one-dimensional slope rainfall simulations with impervious surfaces.

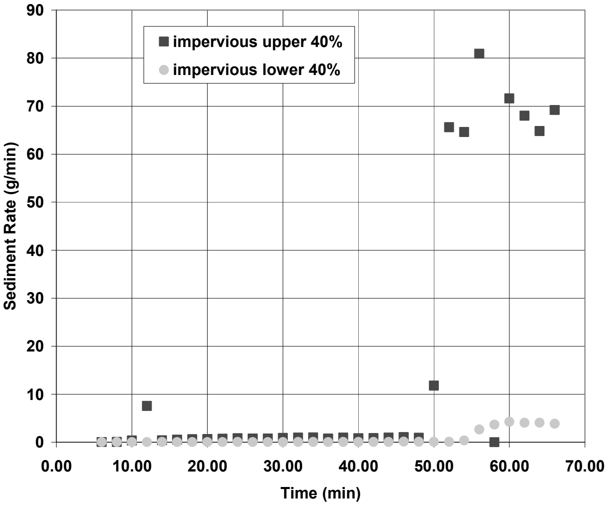

Figure 9. Sediment loss rates from one-dimensional slope rainfall simulations with impervious surfaces.

Impervious treatments yielded differences in both hydrograph and sediment losses, with the most clear differences in sediment losses. The upper impervious treatment yielded initially less runoff, as runoff generated by the impervious surface at the top of the slope infiltrated into the pervious soil surface below. However, this pervious zone became more quickly saturated than its upslope counterpart, due to this run-on. As a result, the upper impervious treatment yielded generally higher runoff and sediment after an initial wetting period.

This one-dimensional slope rainfall simulation approach appears to be sensitive to impervious treatments. However, impervious / pervious transition points were prone to scouring and undercutting at higher rainfall intensities. In order to reduce variability due to inconsistencies in these transitions, a modular segmented soil box system is proposed.

Modular soil box design

A modular soil box design is proposed for use in laboratory urbanization rainfall simulations (Figure 10).

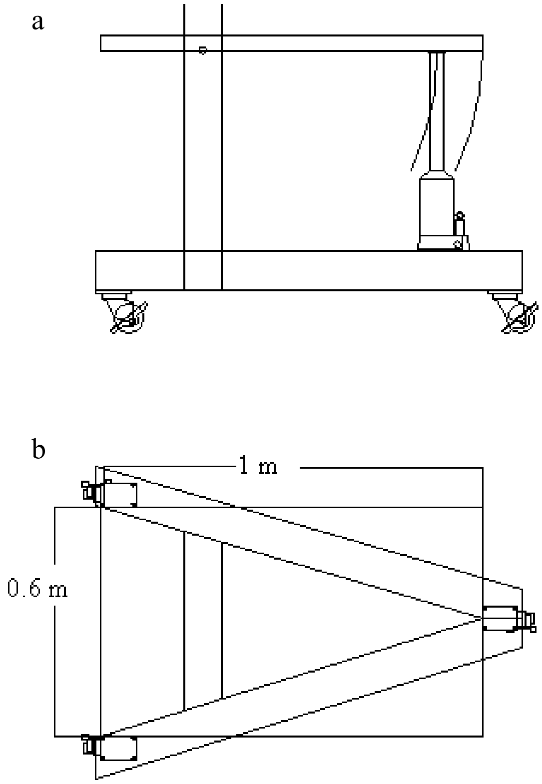

Figure 10. Single modular soil box segment side view (a) and top view (b).

Each soil box has a length of 1 m and is 0.6 m wide. Soil depth is 20 cm. Runoff and sediment will flow from upslope soil boxes into downslope soil boxes through short baffled flumes. Current designs allow up to 8 soil boxes to operate in series, for a maximum slope length of 8 meters. Boxes can be easily transported to and from growth facilities in order to develop different vegetative covers and / or turfs, and can be implemented with a variety of pavers or infiltration bed materials, without the transition concerns associated with the single box design. This modular design will allow researchers to construct specific sequences of land treatments along a one dimensional flow path. This system will be used to evaluate the effectiveness of specific impervious configurations as urban best-management practices, turf best management practices, and to guide the field watershed experiments described by Bonta et al. 2003.

Conclusions

Laboratory rainfall simulation methods can be used to detect hydrologic and erosional differences between impervious surface treatments. A modular soil box system design was developed in order to minimize inconsistencies in soil box preparation and impervious / pervious transitions, while maximizing treatment capabilities and slope length. This system will be used alongside a field watershed study to evaluate the hydrologic, erosional, and water quality impacts of impervious configurations and potential urban best management practices.

References

Bonta, J., W. Shuster, E. Warnemuende, H. Thurston, D. Smith, M. Goss, and H. Cabezas. 2003. Quantification of Urbanization in Experimental Watersheds. In Proceedings of the First Interagency Conference on Research in the Watersheds, Benson, AZ, October 27-30, 2003.

Foster, G. R., F.P. Eppert, and L.D. Meyer. 1979. A programmable rainfall simulator for field plots. In Proceedings of the Rainfall Simulator Workshop, March 7-9, 1979, Tucson, AZ, pp. 45-59. USDA-SEA-ARM.

Hawkins, R.H. 1979. Inferring curve numbers from simulator data. In Proceedings of the Rainfall Simulator Workshop, March 7-9, 1979, Tucson, AZ, pp. 45-59. USDA-SEA-ARM.

Pandit, A., and J. Regan. 1998. What is the impervious curve number? Advances in Modeling the Management of Stormwater Impacts 6:437-449.

Pierson, F.B. K.R. Cooley, S.S. Van Vactor, and A.H. Hawkins. 1995. Estimating curve numbers from rainfall simulation data. In First International Conference on Water Resources Engineering and International Groundwater Management Symposium, San Antonio, TX, August 14-18, 1995.

Shuster, W.D. , H. Thurston, E. Warnemuende, D.R. Smith, and J.V. Bonta. 2003. Impacts of impervious surface on watershed hydrology: A review. Urban Water (in review).