Groundwater Research Report
WR12R002

Effects of Nuanced Changes in Lot Layout and Impervious Area Connectivity on Urban Recharge

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Project Number WR12R002

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PROJECT SUMMARY

Title: Effects of Nuanced Changes in Lot Layout and Impervious Area Connectivity on Urban Recharge

Project I.D.: WR12R002

Investigators: Dr. Steven P. Loheide II, Associate Professor, Department of Civil and Environmental Engineering, University of Wisconsin-Madison

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Period of Contract: July 1, 2012 – June 30, 2014

Background/Need: It has long been assumed that urbanization and the associated loss of pervious area leads to a decrease in groundwater recharge, but recent studies have produced conflicting results. While the importance of impervious area arrangement and connectivity has been demonstrated in rainfall-runoff studies at various scales, very little work has been done to addresses how such differences in impervious area configuration may affect localized recharge rates. There is a need for physically based modeling efforts which are complex enough to calculated percolation through the unsaturated zone and detailed enough to capture nuanced differences in impervious area configuration at the surface.

Objectives: The objective of this study is to determine the extent to which the arrangement and connectivity of impervious areas in urban residential lots impacts growing season recharge using lot-scale, physically based models.

Methods: Model simulations were performed using ParFlow, a parallel watershed model with fully integrated overland flow and coupled land surface processes via the Common Land Model (CLM). A pair of residential lots were simulated under fully connected and downspout disconnect schemes under average and dry precipitation scenarios. Field records of soil moisture near and far from the influence of downspouts were analyzed to provide supporting evidence for simulated differences in percolation among scenarios.

Results and Discussion: Both field and modeling results show that lateral transfers of water from impervious surfaces increase soil moisture near downspouts and affect propagation of wetting fronts, although differences are more substantial during dry years. Connectivity exerts a strong control on the spatial distribution of recharge rates at the lot scale. The amount of precipitation that can be redirected to recharge is non-linearly related to surface runoff, since enhanced infiltration is partially offset by increases to transpiration during dry years, rather than translating directly into recharge.

Conclusions: Decreasing the connectivity of impervious surfaces on residential lots can increase localized recharge substantially and thereby increase overall lot recharge. Model simulations indicate that predictive models of urban catchment recharge rates can be improved with greater attention to the heterogeneity of impervious surface arrangement. The extent to which recharge rates can be enhanced by manipulations in the arrangement and connectivity of impervious areas on residential lots is not the same under all conditions and requires explicit consideration of soil texture, precipitation, evaporation, and the vegetative processes of transpiration/root water uptake.

Related Publications: None.

Key Words: urbanization, recharge, soil moisture, impervious area

Funding: University of Wisconsin System

INTRODUCTION

Background

It is well known that increases in impervious area associated with urbanization increase both the volume of runoff and the rate of runoff leading to “flashier” urban hydrographs that heighten flooding risk and adversely effect downstream ecosystems. These impacts on surface water flow regimes are commonly ameliorated with stormwater detention ponds and/or retention facilities; however, it is not only the surface water component of the water budget that is affected by urbanization and stormwater management strategies. It has long been assumed that urbanization and the associated loss of pervious surfaces leads to a decrease in groundwater recharge but recent studies have produced conflicting results, with some finding increases in recharge (Milczarek et al., 2004) and others finding decreases (Erickson and Stefan, 2009; Yang et al., 1999). To more precisely describe how urban systems, particularly stormwater treatment infrastructure, impact recharge rates, recent studies have divided recharge into three distinct fluxes (Lerner, 2002). *Direct recharge* is decentralized and occurs below the location at which precipitation falls and directly percolates through the unsaturated zone. *Localized recharge* occurs when surface water moves a short distance horizontally before percolating through the unsaturated zone, such as when water runs off a sidewalk onto a neighboring lawn. Finally, *indirect recharge* occurs when runoff flows through surface water bodies or urban stormwater infrastructure and eventually infiltrates far from where it fell as precipitation, potentially carrying with it environmental contaminants including fertilizers, petrochemicals, and disease-causing microbes (Lee and Bang, 2000). The focus of this project is on quantifying the effects of the arrangement and connectivity of impervious areas in residential lots on localized recharge.

Within the vast body of urban hydrology literature, it is possible to group studies in two ways: 1) by the scale of the study (entire urban watershed vs. lot), and 2) by whether or not the study addresses changes in recharge. At the urban catchment scale, many studies explore how the arrangement of impervious surfaces affects the rainfall-runoff relationship of the catchment. For example, Brander et al. (2004) conducted a model experiment to compare the rainfall-runoff response of four different suburban subdivision layouts and found – not unexpectedly - that those with the most pervious area allow the most infiltration. Other studies at this scale more explicitly address changes in catchment-scale recharge due to urbanization, but utilize models at such a large scale that details of the urban landscape, particularly individual lots, are ignored (Erickson and Stefan, 2009; Milczarek et al., 2004; Yang et al., 1999). At smaller scales, there are again many studies that explore how the configuration of impervious surfaces impacts the rainfall-runoff characteristics of a lot. For example, a modeling study of the impacts of zoning on surface runoff in Madison WI found that by making slight modifications to the required layouts of residential land parcels in the city, stormwater runoff volumes from residential subdivisions could be reduced by 30% (Stone and Bullen, 2006). Also in Madison, WI, Mueller and Thompson (2009) conducted 52 runoff volume reduction tests at residential lots and found that homes with green space between the downspout outlet ant the nearest connection to the storm sewer system were able to infiltrate a significant portion of the precipitation that would have otherwise been directed to the sewers. But changes in lot rainfall-runoff relationships and lot infiltration rates do not necessarily describe changes in localized recharge rates, since the fate of infiltrated water may be either evapotranspiration or groundwater recharge.

In fact, very little work has been done to determine how the configuration of impervious surfaces at the lot level impacts *localized recharge* rates. One reason for this is that the models traditionally used in urban hydrology generally lack a complete representation of vadose zone processes, and are therefore not well suited for estimating recharge. In particular, accurate calculation of recharge requires simulation of percolation through the unsaturated zone as well as simulation of root water uptake – processes that persist in time beyond runoff generation and are more computationally demanding to solve for. The second reason is that even models of urban catchments which are physically-based face computational limits which prevent them from simulating detailed, subparcel-scale connections and interactions between impervious areas within catchment-scale models (Borah and Bera, 2003). This project addresses this research gap by utilizing a physically based model to quantify localized recharge at a scale which also captures the effects of alternate impervious surface configurations.

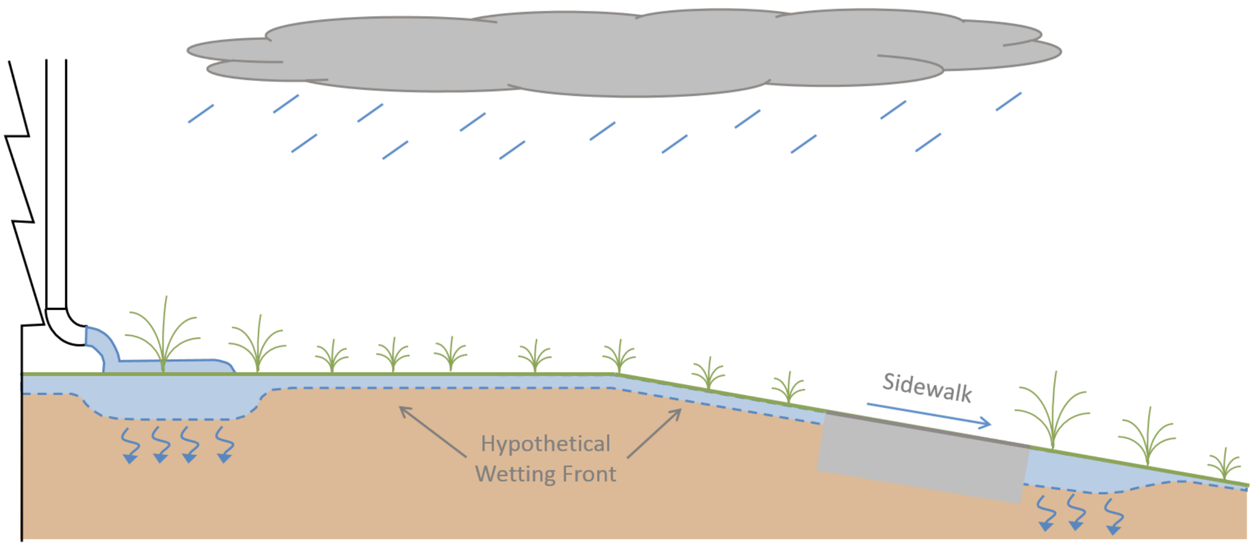

Figure 1: Hypothetical wetting front with an increase in localized infiltration downstream of impervious surfaces which can lead to greater water availability for vegetation and focused groundwater recharge.

Objectives

The objective of this study is to determine the extent to which the arrangement and connectivity of impervious areas in urban residential lots impacts growing season recharge. We believe that nuanced changes to the configuration of impervious areas can have a significant effect on localized recharge rates in a way that cannot be captured with coarse characterizations that are typically employed for urban settings, such as percent impervious area. We hypothesize that for lots with the same impervious to pervious area ratio, there are some connectivity schemes which better transfer water from impervious areas to pervious ones and promote localized recharge by developing well-defined, fast-moving wetting fronts that are able to penetrate the root zone, thus altering the partitioning of infiltration between evapotranspiration and recharge (Figure 1). Our goal is to conduct modeling experiments to identify those impervious connectivity schemes which promote recharge. In this report, we focus on downspouts, which can be directly connected to storm sewers or directed toward pervious areas, as a simple example of connectivity for exploring possible effects on groundwater recharge. We also investigate the sensitivity of these findings to growing season precipitation by comparing results for average and dry years.

PROCEDURES AND METHODS

Field Observations

To assess the influence of downspouts in the field, we examined the record for two nests of soil moisture sensors, one near the outlet of a downspout and one far from the influence of a downspout, at each of three residential lots in Madison. Each nest has sensors at 15cm, 35cm, and 65cm and was analyzed for the 2012 growing season.

Figure 2: Sample locations of soil moisture nests a) near a downspout and b) far from the influence of a downspout.

Lot Scenarios

Archetypical residential lots were designed based on Madison, WI zoning code and property assessor statistics (Figure 3). Two basic lot layouts were explored, both based on the densest residential zone in Madison (TR-C4). Lot A is 40% impervious, with a disconnected garage and small driveway adjacent to a rear alley as well as a front sidewalk adjacent to the street. Lot B is 50% impervious, with an identical disconnected garage located near a rear alley and a front sidewalk adjacent to the street, but with the addition of a driveway leading from the street to the garage. When the house and garage are disconnected via downspouts, the “effective impervious area” directly connected to the storm sewer network is 22% and 32%, respectively. For each lot, two connectivity schemes were explored, fully connected (FC) and downspout disconnect (DS), for two growing season precipitation scenarios, average and dry, for a total of eight simulations.

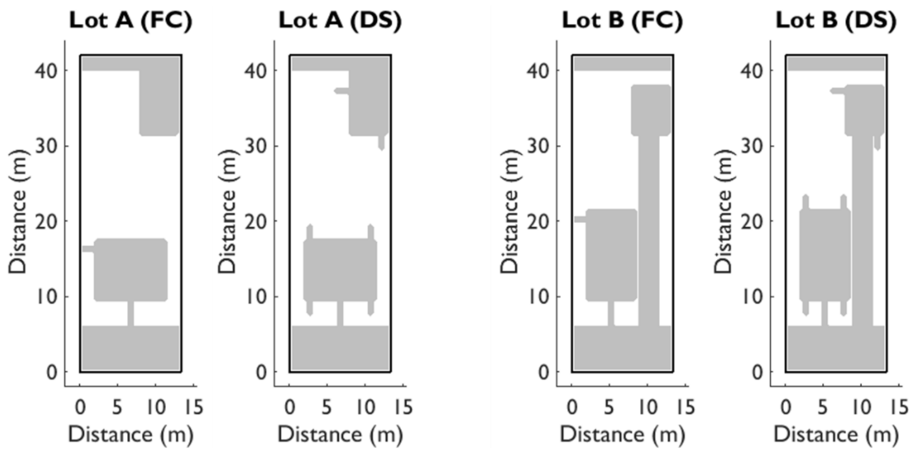

Figure 3: Simulated lot configurations of a small urban lot with rear alley, disconnected garage, and sidewalk adjacent to front street include fully connected (FC) and downspout disconnect (DS) schemes for a 40% impervious lot (Lot A) and a 50% impervious lot (Lot B).

Model Design

Simulations were performed using ParFlow, a parallel watershed model with fully integrated overland flow and coupled land surface processes via the Common Land Model (CLM). ParFlow solves the three-dimensional, time-dependent, variably saturated flow equation for subsurface water movement (Ashby and Falgout, 1996; Jones and Woodward, 2001). A continuity of pressure boundary condition links the subsurface to the surface, where the kinematic wave equation is solved for surface water movement (Kollet and Maxwell, 2006). Transpiration, interception, evaporation, and land surface energy balances are calculated by CLM (Kollet and Maxwell, 2008; Maxwell and Miller, 2005).

All pervious areas were assumed to consist of silt loam soil covered by turfgrass. Soil hydraulic properties were taken from Carsel and Parrish (1988) and turfgrass rooting parameters were adjusted to match observational studies (Erusha et al., 2002; Lyons et al., 2011). For impervious areas, house foundations were assumed to be 3m deep, garage foundations 0.3m deep, and other impervious surfaces (roads, sidewalks, etc.) 0.2m deep. Saturated hydraulic conductivity of impervious features was set to be $1x10^{-6}$ cm/s (Wiles and Sharp, 2008). Slopes in the x and y direction were assumed to be 0.01 m/m and Manning's n value of 0.240 was used.

Models were forced with meteorological input for the appropriate growing season (April 15 – November 15) and a distant (10m deep) water table. Meteorological input from 1984 was selected as "average" based on an analysis of total precipitation, number of days with greater than or equal to 0.1 inch of precipitation, 0.5 inch of precipitation, and 1.0 inch of precipitation for the months of April through November from 1981 to 2010 at three regional weather stations. For "dry" scenarios, meteorological input for the extreme drought year of 2012 was selected. All model simulations were performed using 36 processors on the High Performance Computing Cluster at the University of Wisconsin-Madison Center for High Throughput Computing with computational time ranging from 150 hours to 246 hours per simulation.

RESULTS AND DISCUSSION

Field Soil Moisture Near and Far from Downspouts

Proximity to downspouts has a strong control on soil moisture in the 2012 field record. A representative example from one site is presented in Figure 4; trends are similar across all three lots. Soil moisture is comparable near and far from downspouts at the beginning of the season, but dramatically diverges in early- to mid-summer when soil moisture far from the downspout is persistently below the onset of vegetative water stress. This is most striking at deeper locations (35cm and 65cm), which show no response to precipitation events and do not recover by the end of September. Shallow depths are also much less responsive to late-summer and early-fall precipitation events and stay drier than observations near the downspout. These observations are strong support that lateral transfers of water from impervious surfaces can substantially alter local plant available water, potentially mitigating water stress, as well as induce stronger wetting fronts in nearby pervious areas.

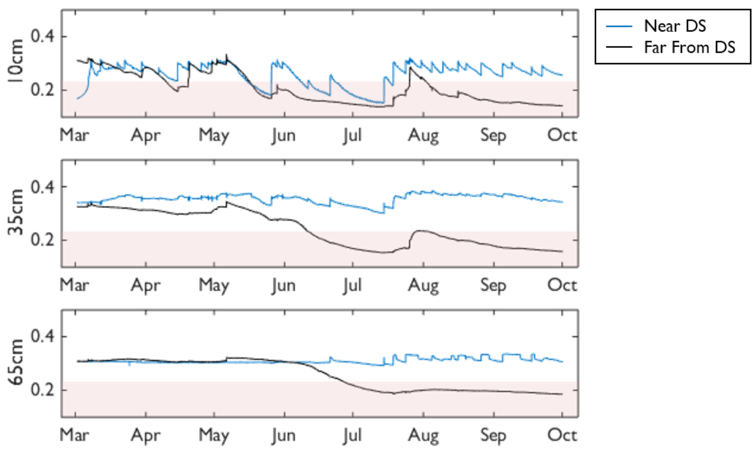

Figure 4: Field soil moisture content near and far from downspout during the 2012 growing season at suburban residence. Red areas indicate soil moisture content at which water stress is expected to occur in this silt loam soil.

Modeled Soil Moisture Near and Far from Downspouts

While the model simulations were not designed to replicate the field observations (e.g., different lot configurations and no attempt to match soil characteristics or heterogeneity of any one site), it is useful to comment on both the observed similarities and differences between the field observations and the generalized simulations. Soil moisture trends observed in the field are also observed in modeling results (Figure 5). In the average precipitation scenario, soil moisture far from downspouts is consistently lower than soil moisture near a downspout but only by a small amount that does not substantially affect sensitivity to precipitation events or transpiration. There is a more noticeable divergence in the dry precipitation scenario, but not to the extent observed in field results. The majority of the difference is likely attributable to differences in soil characteristics between the homogenous silt loam represented in the model and the soils which exist in the field, but another possible contributing factor may be that the simple, shallow-rooted turfgrass specified in the model exerts weaker root water uptake than deeper rooted grasses or more complex vegetation (i.e., shrubs, trees) present in actual lawns. Overall, comparison of modeled soil moisture near and far from downspouts shows that lateral transfers of water from impervious surfaces have more substantial impacts on soil moisture in nearby locations during dry years when soil moisture deficits are high elsewhere in the yard.

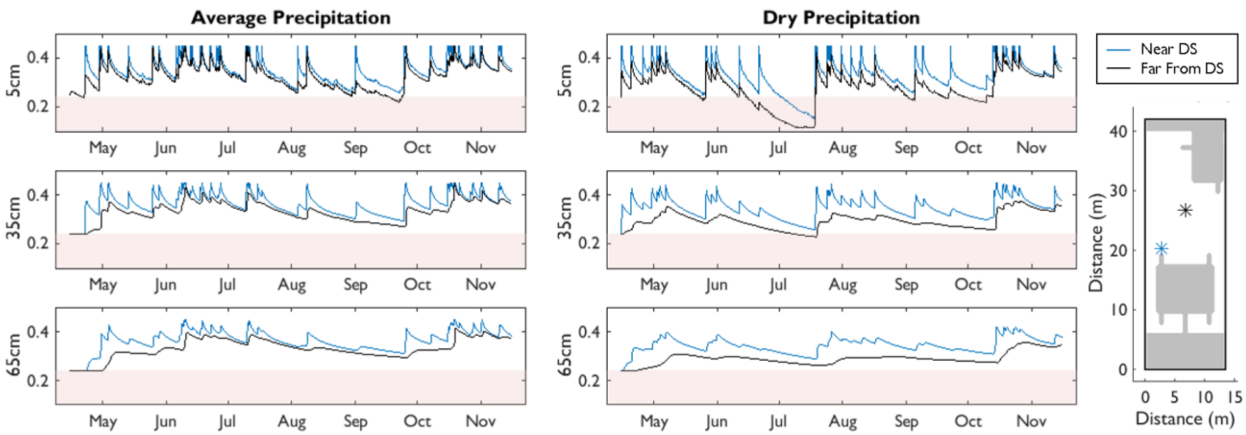

Figure 5: Modeled soil moisture content near and far from downspout for Lot A under average and dry precipitation scenarios. Red areas indicated specified water content at which water stress occurs.

Intraparcel Differences in Recharge

Localized recharge, or enhanced recharge due to the lateral transfer of water across impervious surfaces, is a significant factor in these simulations results, as shown in Figure 6. Lot recharge rates are primarily determined by precipitation (average vs. dry), but the downspout signature is clearly visible in the spatial pattern showing localized recharge near downspouts for both disconnected downspout scenarios. These areas with heightened localized recharge are substantial enough that overall lot recharge is increased by 16% to 31%, even though the rest of the lot performs similarly across connectivity scenarios. We do not intend for these absolute estimates to be used to predict seasonal or annual recharge rates for any specific location, rather we present these findings for an idealized lot with homogeneous soils to demonstrate the possibility of spatial variability in recharge and the sensitivity of recharge rates to nuanced lot scale characteristics. These results demonstrate that recharge at broad scales is highly sensitive to nuanced differences in impervious connectivity at decimeter scales, which are much finer than that which is typically considered in models of urban hydrology.

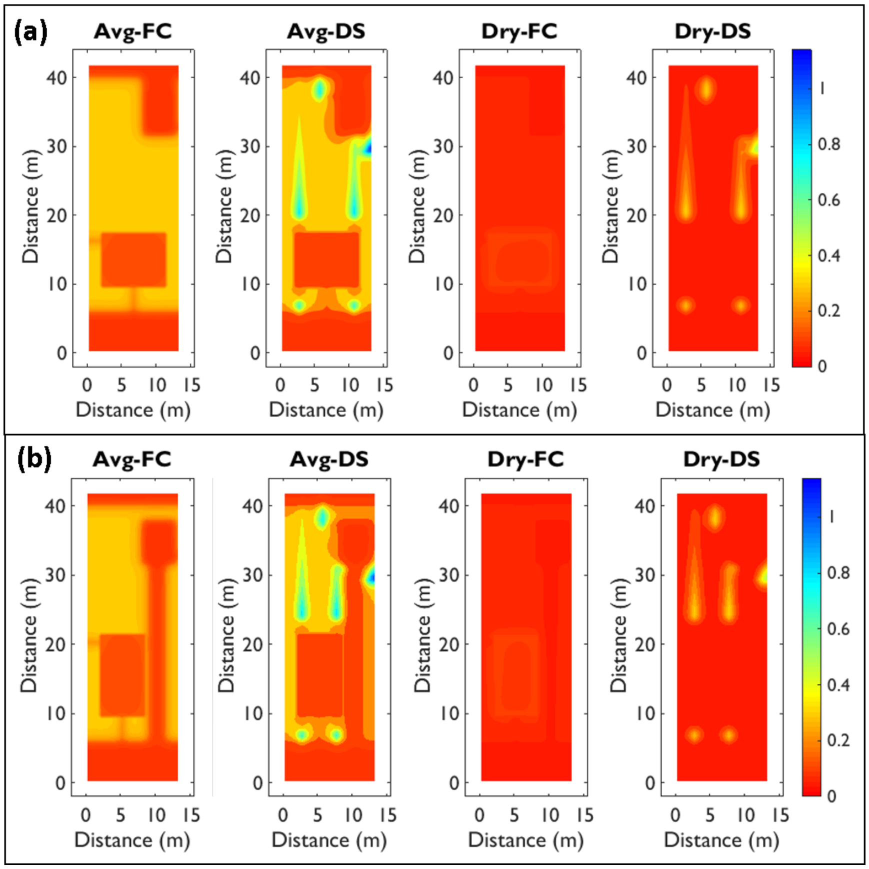

Figure 6: Spatial distribution of cumulative growing season recharge (m) for fully-connected (FC) and downspout disconnect (DS) schemes under average and dry precipitation scenarios for a) Lot A, and b) Lot B. Cumulative average recharge for Lot A is 0.22m (Avg-FC), 0.26m (DS-Avg), 0.07m (FC-Dry), and 0.09m (DS-Dry). Cumulative average recharge for Lot B is 0.20m (Avg-FC), 0.23m (DS-Avg), 0.06m (FC-Dry), and 0.08m (DS-Dry).

Partitioning to Runoff

As might be expected, lot configurations with more drainage from impervious areas to pervious areas (DS schemes) have lower runoff ratios than their fully connected counterparts (FC schemes) (Figure 7). These ratios do not vary substantially with precipitation scenario; in both average and dry years, disconnecting downspouts reduces the runoff ratio from about 0.25 to about 0.20 in Lot A (40% total impervious) and similarly reduces the ratio from 0.32 to 0.27 in Lot B (50% total impervious). This supports the argument that there is significant potential to reduce runoff loads to traditional detention basins by disconnecting impervious area in all years, regardless of total seasonal precipitation, under climate and soil conditions similar to that of Wisconsin.

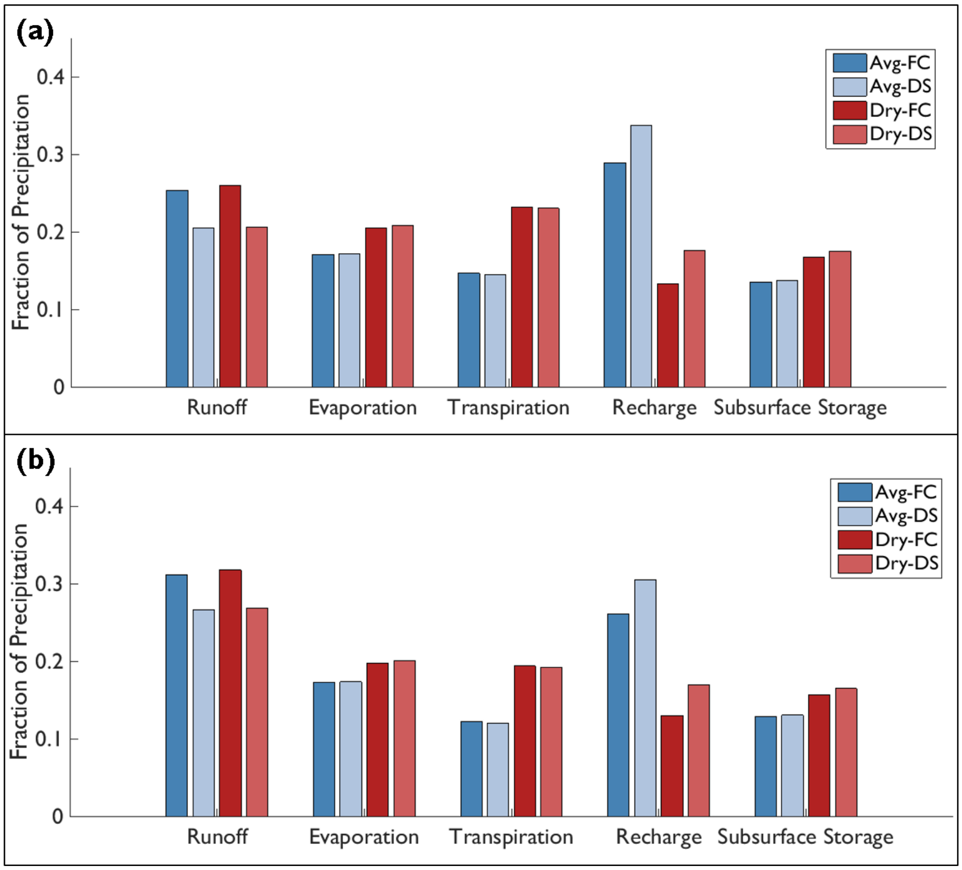

Figure 7: Partitioning of growing season precipitation to surface runoff and subsurface processes for a) Lot A, and b) Lot B scenarios.

Partitioning to Recharge

There is more variability in rainfall-recharge ratios than rainfall-runoff ratios, although similar trends are present (Figure 7). In general, much more precipitation is partitioned to recharge in average years than in dry years. This is to be expected since in dry years, a much greater proportion of precipitation is needed to satisfy evapotranspiration demands and replenish soil moisture so there is less excess available to drain as recharge. For either lot under either precipitation scenario, disconnecting downspouts has a similar effect on recharge as on surface runoff: a difference of roughly 0.05 relative to the precipitation. For average precipitation years, this difference is exactly the same for recharge, indicating that all benefits from enhanced infiltration are directly translated to enhanced recharge. However, for dry years, the difference in enhanced recharge is 0.01 less than the difference in enhanced infiltration, indicating that some of the benefit of enhanced infiltration is shared with other subsurface processes (e.g., evapotranspiration/ root water uptake). The percent increase in recharge resulting from disconnection of downspouts is much larger in dry years because the recharge rate is so low in areas unaffected by downspouts. It is notable that this is observed even though lot vegetation is simplified as a uniform, shallow-rooted turfgrass. Where vegetation with more extensive rooting structures such as native prairie grasses, shrubs, and deeply rooted trees are present, it is expected that they would capture an even greater share of the enhanced infiltration.

CONCLUSIONS & FUTURE WORK

Conclusions

These findings show that decreasing the connectivity of impervious surfaces on residential lots can increase localized recharge substantially and thereby increase overall lot recharge. These trends hold across both average and dry precipitation scenarios, although in absolute terms, the increase in recharge is somewhat diminished during dry years when enhanced infiltration is partially offset by increased transpiration rather than translating directly into recharge. Rainfall-runoff ratios are consistent for a given connectivity scheme across precipitation scenarios simulated in this study but they have a non-linear relationship with rainfall-recharge rates, which makes it difficult to infer recharge behavior from surface runoff behavior. Overall, model simulations indicate that predictive models of urban catchment recharge rates could be improved with greater attention to the heterogeneity of impervious surface arrangement, but that it is important to consider climate, evaporation, and vegetative processes with equal attention to detail.

Future Work

This research represents a first step in simulating the extremely fine-scale variability in subsurface processes of root water uptake, percolation, and groundwater recharge that results from nuanced difference in connectivity of pervious and impervious areas on the land surface. These results show that existing relationships between rainfall and runoff are of little use for predicting recharge even when impervious connectivity is accounted for, but more work is needed to validate these model results. By extending these modeling experiments to additional lot configurations and further probing combinations of variables, there is potential to generate a large database of results which could support empirical relationships between rainfall, lot configuration, and recharge rates. It will be useful to explore these relationships under more prescribed precipitation scenarios with more complex vegetation classes, to better define how enhanced infiltration is distributed among the subsurface processes of deep drainage, soil evaporation, and root water uptake. This model infrastructure will be used to support a small number of larger models which explore how intraparcel differences in impervious configurations interact with interparcel differences in lot layout to affect recharge rates of small neighborhoods. Detailed models at these larger scales will provide valuable insights into how to prioritize outreach and management efforts to efficiently achieve watershed management goals.

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APPENDIX A: Awards, Publications, Reports, Patents, Presentations, Students, Impact

Presentations

Voter, C.B., S.P. Loheide. 2015. Soil Moisture and Evapotranspiration as a Function of Distance from Impervious Features in Residential Parcels. 39th Annual Meeting of the American Water Resources Association-Wisconsin Section, Oconomowoc, WI.

C. B. Voter, S. P. Loheide II, 2014. Modeling the Hydrologic Effects of Parcel-Scale Changes in Lot Layout and Impervious Surface Connectivity. 38th Annual Meeting of the American Water Resources Association-Wisconsin Section, Wisconsin Dells, WI.

Voter, C.B., J.F. Miller, S.P. Loheide. 2013. Modeling the Effects of Nuanced Changes in Lot Layout and Impervious Area Connectivity on Urban Recharge in COMSOL. 37th Annual Meeting of the American Water Resources Association-Wisconsin Section, Brookfield, WI.

Students Supported

Jeffrey F. Miller (jeffreyfmiller@me.com)
MS in Civil and Environmental Engineering, University of Wisconsin-Madison, November 2012
Thesis Title: Visualization techniques and statistical methods for evaluating the impact of root structure on surface runoff generation in freely drained soils
Job Placement: Epic Systems, Madison, WI

John Sourbeer (jsourbeer@gmail.com)
MS in Civil and Environmental Engineering, University of Wisconsin-Madison, December 2013
Thesis Title: Long term soil moisture monitoring and assessing theoretical data interpretation techniques using heated distributed temperature sensing.
Job Placement: US Army Corp of Engineers, Pittsburgh, PA

Carolyn B. Voter (cvoter@wisc.edu)
Ph.D. student in Civil and Environmental Engineering, University of Wisconsin-Madison

Impact

This project investigated how the arrangement of impervious surfaces affects patterns of groundwater recharge within residential lots. Modeled results show that the simple technique of directing downspouts to drain to the lawn rather than to the storm sewer substantially reduces runoff and increases infiltration near the downspout outlets, but the volume of enhanced infiltration is not directly related to the volume of increased recharge. The relationship between the two varies with weather, since during dry years more of the enhanced infiltration is used by vegetation and less remains to recharge groundwater. Overall, our findings show that prediction of urban groundwater recharge rates could be improved with greater attention to fine-scaled differences in impervious surface arrangement which lead to fine-scaled differences in recharge.