AGU100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE

10.1029/2018WR022534

Key Points:
- Practices targeting impervious-pervious interfaces lead to higher runoff but can increase drainage relative to lots with no imperviousness
- Pairing impervious disconnection with soil decompaction synergistically reduces runoff and increases deep drainage and evapotranspiration
- When infiltration is enhanced by low-impact interventions in temperate climates, its fate is strongly controlled by growing season weather

Supporting Information:
- Supporting Information S1

Correspondence to:
C. B. Voter,
cvoter@wisc.edu

Citation:
Voter, C. B., & Loheide, S. P., II (2018). Urban residential surface and subsurface hydrology: Synergistic effects of low-impact features at the parcel scale. *Water Resources Research*, *54*, 8216–8233. https://doi.org/10.1029/2018WR022534

Received 12 JAN 2018
Accepted 24 SEP 2018
Accepted article online 4 OCT 2018
Published online 25 OCT 2018

Urban Residential Surface and Subsurface Hydrology: Synergistic Effects of Low-Impact Features at the Parcel Scale

C. B. Voter[1] and S. P. Loheide II[1]

[1]Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI, USA

Abstract Accurately predicting the hydrologic effects of urbanization requires an understanding of how hydrologic processes are affected by low-impact development practices. In this study, we explored how growing season surface runoff, deep drainage, and evapotranspiration on a residential parcel are affected by several low-impact interventions, including three “impervious-centric” interventions (disconnecting downspouts, disconnecting sidewalks, and adding a transverse slope to the driveway and front walk), two “pervious-centric” interventions (decompacting soil and adding microtopography), and all possible “holistic” combinations. Results were compared to both a highly and moderately compacted baseline parcel under an average and a dry weather scenario for a temperate climate. We find that under reasonable assumptions for highly compacted soil, pervious areas are a major source of runoff and disconnecting impervious surfaces may be relatively less effective without improving soil conditions. Under both highly and moderately compacted soil conditions, combining efforts to decompact soil with impervious disconnection has a synergistic effect on reducing surface runoff and increasing deep drainage and evapotranspiration. All combinations of interventions enhance infiltration, but the partitioning of additional root zone water between deep drainage and evapotranspiration depends on the weather scenario. Importantly, when all low-impact interventions are applied together, growing season deep drainage is higher than that from a vacant lot with no impervious surfaces. We infer that ecohydrologic interfaces between impervious and pervious areas are strong controls on urban hydrologic fluxes and that high-resolution, process-based models can be used to account for these interfaces and thereby improve predictions of the hydrologic effects of low-impact interventions.

1. Introduction

1.1. Urban Hydrology Background

Urbanization—specifically, the land use change associated with the built environment—is notorious for disrupting natural hydrologic processes and creating management concerns for cities. A fundamental issue is that many urban surfaces (e.g., paved surfaces, roofs, and compacted soil) are less pervious than their natural counterparts (e.g., grassland, forest, wetlands, and also agriculture) and thus generate more runoff. Traditionally, cities have dealt with this problem by engineering storm water sewer systems to drain runoff to downstream water bodies. Unfortunately, this leads to a host of issues at the end of the pipe known as “urban stream syndrome”; symptoms include “flashy” flows that increase flood risk and pollution, which impairs ecology and diminishes the public amenity value of waterways (Bannerman et al., 1993; Booth & Jackson, 1997; Paul & Meyer, 2001; Wang et al., 2001; Walsh et al., 2005). Cities want to and are sometimes legally mandated to address these problems (US EPA, 2005), but conventional end-of-pipe solutions are costly and questionably effective (Burns et al., 2012).

As an alternative, cities increasingly aspire to manage storm water runoff with low-impact practices that are distributed throughout the catchment (also called green infrastructure; see Fletcher et al., 2015 for additional synonyms). These practices locally capture, infiltrate, and/or evapotranspire rain and soil moisture; practices include rain gardens, green roofs, disconnected downspouts, permeable pavement, and soil amendment. The efficacy of these practices has been demonstrated in case studies (Eckart et al., 2017), but adoption rates have remained low. The explanations for this are complex (see, e.g., Keeley et al., 2013; Roy et al., 2008) but are due in part to knowledge gaps in our process-based understanding of urban hydrology, including why outcomes vary under slightly different environmental settings or climates. Advancing our knowledge of urban hydrologic processes may help cities identify how to design regulations, installation practices, and long-term plans to facilitate adoption of the most appropriate practices at the most opportune sites (Fletcher et al., 2013; Miles & Band, 2015).

In response to these policy and management needs, there is strong interest in using process-based models to improve our scientific understanding of where storm water runoff is generated and how it interacts with other urban hydrologic fluxes (Salvadore et al., 2015). Because runoff generation is regulated by processes like saturation-excess or infiltration-excess overland flow, this research necessarily relies on coupled surface-subsurface hydrologic models such as RHESSys, GSSHA, or ParFlow.CLM, which can represent the three-dimensional redistribution of soil water within the subsurface. Due to their computational requirements, these models are not as widely used as empirical models, which may not represent the subsurface at all (e.g., LTHIA-LID) or models that cannot simulate 3-D subsurface hydrology (e.g., SWMM), but process-based modeling studies have yielded practical insights into how complex spatiotemporal drivers affect urban hydrologic processes. These insights include identifying where subsurface hydrology may be more strongly controlled by deteriorating water and wastewater infrastructure than by land surface characteristics (Bhaskar et al., 2015), how transpiration in arid settings can be enhanced by manipulating impervious connectivity (Shields & Tague, 2015), and how runoff reduction can be enhanced by manipulating the spatial arrangement of low-impact practices (Fry & Maxwell, 2017; Lim & Welty, 2017). Pursuit of these catchment-scale science questions is helpful for catchment-scale management objectives, but the corresponding model domain size precludes a detailed representation of subparcel features (e.g., the outlets of individual downspouts) and processes.

1.2. Lateral Water Exchanges Across Impervious-Pervious Interfaces on Residential Parcels

Simplifying subparcel features unfortunately means neglecting a key setting in urban hydrology: the interfaces between impervious and pervious surfaces (Figure 1). In a residential parcel, these interfaces exist at downspout outlets and the edges of driveways, sidewalks, and front walks. Scientifically, they are compelling because they are ecohydrological interfaces in the sense of Krause et al. (2017): zones that develop dynamically in time ("hot moments" driven by precipitation) and space ("hot spots" of infiltration) that control the exchange of water and other fluxes between the two types of land cover. At these interfaces, runoff can be transferred laterally from impervious to pervious areas, potentially creating stronger wetting fronts that move past the root zone before evapotranspiration losses can occur and creating the possibility for localized groundwater recharge. Ecohydrologic interfaces can have a disproportionate effect at larger scales and may present opportunities for effective management interventions. In urban areas, impervious-pervious interfaces at single-family homes are especially attractive storm water intervention targets because single family parcels often comprise most of the land within metropolitan areas (Stone & Bullen, 2006), have unique, identifiable owners, and can be managed through storm water utility credits (Kertesz et al., 2014), incentives (Green et al., 2012), or zoning regulations (Stone & Bullen, 2006). Cities might benefit from encouraging management strategies that target the parcel features that most strongly control hydrology. However, it is not necessarily clear which parcel-scale features are most important for urban runoff generation or subsurface hydrologic processes. The traditional viewpoint is that (connected) impervious surfaces dominate urban hydrology (Brabec et al., 2002; Jacobson, 2011; Shuster et al., 2005), while emerging studies suggest that pervious surfaces can have an equally important role in runoff generation (Lim, 2016). To explore this further, we examine low-impact practices as they fall into one of three groups: impervious-centric, pervious-centric, or holistic.

Impervious-centric low-impact interventions developed from the understanding that runoff from parcels are highest when impervious surfaces (e.g., a roof) drain directly to other impervious surfaces (e.g., a driveway or storm sewers) but can be reduced if flow between impervious surfaces is interrupted. Disruption may entail replacing impervious surfaces (e.g., with a green roof or conversion to a vacant lot), but more frequently involves "disconnecting" them and, for example, routing flow to a pervious yard. This approach stems from studies that show that symptoms of urban stream syndrome are well predicted by directly connected impervious area, sometimes called effective impervious area (Shuster et al., 2005); therefore, reducing directly connected impervious area/effective impervious area can reduce runoff and associated consequences. There is also field (e.g., Stephens et al., 2012), laboratory (Shuster et al., 2008), and model (Reyes et al., 2016; Shields & Tague, 2015) evidence that lateral transfers of water may increase local groundwater recharge and/or

Figure 1. When runoff is allowed to flow from impervious surfaces to pervious surfaces via disconnected downspouts, a disconnected sidewalk, or transverse slopes on front walks and driveways, hot spots of run on and infiltration develop at impervious-pervious interfaces, which may lead to increased groundwater recharge and/or increased evapotranspiration. Pervious characteristics (microtopography, soil texture, and compaction) further control surface runoff and infiltration.

enhance evapotranspiration processes, which are often desired secondary benefits of low-impact practices. While there are many ways to disconnect impervious surfaces, downspout disconnection is billed as one of the most cost-effective ways for cities to reduce runoff (Garrison & Hobbs, 2011). Accordingly, ambitious downspout disconnection programs composed of mandates, incentives, and/or physical or technical project assistance are a hallmark of cities profiled as green infrastructure leaders. For example, Portland, OR claims that city downspout disconnection initiatives have diverted over 1 billion gallons of storm water from combined sewer systems each year—equivalent to about 1.4 inches of water (City of Portland, 2012; Garrison & Hobbs, 2011). Yet because studies of impervious disconnection typically assume that urban pervious surfaces are hydrologically equivalent to natural settings (McGrane, 2016), we lack an understanding of how sensitive the success of impervious surface disconnection is to the actual condition of urban yards.

Pervious-centric low-impact interventions are based on the understanding that urban pervious areas such as residential yards are not as effective as natural landscapes at infiltrating runoff and may substantially contribute to urban runoff. Natural variation in soil type strongly affects how sensitive residential areas are to infiltration practices (Brander et al., 2004), but urban soils are also frequently compacted due to construction activities and foot traffic, which reduces their porosity (ability to store water) and hydraulic conductivity (ability to infiltrate water; Gregory et al., 2006; Pitt et al., 2008). Recent studies (e.g., Lim, 2016) have confirmed the suspicion (Booth & Jackson, 1997) that infiltration-excess runoff generation occurs on urban pervious areas as well as on impervious areas, but it is unknown how the amount of runoff generated by pervious surfaces may compare relative to the runoff generated by impervious surfaces. Another understudied aspect of urban pervious areas is fine-scaled variation in surface elevation, or microtopography, which theoretically and in natural settings is an important control on overland flow paths, infiltration, and recharge (Darboux et al., 2002; Van der Ploeg et al., 2012). The urban land surface tends to be smoothed by time, development, and landscaping practices such as lawn leveling, but it is unclear how much this affects runoff relative to other parcel characteristics. In general, pervious-centric interventions are not as enthusiastically backed by cities as impervious-centric interventions, though some green infrastructure plans do recommend minimizing soil compaction during construction, for example, through a combination of deep tillage, soil amendment, and thicker topsoil layers (Schwartz & Smith, 2016), or by amending soil in targeted areas of residential yards (MMSD, 2013). Such practices increase organic matter content and promote aggregation with benefits for infiltration capacity.

Holistic low-impact interventions simultaneously apply both types of practices described above. This can be as informal as disconnecting downspouts, adding a flow spreader, and allowing diffuse sheet flow to infiltration into amended soil at the outlet but also encompasses bioretention facilities like rain gardens that redirect runoff from roofs or streets to engineered soil with high storage and infiltration capacities. The removal of impervious surfaces from a lot, as is common with vacant lots, could also be considered a holistic practice: It addresses impervious surfaces, and while alternate outcomes are possible (Herrmann et al., 2017), such a lot can mature into an area with high infiltration capacity and good vegetative cover (Shuster et al., 2014). However, removing a residential house on a vacant lot also removes impervious-pervious interfaces, so it may have disparate effects on parcel-scale hydrologic processes.

Holistic interventions or any combination of low-impact interventions can have one of four outcomes on runoff and unsaturated zone fluxes: an additive, synergistic, antagonistic, or undetectable effect (Krause et al., 2017). Which of these outcomes is realized by a given combination of interventions may vary depending on which interventions are combined (e.g., impervious-impervious or impervious-pervious), and the magnitude of the effect may be further moderated by location because climate can also control hydrologic processes. Knowing how combinations of low-impact practices interact to affect hydrologic processes would direct cities toward the best mix of practices for their environmental settings and help ensure that their green infrastructure plans are most effective.

1.3. Research Questions

Given these knowledge and management gaps regarding hydrologic processes at impervious-pervious interfaces, we designed a modeling sensitivity study to assess the relative effects of impervious-centric, pervious-centric, and holistic low-impact interventions at the scale of a single-family residential parcel. We used the surface-subsurface hydrologic model ParFlow.CLM to represent parcel features and processes at a very fine (0.5 m) spatial resolution. We focus on how these subparcel characteristics affect cumulative parcel surface runoff, deep drainage (vertical flux at 1-m depth, below the root zone), and evapotranspiration over the course of a temperate growing season (1 April to 1 November), and we explored:

1. How do individual impervious-centric or pervious-centric low-impact interventions affect parcel hydrologic fluxes?
2. How do combinations of low-impact interventions interact with one another?
3. How does growing season weather moderate the effects of low-impact practices on parcel hydrologic fluxes?
4. How do parcel hydrologic fluxes on lots with impervious-pervious interfaces compare to those on a generic vacant lot?

2. Methods

2.1. Single-Family Residential Parcel

We explored growing season surface-subsurface hydrology on a single-family residential parcel (Figure 2). The basic lot layout we designed includes a house (133.5 m^2) with attached garage (3 m $\times$ 6 m) and driveway (3 m $\times$ 9.5 m) that drain to a centralized storm water collection system. The parcel (825 m^2) also includes a front walk (0.5-m wide) and sidewalk (1.0-m wide). Exact dimensions are based on property assessor data for single-family homes in Madison, WI (City of Madison, 2013; City of Madison Assessor, 2017) and are representative of Midwestern cities that experienced a large expansion of single family homes since the 1950s (see supporting information for additional details). The land surface slopes away from the house on all four sides

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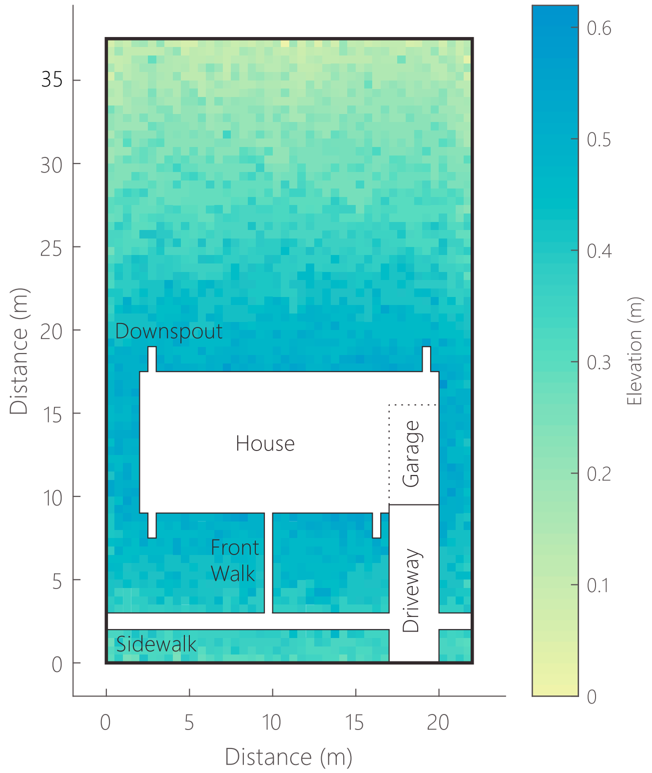

Figure 2. Example lot layout with all five interventions applied and impervious features annotated. The elevation with added microtopography is also shown for the yard.

at a 2% grade. To represent impervious surfaces below the land surface, all paved surfaces (driveway, front walk, and sidewalk) are 10 cm in thick; the garage foundation extends 30 cm in depth, and the house foundation extends 3 m in depth. All pervious areas are covered in turfgrass with a height of 7.5 cm. The resulting lot layout is 25% impervious.

2.2. Low-Impact Intervention Scenarios

We designed three scenarios to simulate *impervious-centric* interventions that reduce the connectivity of impervious surfaces: downspout disconnect, sidewalk disconnect, and the addition of a transverse slope to the driveway and front walk (Figure 3). Downspout disconnection can be done by a homeowner postdevelopment using downspout extenders and flow spreaders available at any hardware store. The other two interventions are best achieved through zoning regulations. The first requires a grass curb strip (2 m) to disconnect the sidewalk from the street. The second is to mandate a transverse slope (2%) on driveways and front walks so that runoff flows laterally to yards. All impervious disconnection is represented in the model through adjustments to site topography (Figure 3).

We designed two scenarios to simulate *pervious-centric* interventions: decompacted soil and introduced microtopography (Figure 3). All pervious areas were modeled with a silt loam soil texture with soil hydraulic parameters altered to represent the degree of compaction. We relied on field and laboratory infiltration tests of compacted soil across a gradient of soil types (Gregory et al., 2006; Pitt et al., 1999, 2008; Schwartz & Smith, 2016) to estimate how urban soil compaction, and the ensuing reduction in soil bulk density affects two key hydraulic parameters: saturated hydraulic conductivity and porosity. To account for the range of variation in these quantitative estimates, we defined one low-impact and two baseline parameterization scenarios: For the low-impact, decompacted soil, we used mean natural silt loam parameters (Carsel & Parrish, 1988); for a "moderately compacted" baseline soil, we reduced hydraulic conductivity by a factor of 2 and porosity by 10%; and for a "highly compacted" baseline soil, we reduced hydraulic conductivity by a factor of 10 and porosity by 10%. While compaction may also decrease the α and n van Genuchten shape parameters (van Genuchten, 1980), we know of no studies that describe observed changes in soil water retention curves due to compaction but rather used mean silt loam van Genuchten shape parameters for all soil scenarios (Carsel & Parrish, 1988). For topography in the baseline scenarios, the yard slopes uniformly away from the house at a 2% incline. A smoothly sloping yard is representative of suggestions in some lawn care guides (e.g., Stier, 2001) but likely shortens runoff pathways. As an alternative, we simulate microtopography by randomly generating normally distributed deviations in elevation and superimposing these microtopographic features on top of the uniform 2% slope at every 0.5 m × 0.5 m pixel. We remove sinks via a pit-filling algorithm (Bhaskar, 2010) because kinematic wave-based overland flow models like ParFlow.CLM cannot drain sinks (Barnes et al., 2016). The resulting standard deviation of elevation relative to the uniform 2% slope, also known as a random roughness index (Onstad, 1984), is 2.8 cm (Figure 2b). While the random roughness index can be converted to equivalent depression storage using empirical relationships (4.8 mm, in this instance), the obligatory pit-filling leads to no actual depressions in this domain. Thus, our study does not evaluate the effects of microtopography on depression storage capacity, but rather on flow paths, which are made longer with the addition of microtopography and therefore offer more opportunity for infiltration.

To explore all possible combinations of the low-impact interventions, we modeled all five scenarios individually and in combinations of 2, 3, 4, and all 5 interventions. In doing so, we also compared the effects of assuming a "highly compacted" versus a "moderately compacted" silt loam soil as the baseline soil condition. To test generalizability across varying weather scenarios, we ran all low-impact combinations under an average temperate growing season and a dry temperate growing season. This resulted in 96 simulations (2 downspout

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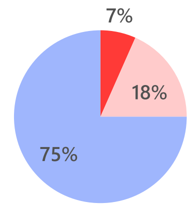
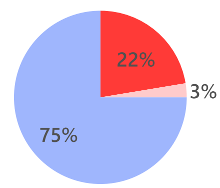
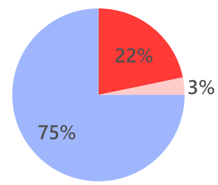
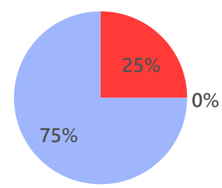
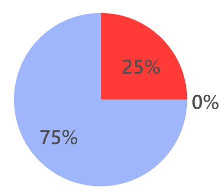
	Intervention	Baseline	Low-Impact	Low-Impact Surfaces Connected Impervious Disconnected Impervious Pervious
Impervious-centric	Disconnected Downspout	Roof is "connected" to the drainage network. Roof runoff is routed to one corner of the house and along an impervious chute (1.5m) off the domain.	Roof is "disconnected" via downspouts. Roof runoff is routed to 4 corners of the house and along impervious chutes (1.5m) to downspout "outlets", i.e. the elements 1.5m away from the corners of the house.	
Impervious-centric	Disconnected Sidewalk	Sidewalk is "connected" to the drainage network. Feature is placed adjacent to where the street would be.	Sidewalk is "disconnected" from the street via a 2m wide grass curb strip.	
Impervious-centric	Transverse Slope on Front Walk and Driveway	Driveway and front walk are "connected" to the drainage network. Both slope toward the street at a 2% incline (as does the rest of the yard).	Driveway and front walk are "disconnected" via a transverse slope. In addition to the original 2% slope toward the street, there is also a 2% slope laterally toward the yard.	
Pervious-centric	Decompacted Soil	Silt loam soil is compacted. Porosity is reduced by 10%. Hydraulic conductivity is reduced by a factor of 10 for a "highly-compacted" baseline and by a factor of 2 for a "moderately-compacted" baseline.	Silt loam soil is decompacted. Assume mean natural hydraulic characteristics (Carsel and Parrish, 1988).	
Pervious-centric	Micro-topography	Yard surface is smooth. All pervious areas uniformly slope away from the house at a 2% incline.	Yard surface is uneven. Deviations from the uniform 2% slope are randomly generated from a normal distribution. After a pit filling algorithm is applied, standard deviation of elevations relative to the 2% slope is 2.8 cm.	

Figure 3. Differences in model realizations of baseline versus low-impact scenario for each explored intervention. Relative percent of connected impervious, disconnected impervious, and pervious surfaces for the low-impact condition also noted.

options × 2 sidewalk options × 2 transverse slope options × 3 soil type options × 2 microtopography options × 2 weather scenarios).

Lastly, to estimate fluxes on a vacant lot where impervious surfaces have been removed, we also simulated a lot with all pervious-centric interventions but no impervious cover. While mixed outcomes have been observed with respect to how pervious infiltration capacity is affected by the removal of structures, fill soils tend to have higher infiltration rates than preexisting soil, especially when preexisting infiltration rates are low (Herrmann et al., 2017). Vacant lots sometimes develop depressions as fill materials settle but are more commonly reported to retain a slope toward the street (Herrmann et al., 2017; Shuster et al., 2014). Therefore, our vacant lot retains the same slopes as the developed lots: 2% slope from the center of the parcel toward the front and rear lot lines. This scenario for both the average and dry growing season required two more simulations.

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Table 1
Surface, Subsurface, and Vegetative Model Parameters

Parameter	Units	Pixel type	Value
Manning's *n*	-	Turfgrass[a]	0.240
		Impervious surfaces[a]	0.012
Saturated hydraulic conductivity, K_s	m/hr	Silt loam soil[b]	4.50×10^{-3}
		Moderately compacted soil[c]	2.25×10^{-3}
		Highly compacted soil[d]	4.50×10^{-4}
		Impervious surfaces[e]	3.60×10^{-9}
Porosity, *n*	-	Silt loam soil[b]	0.45
		Both compacted soils[f]	0.40
		Impervious surfaces[g]	0.01
Saturated moisture content, S_{sat}	-	All	1.00
Residual moisture content, S_{res}	-	Silt loam soil[b]	0.15
		Both compacted soils[h]	0.17
		Impervious surfaces[g]	0.01
Van Genuchten α	m^{-1}	All soil[b]	2.00
		Impervious surfaces[g]	2.00
Van Genuchten *n*	-	All soil[b]	1.41
		Impervious surfaces[g]	3.00
Specific storage, S_s	m^{-1}	All[i]	1.0×10^{-4}
Crop height	m	Turfgrass[j]	0.075
Displacement height	m	Turfgrass[k]	0.050
Aerodynamic roughness length	m	Turfgrass[k]	0.010
Maximum leaf area index	-	Turfgrass[l]	2.0
Minimum leaf area index	-	Turfgrass[l]	0.5
Root fitting parameter a[m]	-	Turfgrass[m]	10.74
Root fitting parameter b[m]	-	Turfgrass[m]	6.608

[a]Mays (2011). [b]Carsel and Parrish (1988). [c]0.5 of silt loam soil value. [d]0.1 of silt loam soil value. [e]Bowders et al. (2003). [f]0.9 of silt loam soil value. [g]Authors' choice to minimize storage within impervious surfaces. [h]Calculated using same residual volumetric water content as silt loam but with compacted soil porosity. [i]Schwartz and Zhang (2003). [j]Stier (2001). [k]Box 4 in Allen et al. (1998). [l]Fontanier (2010). [m]Short grass in Zeng (2001) modified so that >80% of roots are within top 30 cm and >99% of roots are within top 75 cm, per Wu (1985) and Erusha et al. (2002).

2.3. Simulations

2.3.1. ParFlow.CLM

We performed simulations using ParFlow.CLM, a watershed model with fully integrated overland flow that uses the Common Land Model (CLM) to simulate land surface processes. ParFlow uses parallelized computing to solve the three-dimensional, time-dependent, variably saturated flow equation for subsurface water movement (Ashby & Falgout, 1996; Jones & Woodward, 2001). The subsurface is linked to the surface with a continuity of pressure boundary condition, and surface water movement is modeled using the kinematic wave equation (Kollet & Maxwell, 2006). Transpiration fluxes, evaporation, and land surface energy balances are evaluated by CLM (Dai et al., 2003; Kollet & Maxwell, 2008; Maxwell & Miller, 2005). Simulations typically required a computation time of 3–5 days for each growing season simulation.

To develop a representative initial soil moisture profile, we ran a 30-year, 1-D model of turfgrass 10 times (for a total of 300 years) for all three soil conditions until dynamic equilibrium conditions developed. We used the vertical pressure head profile on 1 April of the last simulated year as the initial conditions for parcel simulations. At this time of year, near-surface soil moisture is close to saturation due to snowmelt and the growing season is imminent.

Models are forced with hourly meteorological inputs from the North American Land Data Assimilation System (NASA, 2015) for a temperate location (Madison, Wisconsin; 43.09°N, 89.43°W) with a growing season defined as 1 April to 1 November (Dane County Board of Supervisors, 2017; Hopkins, 2016; National Weather Service, 2012). For the average growing season (see supporting information for additional details), total precipitation (*P*) was 692 mm and the aridity index (ET_o:*P*) was 1.0; a value of 1.0 indicates that the cumulative energy demand equaled available water. For the dry growing season scenario, *P* = 475 mm and ET_o:*P* = 2.1; the energy demand exceeded available water, so this scenario was water-limited. Additional model parameters for surface, subsurface, and vegetative processes are displayed with references in Table 1.

In order to resolve hydrologic processes of interest, particularly lateral flow from individual downspout outlets and vertical root water uptake by turfgrass, the model spatial domain is discretized at a horizontal resolution of 0.5 m and a vertical resolution of 0.1 m. No-flow boundary conditions are applied to all sides of the subsurface. To isolate the drivers of interest in this study (impervious and pervious low-impact interventions) and minimize interactions between a shallow water table and near-surface deep drainage and evapotranspiration (Ferguson & Maxwell, 2010; Lowry & Loheide, 2010; Zipper et al., 2015), we specified a constant pressure head boundary condition of zero (i.e., the groundwater table) at the bottom of the domain, 10 m below the surface. The top of the domain has a kinematic wave overland flow boundary condition, which is triggered whenever the pressure head in the top layer of the domain (i.e., the surface) is greater than zero. Runoff out of the domain is controlled by the topographic slope, also known as a zero depth gradient boundary condition.

2.4. Evaluation of Results

When evaluating model results, we concentrated on the change in growing season surface runoff, deep drainage, and evapotranspiration relative to two different baseline lots: one with a highly compacted soil and one with a moderately compacted soil. The differences in growing season fluxes were calculated as both a depth (all values included in the supporting information) and as a percent of growing season precipitation in order to facilitate comparison across the average and dry scenarios. In addition, we ranked lot layouts based on the magnitude of change in runoff in an average year from smallest to largest. This ordering was similar to the ranking that would emerge by using any other flux in either growing season scenario. We include the entire parcel—both pervious and impervious areas—when calculating growing season fluxes, but to present spatial results of deep drainage and evapotranspiration we mask the (near-zero) results for impervious surfaces to more clearly highlight differences on pervious areas, where fluxes are largest and most dynamic.

3. Results

3.1. Effects of Individual Low-Impact Interventions

We answer our first research question about the effects of individual interventions on parcel hydrology by examining the lot layout scenarios with a single low-impact intervention (layouts #2, #4, #6, #10, and #18 in Figure 4).

When compared to a highly compacted baseline (Figure 4), the individual intervention most effective at reducing runoff is decompacting the soil (layout #18). Relative to this pervious-centric intervention, the effect of impervious-centric interventions are small; the magnitude of change induced by decompacting the soil (layout #18) is 3.5× greater than the change affected by all three impervious-centric interventions combined (layout #16). The two modest impervious disconnection scenarios—adding a transverse slope to the driveway and front walk (layout #4) and disconnecting the sidewalk (layout #6)—disconnect about 10% of impervious surfaces but reduce the percent of precipitation, leaving the parcel as runoff by no more than 1%. The most dramatic impervious-centric intervention—allowing downspouts to spill to the yard (layout #10)—disconnects about 75% of impervious surfaces, but the reduction in runoff as a percent of precipitation is still only 1%–2%. By contrast, decompacting the soil (layout #18) reduces runoff by 4% (dry weather) to 7% (average weather), even though all impervious surfaces are still directly connected to the drainage network. The other pervious-centric intervention, adding microtopography (layout #2), leads to a much smaller increase in runoff.

The relative effectiveness of low-impact interventions is reordered under a moderately compacted baseline scenario (Figure 4) where impervious-centric interventions are most effective. Again, the pervious-centric microtopography intervention (layout #2) leads to a very small increase in runoff; longer flow paths do not perceptibly reduce runoff in these simulations. More strikingly, decompacting the soil (layout #18) no longer has a meaningful effect on parcel fluxes; instead, this intervention reduces the percent of precipitation leaving the parcel as runoff by at most 1%. The two more minor adjustments to impervious connectivity—adding a transverse slope to the driveway and front walk (layout #4) and disconnecting the sidewalk (layout #6)—reduce runoff 2 to 4 times as much as under highly compacted conditions, although this still only amounts to 1% to 2% of precipitation. The greatest change from a single intervention occurs when downspouts are disconnected (layout #10), which reduces runoff by 5% as a percent of precipitation, or 3 to 5 times the change observed under highly compacted conditions.

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Highly-compacted Baseline

Lot Layout						Average Year			Dry Year		
Number	Disconnected Downspout	Disconnected Sidewalk	Transverse Slope	Decompacted Silt Loam	Micro-topography	Surface Runoff	Deep Drainage	Evapo-transpiration	Surface Runoff	Deep Drainage	Evapo-transpiration
1						0%	0%	0%	0%	0%	0%
2					✓	0%	0%	0%	0%	0%	0%
3			✓		✓	0%	0%	0%	0%	0%	0%
4			✓			0%	0%	0%	0%	0%	0%
5		✓			✓	0%	0%	0%	-1%	0%	1%
6		✓				-1%	0%	0%	-1%	0%	1%
7		✓	✓		✓	-1%	0%	0%	-1%	0%	1%
8		✓	✓			-1%	0%	0%	-1%	0%	1%
9	✓				✓	-1%	1%	0%	-2%	0%	1%
10	✓					-1%	1%	0%	-2%	0%	1%
11	✓		✓			-1%	1%	0%	-2%	0%	1%
12	✓		✓		✓	-1%	1%	0%	-2%	0%	1%
13	✓	✓			✓	-1%	1%	0%	-2%	0%	2%
14	✓	✓				-2%	1%	0%	-3%	0%	2%
15	✓	✓	✓		✓	-2%	1%	0%	-3%	0%	2%
16	✓	✓	✓			-2%	1%	0%	-3%	0%	2%
17				✓	✓	-7%	8%	-1%	-4%	1%	2%
18				✓		-7%	8%	-1%	-4%	1%	2%
19			✓	✓		-8%	9%	-1%	-5%	2%	3%
20			✓	✓	✓	-8%	10%	-1%	-6%	2%	3%
21		✓		✓	✓	-9%	10%	0%	-6%	2%	3%
22		✓		✓		-9%	10%	0%	-6%	2%	3%
23		✓	✓	✓		-10%	11%	0%	-7%	3%	3%
24		✓	✓	✓	✓	-10%	11%	0%	-8%	3%	3%
25	✓			✓		-15%	15%	0%	-12%	5%	5%
26	✓			✓	✓	-15%	16%	0%	-12%	5%	4%
27	✓		✓	✓		-16%	17%	0%	-13%	5%	5%
28	✓	✓		✓	✓	-17%	17%	0%	-13%	6%	5%
29	✓	✓		✓		-17%	17%	0%	-14%	6%	5%
30	✓		✓	✓	✓	-17%	17%	0%	-13%	6%	5%
31	✓	✓	✓	✓		-18%	18%	0%	-15%	6%	5%
32	✓	✓	✓	✓	✓	-18%	18%	0%	-15%	7%	5%

Moderately-compacted Baseline

Lot Layout						Average Year			Dry Year		
Number	Disconnected Downspout	Disconnected Sidewalk	Transverse Slope	Decompacted Silt Loam	Micro-topography	Surface Runoff	Deep Drainage	Evapo-transpiration	Surface Runoff	Deep Drainage	Evapo-transpiration
1						0%	0%	0%	0%	0%	0%
2					✓	0%	0%	0%	0%	0%	0%
17				✓	✓	-1%	1%	0%	0%	0%	2%
18				✓		-1%	1%	0%	0%	0%	2%
4			✓			-1%	1%	0%	-1%	0%	0%
3			✓		✓	-1%	1%	0%	-1%	0%	0%
5		✓			✓	-2%	1%	0%	-2%	1%	1%
6		✓				-2%	1%	0%	-2%	1%	1%
19			✓	✓		-2%	2%	0%	-2%	1%	2%
20			✓	✓	✓	-2%	2%	0%	-2%	1%	2%
8		✓	✓			-3%	2%	0%	-3%	1%	1%
7		✓	✓		✓	-3%	2%	0%	-3%	1%	1%
21		✓		✓	✓	-3%	2%	1%	-2%	1%	3%
22		✓		✓		-3%	2%	1%	-2%	1%	3%
23		✓	✓	✓		-4%	4%	1%	-3%	2%	3%
24		✓	✓	✓	✓	-4%	4%	1%	-4%	2%	3%
10	✓					-5%	5%	0%	-5%	2%	2%
9	✓				✓	-5%	5%	0%	-5%	2%	2%
11	✓		✓			-6%	6%	0%	-6%	2%	2%
13	✓	✓			✓	-6%	6%	0%	-6%	3%	2%
12	✓		✓		✓	-7%	6%	0%	-6%	3%	2%
14	✓	✓				-7%	6%	0%	-7%	3%	3%
15	✓	✓	✓		✓	-8%	7%	0%	-7%	3%	3%
16	✓	✓	✓			-8%	7%	0%	-8%	3%	3%
25	✓			✓		-9%	8%	1%	-8%	4%	4%
26	✓			✓	✓	-9%	9%	1%	-8%	5%	4%
27	✓		✓	✓		-10%	9%	1%	-9%	4%	5%
28	✓	✓		✓	✓	-10%	10%	1%	-9%	5%	4%
29	✓	✓		✓		-11%	10%	1%	-10%	5%	5%
30	✓		✓	✓	✓	-11%	10%	1%	-10%	5%	4%
31	✓	✓	✓	✓		-12%	11%	1%	-11%	5%	5%
32	✓	✓	✓	✓	✓	-12%	11%	1%	-11%	6%	5%

Figure 4. Change in runoff, deep drainage, and evapotranspiration relative to the (left) highly compacted baseline lot and the (right) moderately compacted baseline lot as a percent of precipitation. The black icons indicate which low-impact characteristics are included in a given (numbered) layout. Layouts are ordered from (top) smallest change in runoff in an average year to (bottom) largest change, with shading further indicating the magnitude and direction of change. The pattern emerging from the most effective and second most effective interventions under each baseline condition are highlighted in yellow.

3.2. Effects of Combining Low-Impact Interventions

We address our second research question about how individual interventions interact with one another by looking closely at all possible pairs of features (Figure 5).

When similar interventions are adopted in pairs (e.g., impervious-impervious), the effects on parcel fluxes are typically additive (Figure 5). One exception is with microtopography; just as the individual intervention has the smallest impact on parcel fluxes, any microtopography pair exhibits limited interactions. However, with

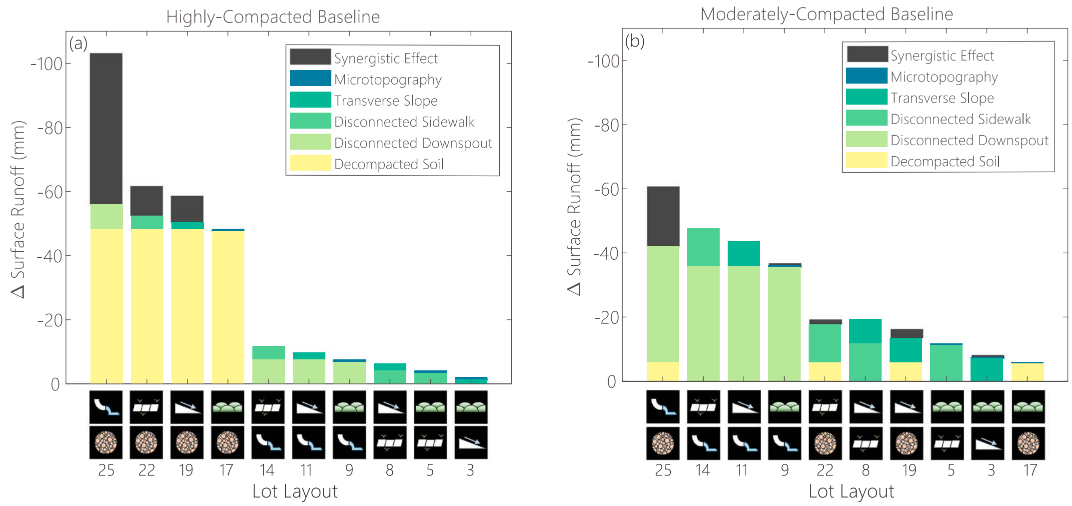

Figure 5. Change in growing season surface runoff (mm) relative to a (a) highly compacted baseline and a (b) moderately compacted baseline for each possible pair of interventions (denoted by icons along the *x* axis; numbers correspond to lot layout number in Figure 4). The sum of what is observed in individual interventions is the predicted additive result of combining interventions. Where the actual observation is higher than the additive results, the additional "synergistic" effect is highlighted in gray.

impervious-impervious pairs, it is possible to predict how combining interventions affects runoff by summing the reductions observed from changing each feature one at a time. For example, under average weather on a highly compacted parcel, the sum of disconnecting the sidewalk (4.2 mm) plus disconnecting downspouts (7.7 mm) is 11.9 mm, nearly identical to the actual observed change of 11.7 mm from doing both simultaneously. This is true of other impervious-impervious pairs as well; the nonadditive effects shown in gray in Figure 6 are imperceptibly small or nonexistent for all impervious-impervious pairs.

By contrast, holistic impervious-pervious interventions demonstrate synergistic behavior (Figure 5). If the individual reductions in runoff from disconnected downspouts and decompacted soil are added together, the sum represents as little as half of the actual effect observed when both interventions are made simultaneously. Importantly, these synergistic effects are not limited to the highly compacted scenarios (Figure 5a) but are also present when a lower level of compaction is assumed (Figure 5b).

3.3. Changes in Intervention Effectiveness With Growing Season

We explore our third research question about the impact of growing season weather by focusing on results from the lowest-impact lot layout (layout #32 in Figure 4; also shown in Figure 6) because it is representative of weather-dependent patterns observed across all lot layouts.

The growing season weather has a minor effect on how low-impact interventions reduce runoff. As a depth, the reduction in runoff due to low-impact interventions is consistently smaller under dry conditions (P = 475 mm) than under average conditions (P = 692 mm; Figure 6). But as a percent of precipitation, the change is similar in any given layout. For example, the lowest-impact intervention reduces runoff by 15% (dry) versus 18% (average) under a highly compacted baseline and 11% (dry) versus 12% (average) under a moderately compacted baseline (Figure 4).

By contrast, growing season weather dramatically alters how root zone water is partitioned between deep drainage and evapotranspiration. Under average conditions, when energy demand is met by water availability (ET_o:P = 1.0), virtually all reductions in runoff are translated directly to increases in deep drainage. Even when runoff is reduced by as much as 18% as a percent of precipitation, evapotranspiration changes by no more than 1%. We see this visually through the shading in Figure 4: Under average years, change in evapotranspiration remains near zero (white) across all lot layouts, even as the magnitude of change increases for runoff (deeper red) and deep drainage (deeper blue). However, under dry, water-limited conditions (ET_o:P = 2.1), increases to root zone fluxes are shared almost evenly between deep drainage and

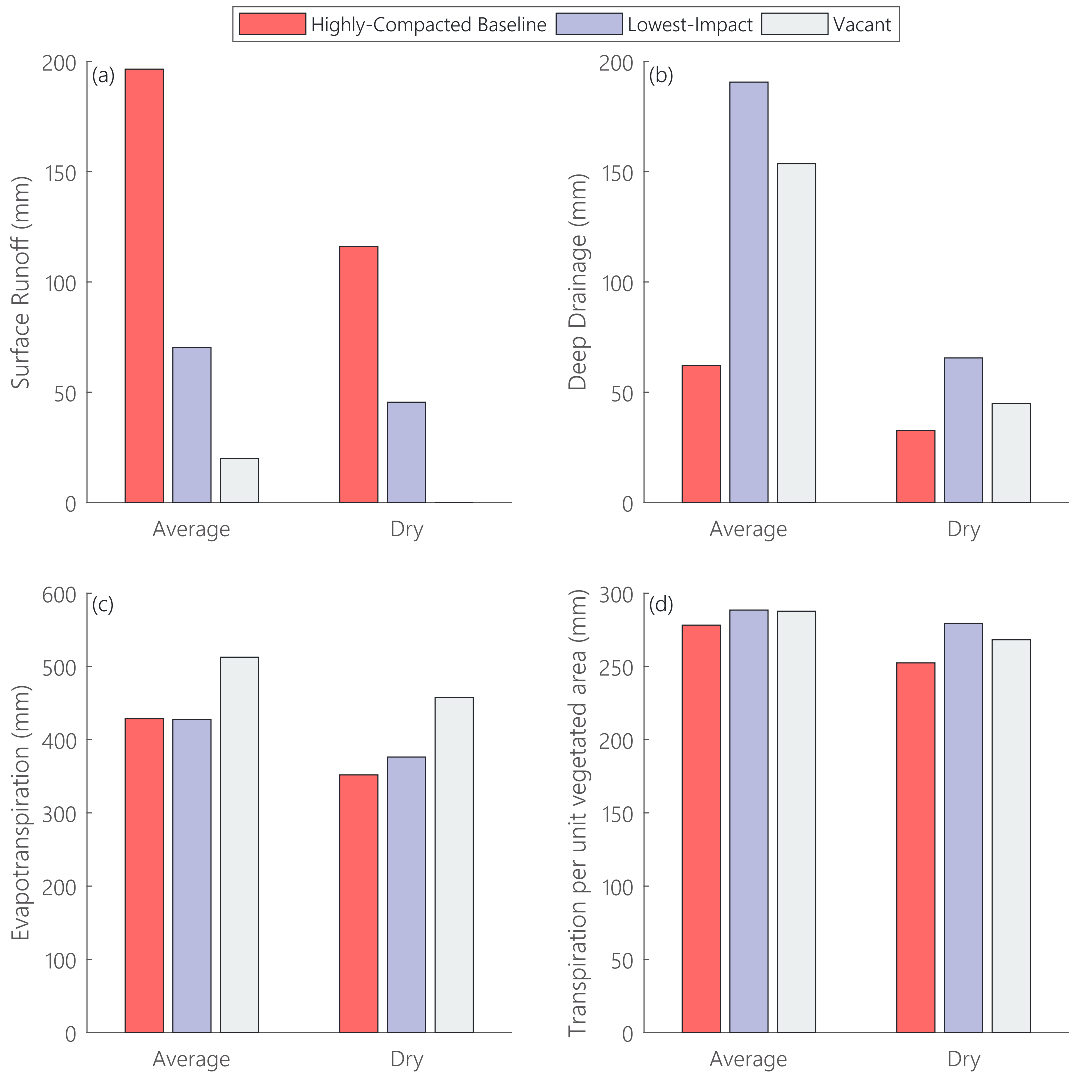

Figure 6. (a) Growing season runoff, (b) deep drainage, (c) evapotranspiration, and (d) transpiration per unit vegetated area for a baseline (highly compacted), lowest-impact (Figure 4, layout #32), and vacant lot with no impervious surfaces under average and dry weather conditions.

evapotranspiration; the shades of blue are muted compared to average deep drainage, but the same across dry deep drainage and dry evapotranspiration.

Additionally, "hot spots" of deep drainage and evapotranspiration at impervious-pervious interfaces develop differently under average versus dry growing season conditions (Figure 7). Under average conditions deep drainage is highly concentrated at impervious-pervious interfaces (Figure 7a), while the evapotranspiration shows little spatial variation (Figure 7c). Under dry conditions, deep drainage is still several hundred millimeters higher at impervious-pervious interfaces than elsewhere in the yard (Figure 7b), but this is more muted than under average conditions. Additionally, evapotranspiration hot spots are more pronounced (Figure 7d).

3.4. Comparison of Holistic Interventions Versus a Vacant Lot

We answer our final research question by comparing parcel hydrologic fluxes from the highly compacted baseline and the lowest-impact lots to those from a vacant lot without impervious surfaces (Figure 6).

In terms of surface runoff, the lowest-impact lot is substantially lower than the baseline lot, but the vacant lot is lower yet (Figure 6a). If growing season runoff is compared to the baseline lot (197 mm) under average

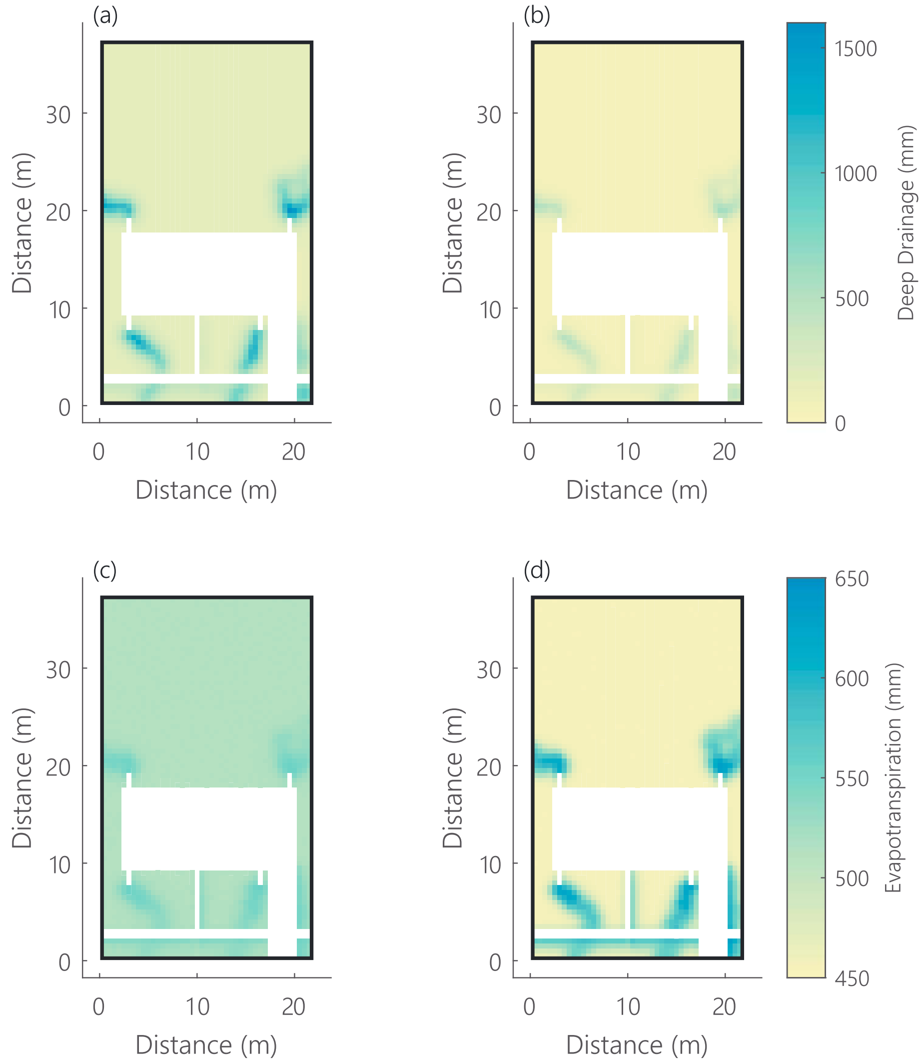

Figure 7. (a and b) Cumulative depth of deep drainage and (c and d) evapotranspiration for the lowest-impact lot layout (Figure 4, layout #32) under average (a and c) and dry (b and d) weather years for the highly compacted baseline scenario.

weather conditions, the lowest-impact lot (70 mm) generates about one third of that runoff, while the vacant lot (20 mm) generates only one tenth. Under dry conditions, runoff from the lowest impact lot (45 mm) is similarly about one third that from the baseline lot (116 mm), but there is no runoff from the vacant lot (0 mm).

The lowest-impact lot exhibits higher growing season deep drainage than either the baseline lot or the vacant lot (Figure 6b). Under average conditions, deep drainage on the lowest-impact lot (191 mm) is not only over 3× that on the baseline lot (62 mm) but also 24% higher than on the vacant lot (154 mm). Similarly, under dry conditions, deep drainage on the lowest-impact lot (66 mm) is both 2× that on the baseline lot (33 mm) as well as 36% higher than on the vacant lot (45 mm).

Evapotranspiration is consistently higher on a vacant lot than on either developed lot on which 25% of the vegetated area has been replaced with impervious area (Figure 6c). Under average conditions, evapotranspiration on the developed lots is nearly identical (428-mm lowest-impact versus 429-mm baseline), while evapotranspiration on the vacant lot is 20% higher (513 mm). Under dry conditions, evapotranspiration is notably higher on the lowest-impact lot than on the baseline lot (376-mm lowest-impact versus 352-mm baseline), but evapotranspiration on the vacant lot (458 mm) is higher yet.

On a transpiration per unit vegetated area basis, the lowest-impact lot is slightly higher than the vacant lot, but only under dry conditions (Figure 6d). All three lots exhibit similar transpiration per unit vegetated area under average conditions (around 285 mm). The slightly lower transpiration per unit area in the baseline lot is driven by the compacted soil conditions; soil water potential is slightly lower throughout the growing season, so in dry times, the water stress function reduces transpiration by a greater amount. But in the dry growing season, transpiration per unit vegetated area on the lowest-impact lot (279 mm) is both 11% higher than on the baseline lot (252 mm) and 4% higher than on the vacant lot (268 mm).

4. Discussion

4.1. Implications for Urban Hydrologic Processes

4.1.1. Urban Runoff Generation

Our comparison of individual impervious-centric versus pervious-centric interventions demonstrates that residential yards can be large sources of infiltration-excess overland flow—so much so, that disconnecting impervious surfaces to a highly compacted yard might have virtually no effect on total parcel runoff under some conditions. The degree to which residential yards exhibit this extreme behavior is dependent on where a parcel falls along a spectrum of soil compaction as well as soil texture. Yards with coarsely textured soil (e.g., a sandy soil or NRCS Group A soil) are more likely to be sensitive to impervious-centric interventions (Brander et al., 2004), even if those soils are compacted. In addition, the extent to which compaction modifies soil hydraulic characteristics in a yard is likely to be more nuanced than the uniform highly compacted and moderately compacted scenarios we explored, and compaction would have additional effects on the shape of the soil water retention curve that we did not include due to lack of observational data. That said, in our study based on a silt loam soil texture, the impervious-centric interventions did change parcel hydrologic fluxes more than decompacting soil for a moderately compacted lot but led to smaller changes in parcel fluxes on a highly compacted lot. Others have speculated (Booth & Jackson, 1997) or observed (Lim, 2016) that infiltration-excess overland flow is prevalent on developed pervious areas, but the implications have typically been that impervious-centric interventions can only do so much; therefore, pervious-centric interventions are needed to achieve greater reductions in runoff. We find that in developed areas like the lot modeled in our study, impervious-centric interventions may do little to reduce runoff unless pervious-centric interventions are also applied.

Even when pervious areas are not major sources of runoff on their own, holistic interventions have an outsized, synergistic effect on parcel fluxes due to hydrologic interactions at impervious-pervious interfaces. By synergistic, we mean that disconnecting impervious surfaces and simultaneously decompacting soil changes parcel fluxes more—up to 2× more—than would be expected from summing the effects of individual interventions (Figure 5). We conclude that these synergies occur at impervious-pervious interfaces within the parcel for two reasons. First, when cumulative deep drainage and evapotranspiration are mapped spatially, there are clear hot spots at the impervious-pervious interfaces (Figure 7), as is suggested by the ecohydrologic interfaces theory proposed by Krause et al. (2017). Second, removing impervious surfaces—and with them, the impervious-pervious interfaces—on a vacant lot results in less deep drainage than leaving impervious surfaces in place, but disconnected (Figure 6). Accordingly, low-impact practices must address the impervious-pervious interface holistically in order to most effectively reduce surface runoff and increase subsurface hydrologic fluxes.

Because these within-parcel feedbacks are important to parcel-scale fluxes, they likely also have implications for urban runoff generation at larger, catchment scales. One concept about urban runoff generation is urban variable source area, which suggests that urban runoff has two main sources: infiltration-excess overland flow generated at impervious or low permeability surfaces throughout the catchment and saturation-excess overland flow generated primarily at topographic lows where flow accumulates, antecedent soil moisture conditions are wetter, and the water table may be closer to the surface (Miles & Band, 2015). An implication of urban variable source area is that the topographic position of low-impact practices should control the degree to which impervious disconnection reduces runoff and increases recharge or evapotranspiration (Endreny & Collins, 2009; Lim & Welty, 2017). Our study identifies additional feedbacks within parcels (at impervious-pervious interfaces) that are independent of larger patterns in topography or groundwater saturation but that also describe how urban runoff generation occurs and may suggest opportunities for management.

4.1.2. Urban Subsurface Hydrology

Our results substantiate the idea that localized increases in infiltration at impervious-pervious interfaces may increase localized groundwater recharge and be a significant contributor to total urban recharge (Lerner, 2002). Others have demonstrated that recharge can increase due to lateral transfers of runoff from a collection of residential parcels to focused infiltration basins (e.g., Bhaskar et al., 2016; Göbel et al., 2004) or due to leaks in water and wastewater infrastructure (Bhaskar et al., 2015), but our study is novel in its focus on how these lateral transfers play out within single-family residential parcels. We find that even short, local transfers of runoff to a sufficiently pervious residential yard can promote development of stronger, deeper penetrating wetting fronts that escape the influence of the root zone and thereby increase larger-scale deep drainage.

While low-impact interventions are the primary driver of increases in root zone hydrologic fluxes, the way in which this increase is partitioned to deep drainage versus evapotranspiration is also affected by climatic conditions. All increases in infiltration are translated to deep drainage in the average growing season when there is sufficient water to meet energy demands (ET_o:P = 1.0), but they are evenly split between deep drainage and evapotranspiration in the drier, water-limited scenario (ET_o:P = 2.1). The total parcel increase in evapotranspiration in the dry scenario is not enough to compensate for the loss of vegetated area to impervious surfaces, but it does increase transpiration per unit vegetated area relative to a vacant lot with no impervious surfaces (Figure 6). This behavior in a relatively dry, temperate setting is similar to findings from other process-based modeling studies of impervious disconnection in semiarid locations (Reyes et al., 2016; Shields & Tague, 2015). In particular, Shields and Tague (2015) found that transpiration per unit vegetated area increases with increasing impervious area, provided 25% or more of the impervious surfaces are disconnected. The similarities between our results and other studies indicate that further improving our understanding of how climate forcing affects the outcomes of low-impact interventions may help us extrapolate the relevance of case-studies to new locations.

4.2. Implications for Urban Hydrologic Modeling

We recognize that currently, the computational power required for our study is not widely available and it is not practical to adopt the same level of resolution for catchment-scale process-based models. However, because impervious-pervious interfaces are important to urban hydrologic processes, it is important to improve their representation in urban hydrologic models. Fortunately, our ability to identify where impervious-pervious interfaces exist and incorporate them in models is helped by the increasing availability of high-resolution remotely-sensed land cover data (Weng, 2012) and the trend toward spatially explicit urban hydrologic models (Salvadore et al., 2015). Although submeter resolution is not feasible for many urban hydrologic models, at coarser resolutions it is still possible to identify which model pixels contain impervious-pervious interfaces and in which direction water flows across these interfaces.

Understanding what type of impervious-pervious interfaces exist within a model grid cell could also improve the parameterization of coarser resolution models. Instead of relying on the weighted average soil hydraulic parameters of land cover types within a grid cell (e.g., Bhaskar et al., 2015; Lim & Welty, 2017) modelers could explore nonlinear algorithms that account for the synergistic effects of pervious yard characteristics and impervious disconnection on hydrologic processes at impervious-pervious interfaces. At a minimum, modelers should be wary of defaulting to natural soil hydraulic parameters when representing urban pervious areas (McGrane, 2016); our study indicates erroneous parameterization can shift how growing season precipitation is partitioned to parcel fluxes by as much as 15% (compare lots #16 and #31, Figure 4).

4.3. Implications for Urban Hydrologic Policy and Management

The most important message for cities is impervious-pervious interfaces within residential parcels can substantially influence larger-scale hydrology; selectively managing these interfaces through mandates or zoning regulations could increase groundwater recharge even more than vacating a developed residential parcel. Manipulating these interactions at some parcels within a city could perhaps compensate for other areas where infiltration remains reduced due to development, soil condition, or position within the watershed. Reducing runoff by increasing deep drainage is often viewed as a two-in-one beneficial change, but this may not be true for all locations within every city. Potential negative effects include increased infiltration and inflow to already burdened water and wastewater pipes (Endreny & Collins, 2009), basement flooding, or increased transport of contaminants to groundwater (Andres et al., 2018). Regardless of whether increasing recharge is desired or not, impervious-pervious interfaces are critical control points and manipulating this environmental setting can have outsized effects on urban hydrologic fluxes.

In practical terms, cities can take advantage of these interfaces by expanding already-popular impervious disconnection programs while adding new incentives to address soil compaction for new development during or after construction. Downspout disconnection programs like those promoted by cities leading in green infrastructure adoption (Garrison & Hobbs, 2011) could be augmented with zoning regulations that require disconnecting sidewalks and redirecting flow from other impervious surfaces; disconnecting additional impervious surfaces had additive effects on the low-density single-family parcel we explored. To address soil compaction and the associated changes in soil hydraulic properties, cities can promote practices like decompacting soil with deep tillage, amending soil with compost, and applying thicker layers of coarser textured, highly permeable soils (Schwartz & Smith, 2016), which can minimize the effects of compaction during construction. Postconstruction, installing a French drain or amending soil with compost (Cogger, 2005) could also enhance the effectiveness of impervious disconnection. Because our study indicates that impervious-pervious interfaces are particularly sensitive locations for soil amendment, cities can target small areas for postconstruction soil amendment instead of setting a costly and daunting goal of altering soil hydraulic properties throughout the city. Another way to combine both types of low-impact interventions is through rain gardens, which by design route downspouts to depressions with amended soil that is engineered for higher infiltration.

In order to identify regions that would benefit most from soil amendment, cities should also consider allocating resources to collecting and sharing information about local soil hydraulic properties. Assembling a complete record of city-wide soil hydraulic characteristics can be a formidable task for many reasons. For one, there is very little extant information about urban soils; most soil maps (e.g., Soil Survey Geographic Database) do not have postdevelopment soil information. Urban soils are also extremely heterogeneous; there can be as much variation in soil hydraulic characteristics within a parcel as there is among parcels (Ziter & Turner, 2018). In addition, most urban land is private property; obtaining permission to measure soil properties across many properties can be logistically challenging. However, it is possible to measure field infiltration capacity reasonably quickly (<1 hr) using techniques like a mini disk infiltrometer (e.g., Shuster et al., 2014), and some cities may also gather soil information incidentally as part of routine construction or maintenance projects. Given the importance of pervious hydraulic characteristics to hydrologic processes at impervious-pervious interfaces, even rudimentary databases on urban soil characteristics would represent progress toward identifying the optimal locations within a city for low-impact interventions.

5. Conclusion

Within single-family residential parcels, impervious-pervious interfaces are key controls on urban hydrologic processes. Our study shows that holistically adopting both (1) *impervious-centric* low-impact practices that disconnect impervious surfaces and allow run on to pervious areas and (2) *pervious-centric* low-impact practices, especially decompacting soil, has a synergistic (i.e., greater than additive) effect on reducing growing season runoff and increasing deep drainage and evapotranspiration from a single-family residential parcel. These subparcel features are rarely captured in urban hydrologic models but have the potential to substantially alter the urban hydrologic water balance; our results show that combining all five low-impact practices explored here (disconnected downspouts, disconnected sidewalk, transverse slope added to driveway and front walk, decompacted soil, and added microtopography) increases deep drainage relative to a highly compacted baseline lot even more than conversion to a vacant lot with no impervious surfaces. We suggest that cities can advance their urban hydrologic management goals through incentives and policies that holistically address impervious-pervious interfaces, but predicting outcomes for subsurface fluxes may require explicit consideration of climate.

Acknowledgments
This project was funded by the University of Wisconsin Sea Grant Institute (2016–2018 R/RCE05), Wisconsin Water Resources Institute (WR12R002), and the National Science Foundation Northern Temperate Lakes Long-Term Ecological Research (DEB 1440297). This research was performed using the computational resources and assistance of the UW-Madison Center for High Throughput Computing (CHTC) in the Department of Computer Sciences. The CHTC is supported by UW-Madison, the Advanced Computing Initiative, the Wisconsin Alumni Research Foundation, the Wisconsin Institutes for Discovery, and the National Science Foundation and is an active member of the Open Science Grid, Thanks to Reed Maxwell for making the ParFlow model available and for advice about modifying solver settings to reduce computational time, as well as the ParFlow users group for additional support. Model input data to replicate results is included in tables and references in this paper; input data, processing scripts, and summary output data are also posted publicly on github (https://github.com/cvoter/low_impact_lot_practices). Full simulation results are also freely available from the authors.

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