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Urban Ecohydrology: Resolving Sub-Grid Lateral Water and Energy Transfers in a Land Surface Model

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Key Points:
- We develop an urban land surface model representation of impervious to pervious runon and canopy overhanging impervious surfaces
- Using idealized land use distributions, we systematically examine the effects of lateral transfers on water and energy over warm seasons
- We found large differences in runoff generation, water balances, and energy partitioning between standard and lateral transfer simulations

Abstract
Although urbanization fundamentally alters water and energy cycles, contemporary land surface models (LSMs) often do not include key urban vegetation processes that serve to transfer water and energy laterally across heterogeneous urban land types. Urban water transfers occur when rainfall landing on rooftops, sidewalks, and driveways are redirected to lawns or pervious pavement and energy/water transfers occur when transpiration occurs from branches overhanging impervious surfaces with the corresponding root water uptake occurring in nearby portions of the yard. We introduce Noah-MP for Heterogenous Urban Environments (Noah-MP HUE), which adds sub-grid water transfers to the widely used Noah-MP LSM. We examine how sub-grid water transfers change surface water and energy balances by systematically increasing the amount of water transfer during simulations for four scenarios: tree canopy expanding over pavement (Urban Tree Expansion), tree canopy shifting over pavement (Urban Tree Shift), directing impermeable runoff onto surrounding vegetation (Downspout Disconnection) or into an engineered pavement (Permeable Pavement). Even small percentages of a sub-grid water transfer can reduce runoff and enhance evapotranspiration and deep drainage. Runoff reduction depends on storm depth, rainfall intensity, and antecedent soil moisture. Sub-grid water transfers also tend to enhance (reduce) latent (sensible) heat. Results highlight the importance not only of fine-scale heterogeneity on larger scale surface processes, but also the importance of urban management practices that enhance sub-grid water transfers and water storage—so-called green infrastructure—as they may change atmospheric processes. This work opens a pathway to directly integrate these urban practices in regional climate simulations.
1 Introduction

Urbanization creates heterogenous patchworks of green spaces (e.g., yards, parks, street terraces) and engineered features central to modern life (e.g., roadways, sidewalks, buildings). Within this patchwork, green spaces differ fundamentally from engineered impervious surfaces in terms of their response to and influence on regional climate. Rain falling on vegetated surfaces typically infiltrates into underlying soils, where a portion of this water is then returned to the atmosphere via evapotranspiration (ET). Because converting water from liquid to vapor form (i.e., ET) requires energy, this process creates a “sink” for incoming solar radiation that cools the surrounding environment and the overlying atmosphere. Impervious surfaces, in contrast, impede infiltration—often totally—while converting incoming radiation into sensible heat flux that generates temperature increases. Increased runoff from impervious surfaces creates “flashy” flows that can enhance floods and impair downstream ecosystems (Hollis, 1975; Leopold, 1968; Walsh et al., 2005; Wright et al., 2012, amongst many others). Elevated sensible heat can cause Urban Heat Islands (UHI), whereby ambient temperatures in urban areas are higher than those of the surrounding region, especially during calm nighttime conditions (Oke et al., 2017). These impacts are often greatest in neighborhoods that have historically experienced practices like redlining and which remain socially and economically vulnerable today (Hoffman et al., 2020; Wilson, 2020).

Land surface models (LSMs) are one of the tools available to estimate current and future water and heat impacts in urban and other land areas. LSMs take atmospheric inputs such as precipitation, air temperature, and wind speed, and simulate their effects on terrestrial water, energy, and carbon cycles (Fisher & Koven, 2020). LSMs are also critical components of the modern earth system models used in numerical weather prediction and to quantify the impacts of climate change, as feedbacks between the land surface and atmosphere can impact precipitation patterns (Barlage et al., 2021; Koster et al., 2004; Wakefield et al., 2021; Welty et al., 2020, amongst many others), near surface meteorology (Alexander et al., 2022; Berg et al., 2014; Sun et al., 2017) and hydrometeorological extremes (Lorenz et al., 2016; Miralles et al., 2019; Vogel et al., 2017). Disparity of scale is an important challenge for LSMs in earth systems models, especially when simulating built environments. Land-surface processes vary on scales of 0.1 m–1 km, but current numerical weather prediction and earth system models resolve processes on the order of 1 – 100 km, thus requiring substantial parametrization of sub-grid processes (Fisher & Koven, 2020; Sharma et al., 2021).

Due to the relatively coarse scales at which they are typically used, LSMs often ignore urban landscape heterogeneity. For example, the widely used Weather Research and Forecasting (WRF) model often employs a single layer “urban canyon model”. This parameterization assumes all urban area to be impervious, exclusively partitioning rainfall to runoff or evaporation from ponded water (Chen et al., 2011; Yang et al., 2015). Vegetation in the case of the urban canyon model is either a green roof parametrization identical to the grassland land cover simulated by the Unified Noah LSM or is an averaging of outputs from X% urban and 100-X% of grassland run through the same LSM (Chen et al., 2011). These averaging methodologies can improve model skill (e.g. Vahmani & Hogue, 2015), spurring the inclusion of more grid fractions to further increase accuracy of simulated thermal resistances and aerodynamic roughness values in the Noah Multi-Physics (Noah-MP) and Unified Noah LSMs (Chen & Zonato, 2021; Mu et al., 2020; Ribeiro et al., 2021). Current methodologies fail to explicitly depict ubiquitous urban features like tree
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canopies overhanging roads or downspout drainage from roofs onto surrounding vegetation.
Furthermore, they are unable to represent low-impact development and green infrastructure, which
are increasingly used to manage urban hydrology and reduce UHIs (Avellaneda et al., 2017;
Marando et al., 2022; Schwaab et al., 2021).

A potentially important omission from existing urban conceptual representation within LSMs
are the lateral water and energy transfers among adjacent or overlapping land types and vegetation
features. For example, urban tree canopies often overhang streets, intercepting some rainfall that
would otherwise become runoff (Selbig et al., 2022). This intercepted water can evaporate, cooling
temperatures (Schwaab et al., 2021; Ziter et al., 2019) and modifying energy balances (Meili et
al., 2021; Ryu et al., 2016; Zipper et al., 2017). Lateral transfers of water can also result from
human interventions that move rainfall from impermeable surfaces to permeable surfaces. ‘Run-
on’ to an engineered permeable pavement is one such example. Such lateral transfers—below the
grid scale of regional and earth systems models—can generate meaningful changes to surface runoff
and urban hydrologic balances at the scale of single family homes (Voter & Loheide, 2018), city
blocks (Avellaneda et al., 2017; Wang et al., 2022) and entire cities (Arjenaki et al., 2021).

In this paper, we present modifications to a commonly-used LSM to explicitly represent sub-
grid lateral water and energy transfers—particularly those related to vegetation—within urban
environments. We combine multiple land-types to explore a range of realistic land-cover scenarios,
with the goal of identifying effects of sub-grid water and energy transfers on surface water and
energy balances. Specifically, we aim to answer:

1. How does the inclusion of sub-grid lateral water transfers affect runoff generation in
   urban environments?
2. How do lateral water transfers affect warm season distributions of deep drainage,
   evapotranspiration, and runoff?
3. How do changes in hydrologic fluxes link to the changes of soil moisture over the warm
   season?
4. How does sensible and latent heating change on daily and seasonal scales when sub-
grid surface water transfers are integrated?
Figure 1: Conceptual diagram of new paired land types in HUE Noah-MP: Expanding Tree (a), Shifting Tree (b), Downspout Disconnection (c), and Permeable Pavements (d). Blue arrows denote new sub-grid lateral water transfers; red arrows denote the resulting changes in energy fluxes.

2 Methods
2.1 Outline of Simulation Experiments

We were interested in systematically understanding the water and energy impacts of lateral transfers in LSMs, with a focus on three common “greening strategies” found within emerging climate mitigation plans: increasing urban tree canopy, disconnecting impervious areas, and installing impervious pavement (e.g. Milwaukee Metropolitan Sewerage District, 2013). To do this, we designed four scenario sets: two representing tree overhanging pavement (Figure 1a & 1b), one representing downspout disconnection (Fig 1c), and one representing permeable pavement (Figure 1d). Within each set, a typical case, referred to as “baseline” for each scenario, is included which represents how current LSMs represent our situations of interest. Then we integrate sub-grid water transfers between land-cover types, and incrementally increase the amount active water transfer in each scenario, using our customized LSM. How these transfers are implemented within the model is described in more detail in Section 2.2.

Tree overhanging pavement represents the lateral transfers of water due to tree canopy that extends over an impermeable surface such as a sidewalk or road, which intercepts rainfall, shades the underlying surface, and evapotranspires. While transpiration occurs across the entire footprint of the tree’s canopy, we assume that root water uptake only occurs from pervious areas beneath
this footprint. Within this representation, we explored two plausible situations: Urban Tree Expansion and Urban Tree Shift.

*Urban Tree Expansion* ‘grows’ the tree canopy to cover more impermeable surface while maintaining the amount of tree canopy located over the permeable yard. We ran a series of simulations that varied the amount of canopy overlying the impermeable surface. The “baseline” for Urban Tree Expansion was 50% urban tree and 50% impermeable surface (i.e. no overlying canopy). Individual simulations then increased the amount of tree canopy over pavement by 0.5% with respect to the entire simulation area, up to a maximum of 35%, meaning the other end member simulation consisted of 50% urban tree over pavement, 35% urban tree over yard, and 15% uncovered pavement.

*Urban Tree Shift* maintains a constant total amount of tree canopy but places varying amounts of it over an impermeable surface. This was done to determine whether the results in Urban Tree Expansion were due to an increased capacity to transpire or if other mechanisms were responsible for simulated changes. In the real world, *Urban Tree Shift* can be understood as connected to where a tree is placed within a street terrace. As with Urban Tree Expansion, the “baseline” contains 50% urban tree and 50% impermeable surface. Simulations then increased the amount of tree canopy over pavement by 0.5%, up to a maximum of 35%. Area “uncovered” as a result of this shift was replaced with turfgrass. The end member case of Urban Tree Shift consisted of 35% turfgrass, 15% urban tree over yard, 35% urban tree over pavement, and 15% uncovered pavement.

*Downspout Disconnection* is a practice that eliminates the direct connection of rain gutter downspouts to impermeable surfaces like roadways or sidewalks. Instead, rainfall on rooftops is directed to surrounding vegetation—typically lawns planted with turfgrass. Simulations examining Downspout Disconnection assumed a land surface that is 30% impermeable surface and 70% turfgrass, consistent with the National Land Cover Database low-intensity urban land type, which is defined as 20%-49% impervious (Dewitz, 2021). Individual simulations then increased the amount of impermeable surface that transfers water to turfgrass from no disconnection, e.g., 0%, to full disconnection, e.g., 100%. The 0% scenario represents the “baseline” for LSMs and contains 30% impermeable surface and 70% turfgrass, with no run-on between the two. We increased the amount of disconnection by 1% for each simulation, which corresponds to an additional 0.3% of the total area that is disconnected in each successive simulation.

Lastly, *Permeable Pavement* simulates flow from impervious surfaces to engineered permeable pavements, designed to infiltrate water and promote groundwater recharge, e.g., deep drainage. Permeable Pavement simulations were influenced by the guidance published by the Wisconsin Department of Natural Resources (2021), which recommends a depth 21 inches (53 cm) and a ratio of impervious surface flowing onto permeable pavement between 4:1 and 3:1. Simulated scenarios ranged from 100% impervious pavement to 50% impervious pavement and 50% permeable pavement. We increase the amount of Permeable Pavement from the base (0% permeable) by 1% for each successive simulation.

In total, this experimental design yielded 254 simulation configurations across the four different scenarios: 71 Urban Tree Expansion, 71 Urban Tree Shift, 61 Downspout Disconnection, and 51 Permeable Pavement. This suite of simulation configurations gave us systematic insights
into the importance of lateral water transfers in urban environments across plausible distributions of urban land cover for a single temperate climate region. These simulations represent individual grid cells with fractional cover of different land types, but we do not simulate spatially explicit impacts across a city.

### 2.2 Description of Noah-MP HUE

Noah Multi-Physics (Noah-MP) is a LSM that describes the evolution of energy, water, and carbon cycles at the earth’s surface (Niu et al., 2011). It is integrated within the WRF regional climate model (Skamarock et al., 2019), and has been used in a variety of studies pertaining to land-atmosphere interactions at different scales (e.g. Alexander et al., 2022; Barlage et al., 2015, 2021). Noah-MP is also integrated into WRF-Hydro and NOAA’s National Water Model for flood forecasting (Gochis et al., 2018), and has been used in uncoupled hydrologic studies (Cai et al., 2014; Lin et al., 2018; Ma et al., 2017). Noah-MP addresses noted shortcomings of the earlier Unified Noah LSM (Chen et al., 1996; Ek et al., 2003) through both fundamental changes to model structure and the inclusion of multiple physics options. A major difference between Noah-MP and Noah is the treatment of vegetation; Noah-MP contains a separate vegetation canopy layer and uses an energy balance calculation method that accounts for differences between bare soil and plants, while Noah only uses an integrated surface layer. Further information on specific differences between Noah-MP and Unified Noah LSMs can be found in Niu et al. (2011).

We have developed **Noah-MP HUE**: Noah-MP for Heterogenous Urban Environments. The Noah-MP HUE framework introduces two changes: 1) a land use mosaicking scheme and 2) new “paired” urban land-types (Figure 1) with the ability to transfer water between these land-types. Mosaicking schemes are ways to represent heterogeneity by calculating weighted averages of fluxes and stores based on fractional areas within an individual LSM grid cell over different land types. They can improve the representation of the land surface (Essery et al., 2003; Fisher & Koven, 2020; Li et al., 2013). The mosaic scheme we implemented in Noah-MP HUE follows the one previously implemented in the Unified Noah model by Li et al. (2013).

We now outline the three new paired land cover types, which include a total of six new land categories, that transfer water within Noah-MP HUE. The first paired land cover types represent tree cover that overhangs pavement, which intercepts rainfall proportional to the overlying Leaf Area Index (LAI), like all other vegetated land types in Noah-MP. Rainfall that is not intercepted by tree canopy becomes runoff, exactly like the impervious surfaces in Noah-MP. Tree canopy located over pavement transpires by extracting water from the soil zone beneath the adjacent pervious area where the urban tree is planted—not the soil zone under the pavement—by first calculating a soil transpiration reduction factor—a simplified Feddes Function common in LSMs—based on available soil moisture (Feddes et al., 1976; Niu et al., 2011). When the root water uptake from the adjacent pervious area with an urban tree is calculated, the previously calculated transpiration from the tree canopy over pavement is added to ensure an appropriate reduction of soil water in each soil layer, as shown in Equation 1:

\[
RWU_{Tree over Pavement} = \chi_i \cdot T_{Tree over Yard} \cdot \beta_i + \frac{A_{Tree over Pavement}}{A_{Tree over Yard}} \cdot \chi_i \cdot T_{Tree over Pavement} \cdot \beta_i \quad (1)
\]

where \( i \) denotes Noah-MP’s different soil layers (typically four), \( RWU_{Tree over Pavement} \) is the rate of root water uptake that accounts for both the Urban Tree over Yard and the Urban Tree over Pavement distributed across soil layers in Noah-MP HUE, \( \beta_i \) is the unitless soil transpiration reduction factor.
that is calculated for the soil layers in the yard, $T_{\text{Tree over Yard}}$ is potential transpiration rate of Urban Tree over Yard, $T_{\text{Tree over Pavement}}$ is the same for Urban Tree over Pavement, and $\chi_i$ is the fraction of roots contained in layer $i$. Within Noah-MP, root distribution functions are simplistic compared to the exponential distributions in CLM or widely used asymptotic root distribution, effectively making $\chi_i$ a one if roots are present or zero if there are no roots present (Gale & Grigal, 1987; K. Oleson et al., 2013; Zeng, 2001). The root water uptake from the Tree over Pavement is scaled by the relative ratio of the Urban Tree over Pavement and the Urban Tree over Yard areas. This methodology is agnostic to the multiple vegetation physics options within Noah-MP.

The second new paired land cover type (Downspout Disconnection) moves water from an impervious surface to turfgrass laterally. We developed an urban turfgrass land cover that uses parameters based on, with the additional required parameters coming from the grassland land cover type already in Noah-MP and literature. Table S1 in supplementary material gives turfgrass parameter values that are not defaults from Noah-MP grassland (Niu et al., 2011). Runoff generated by impervious surfaces is redirected to turfgrass at each time step within the model. This process is governed Equation 2:

$$W = P + \frac{A_{\text{Impervious}}}{A_{\text{Receive}}} \cdot R_{\text{Impervious}} \quad (2)$$

where $W$ denotes the depth of water reaching the land surface, $P$ is the depth of precipitation incident to turfgrass, and $R_{\text{Impervious}}$ is the depth of runoff generated by the laterally connected impervious surface. $R_{\text{Impervious}}$ is scaled by the ratio of the impervious surface area and the receiving land area to appropriately scale the depth of run-on received by the turfgrass. The final paired land cover type—impervious surface laterally transferring water to permeable pavement—is also governed by Equation 2, with permeable pavement receiving water instead of turfgrass.
2.3 Study Location and Model Configuration

All simulations are forced using hourly meteorological inputs from the North American Land Data Assimilation System version 2 (NASA, 2015) centered on Milwaukee, Wisconsin (43.04°N, 87.91°W). Simulations were carried out for three continuous years, 2018 to 2020, and all analyses focused on warm seasons, defined as 1 May to 1 November. Each simulation started on 1 April 2018 and utilized the first month (until 1 May 2018) as spin-up. The three simulated years had warm season rainfall depths of 841 mm in 2018, 809 mm in 2019, and 648 mm in 2020–substantially higher than the average of 533 mm in the region over the past 30 years, consistent with the recent increases in precipitation associated with climate warming.

We used soil hydraulic properties representative of a silt loam, and assumed saturated soil conditions, 0.476 m$^3$ m$^{-3}$, for initialization of all land types except the Permeable Pavement investigation. This is reasonable, as spring snowmelt brings soils to saturation in the region. The top two soil layers of Permeable Pavement used a modified sand soil classification to achieve an infiltration rate between 10 in hr$^{-1}$ and 100 in hr$^{-1}$, in line with the requirements from the Wisconsin Department of Natural Resources (2021). We then only increased the maximum soil moisture available to be 0.4 m$^3$ m$^{-3}$ and the saturated hydraulic conductivity to be 1.0 $\cdot$ 10$^{-4}$ m s$^{-1}$, giving an estimated infiltration capacity of 14.2 in hr$^{-1}$ into the first soil layer.

In terms of model physics parameterization, we used approaches that have been previously recommended for non-atmospherically coupled Noah-MP simulations (Chen et al., 2023). These options include using table-specified vegetation fractions and interpolated monthly LAI (i.e., no dynamic vegetation model or crop model), the Ball-Berry formulation for canopy stomatal resistances, the CLM formulation for soil transpiration reduction factor (Niu et al., 2011), the original Unified Noah surface and subsurface runoff, the Monin Obukov similarity theory solver for surface layer coefficients (Brutsaert, 1982), linear effects of frozen soil on permeability, direct solving of supercooled liquid water within the soil (Niu & Yang, 2006), the CLASS formulation for dynamic ground snow surface albedo (Verseghy, 2007), the Jordan approach for partitioning precipitation into rainfall or snowfall (Verseghy, 2007), a semi-implicit flux top boundary condition for top layer soil temperature, and the Sakaguchi & Zeng (2009) approach for surface resistance to evaporation and sublimation. All simulations used default parameters in the Noah-MP unless otherwise specified (Niu et al., 2011).

3 Results

3.1 Event Scale Hydrology

Lateral water transfers reduce event scale runoff across all scenarios when compared to that generated by the baseline LSM (Figure 2). The magnitude of runoff reduction varies based on the type and amount of transfer. For example, the baseline LSM simulations of the largest storm in our analysis—a rainfall depth of 130 mm—generated 72 mm of runoff for tree scenarios, 51 mm for non-disconnected downspout, and 130 mm for impervious pavements. For this same storm, runoff totals were 66 mm for Urban Tree Expansion (35% canopy over pavement), 68 mm for Urban Tree Shift (35% canopy over pavement), 30 mm for Downspout Disconnection (100% disconnection), and 71 mm for Permeable Pavement (75% traditional pavement running onto 25% permeable pavement). These correspond to a runoff reduction associated with lateral transfers ranging from 6% (Urban Tree Shift) to 45% (Permeable Pavement). Downspout Disconnection and Permeable Pavement reduce runoff more than the urban tree scenarios.
Figure 2: Warm season event-scale runoff ordered by storm depth Urban Tree Expansion (a), Urban Tree Shift (b), Downspout Disconnection (c), and Permeable Pavement (d) in Milwaukee, WI. Colored bars below the x-axis are the amount of runoff generated with lateral transfers using Noah-MP HUE, while grey bars indicated additional runoff with no lateral transfers. Breakdowns of land cover are 35% canopy over pavement for both tree scenarios, 100% downspout disconnection (e.g., 30% roof pavement transferring water to an adjacent 70% turfgrass), and 75% traditional pavement running onto 25% permeable pavement. Percentage differences between the typical LSM representation (i.e., Noah-MP) and Noah-MP HUE representations are also provided (e). Storm events, e.g., each bar, are defined by a dry period of at least 12 hours.

The extent of runoff reduction varies with storm depth, though not monotonically. While runoff reduction generally increases as storm depth decreases, this trend is punctuated by storms with similar depths but vastly different runoff reductions (Figure 2d). This variability is likely due to effects of antecedent soil moisture and within-storm rainfall temporal variability. For example, the minimum runoff reduction relative to rainfall depth due to sub-grid lateral transfers is not during the largest storm of 130 mm for interventions other than Permeable Pavement, but instead the 21st largest storm (depth of 36 mm) for both Urban Tree Expansion and Urban Tree Shift, and the 7th largest storm (depth of 73 mm) for Downspout Disconnection. The 21st largest storm was characterized by light rainfall in the mid-summer over dry soil conditions, while the 7th largest storm included a large pulse of heavy rainfall—30 mm hr⁻¹—which likely overwhelmed soil
infiltration capacity. Complete reduction of runoff does occur for Permeable Pavements (below 18 mm storm depth) and Downspout Disconnection (below 2 mm), but never occurs for either urban tree scenario, which stagnate at 35% runoff reduction because of the existence of uncovered pavement in the baseline LSM.

### 3.2 Seasonal Water Fluxes

Lateral water transfers impact warm season hydrology by changing the partitioning of rainfall into surface runoff, evapotranspiration (ET), soil moisture storage, and deep drainage. Figure 3 & Figure 4 provide the breakdown of average warm season fluxes for all simulations and Figure 5 provide breakdowns of select simulations in each scenario.

Urban Tree Expansion increases ET and decreases runoff and deep drainage (Figure 3a). Runoff decreases range from 1 to 64 mm in total, but only a small fraction—0.1 to 3.8 mm—of the observed decrease comes from vegetated surfaces in simulations. Thus, even as the canopy expands in simulations, runoff is generated (95% on average) primarily over paved areas. ET increases range between 0.1% and 16% relative to rainfall, but there are opposing trends if the ET occurs over a vegetated surface or pavement: ET from a paved area increases from 0 to 160 mm—a 20% increase relative to precipitation—by adding 35% overhanging canopy. Simultaneously, ET decreases from 376 mm to 340 mm over vegetated surfaces—a decrease of 4% relative to precipitation. Deep drainage (soil moisture storage) decreases between 0.3% and 1.3% (0.1% and 6%). In short, the Urban Tree Expansion scenario increases root water uptake and ET, causing a reduction in soil moisture and deep drainage, while runoff reduction is mostly driven by intercepting rainfall by the new, overlying tree canopy (Figure 3a).

Compared to Urban Tree Expansion, Urban Tree Shift causes smaller decreases in runoff and creates smaller, non-linear changes in both ET and deep drainage (Figure 3b). Runoff generation over the paved portion of simulations for this case is identical to those in Urban Tree Expansion. Runoff generation over vegetated surfaces is larger, however: 25 mm in the most extreme case. ET increases until 29% of the domain is tree canopy shifted over pavement, releasing 440 mm over the warm season, but then decreases to 437 mm for the 35% shifted tree end member. In contrast with Urban Tree Expansion, deep drainage now increases by 2% compared to baseline. Soil moisture deficit mirrors the behavior of ET, increasing until 25% of the simulated domain is tree canopy over pavement – achieving a deficit of 61 mm – and then decreases. Changes in soil water fluxes in Urban Tree Shift scenarios are associated with the replacement of deep-rooted tree with a shallow shallow-rooted turfgrass (200 cm vs. 30 cm rooting depth) and areal extent of the tree roots decreasing as less of the simulated domain is available for root water uptake, causing simulated ET to decrease. While parts of the domain are drier, the overall domain is moister compared to the baseline LSM, causing greater runoff in vegetated portions.

Downspout Disconnection (Figure 4a) decreases runoff, slightly increases ET, and markedly increases deep drainage. Seasonal runoff reduction ranges from 0.4% to 22% relative to the baseline despite runoff generated by turfgrass increasing as more water is added to the vegetated portion of the domain due to the disconnection intervention. ET increases up to 27 mm as simulations transition from no downspout disconnection to full disconnection. Virtually no water stress occurs, meaning depleted soil moisture from root water uptake in the upper 30 cm of the soil column is readily replenished by frequent rainfall. As a result, rainfall, enhanced by run-on from
adjacent pavement, is preferentially partitioned into deep drainage, which increases from 67 to 187 mm. Finally, soil moisture deficit decreases slightly due to increased run-on compared to the baseline LSM case, by roughly 2% on average.

Permeable Pavement interventions reduce runoff and funnel this water into deep drainage, though there are still nuances across simulations (Figure 4b). A small increase in permeable pavement can lead to large water balance changes. By increasing the amount of permeable pavement from none to 5% of the simulated domain, surface runoff is reduced by 24%. By further increasing to 10% permeable pavement, runoff is reduced by 44%. Soil moisture storage also decreases slightly—a maximum of 3% of the average warm season rainfall—though the decrease is due to rainfall depths becoming less likely to fill available soil water storage.
Figure 3: Change in the partitioning of rainfall (mm) to different water fluxes over a suite of Urban Tree Expansion (a) and Urban Tree Shift (b) averaged over three warm seasons from Noah-MP HUE. Average
seasonal rainfall is shown by the solid black line, while the zero line is denoted in solid grey. Icons depict different key scenarios’ flux volume breakdown.

Figure 4: As in Figure 3, but for Downspout Disconnection (a) and Permeable Pavement (b) simulations.
Figure 5: Average season total water fluxes across all simulations for the four intervention scenarios. Additionally, change in fluxes relative to baseline (Noah-MP without sub-grid lateral water transfer) as a percentage of warm season rainfall are reported.

3.3 Seasonal Soil Moisture
Figure 6: Total column-averaged soil moisture time series of the pervious portion of the domain (e.g., soil moisture under vegetation or pervious pavement) for Urban Tree Expansion (a), Urban Tree Shift (c), Downspout Disconnection (e), and Permeable Pavement (g) for different scenarios. Warm seasons are shaded in panels. Empirical PDFs estimated from all three simulated warm seasons shown for Urban Tree Expansion (b), Urban Tree Shift (d), Downspout Disconnection (f), and Permeable Pavement (h). No baseline simulation is plotted for Permeable Pavement, as typical pavement does not change soil moisture.

Time series of soil column (200 cm) soil moisture (SM) in the vegetated/permeable parts of simulations, when paired with empirical probability density functions (PDFs) give insight as to why changes in runoff, deep drainage, and ET occur throughout the warm season (Figure 6).

Urban Tree Expansion, which decreased runoff and deep drainage and increased ET, tended to dry SM throughout the column. The magnitude of changes varied greatly with the amount of extra canopy present in simulations (Figure 6a). Similarly, Urban Tree Shift decreased runoff and
increased both deep drainage and ET, also tending to lower SM compared to the baseline simulation (Figure 6c). Despite the apparent similarities, there are nuances between these two scenarios. SM stress begins at 0.25 m$^3$ m$^{-3}$ for the silt loam soil class and chosen parameter scheme. During Urban Tree Expansion (Figure 6a & b), SM stress is common in simulations with more tree canopy over pavement and shifts simulated SM PDFs to the left (Figure 6b), especially during the height of the warm season due to increased canopy ET. This translates to enhanced infiltration at the expense of deep drainage.

SM stress is more subtle in the Urban Tree Shift scenario, as the soil column does not dry below 0.25 m$^3$ m$^{-3}$, seemingly avoiding soil water stress (Figure 6c & d). However, by examining separately the turfgrass and urban tree components of the vegetated portion of the domain, one finds that the column of the urban tree SM drops below this soil stress threshold (not shown) when 28.5% of the tree canopy is located over pavement and onward, limiting ET in more extreme simulations and increasing deep drainage. SM PDFs from the Urban Tree Shift simulations “flatten out” by both moving slightly to the left, signaling drying of the urban tree soil, and slightly right, signaling moister turfgrass conditions compared to the baseline (Figure 6d). The slight shift right is likely due to wetting fronts more easily moving past shallow-rooted turfgrass, which is a key reason for the dramatic increase in deep drainage in this scenario.

Downspout Disconnection results in a net increase in SM, shifting the SM time series upward (Figure 6e) and pushing the SM PDF to the right (Figure 6f) as the degree of disconnection is increased. Routing rooftop water to the yard through downspouts makes available water for infiltration, generating an increase of SM throughout the soil column in the yard and ultimately resulting in increased deep drainage. Higher SM also reduces the soil infiltration capacity and increases the likelihood of runoff generation, though not enough to match runoff from the baseline LSM with no disconnection (Figure 4).

Permeable Pavement integration opens a new pathway for urban rainfall to infiltrate, leading to increases in deep drainage. More permeable pavement leads to a decrease in the permeable pavement SM throughout the column as the engineered soil beneath the permeable pavement drains very efficiently (Figure 6g & h). In the selected SM time series (Figure 6g), the SM of the 25% permeable pavement simulation “flatlines” due to reaching porosity multiple times, while the same phenomenon does not happen in the 50% permeable pavement simulation.
Figure 7: Median diurnal patterns (solid lines) and interquartile ranges (shaded areas) for sensible (red) and latent heat (blue) fluxes for Urban Tree Expansion (a and d), Urban Tree Shift (d and f), and Downspout Disconnection (g and i). Leftmost column depicts “typical” simulations, while the rightmost column depicts ‘extreme’ simulations (e.g., most canopy over pavement or full downspout disconnection). Middle column (b, e, h) show median diurnal maximum heat flux and interquartile range across all simulations. Circles correspond to the leftmost column’s maxima, while squares correspond to extreme simulations’ maxima from the rightmost column.

3.4 Diurnal Energy Evolution

Sub-grid lateral water transfers not only affect water fluxes but also lead to increases in daily latent heat fluxes (LE) and decreases in sensible heat fluxes (H). We aggregated sensible and latent heat fluxes by time of day and found the median, thus estimating typical diurnal patterns, with uncertainty bounds of the 25% and 75% (i.e., the interquartile diurnal pattern; Figure 7). We do not report changes in Permeable Pavement (max difference of 0.01% across simulations).

The magnitude of change in diurnal energy evolution differs dramatically between scenarios. The mechanisms for enhancing daily LE differ across scenarios: more canopy to transpire water
(Urban Tree Expansion), exposure of more transpiring vegetation (Urban Tree Shift), larger thermal loading in portions of the tree canopy that overlay pavement (Urban Tree Expansion and Urban Tree Shift), and decreased soil water stress (Downspout Disconnection). Urban Tree Expansion peak LE range by 60 W m⁻² between baseline and 35% canopy scenarios (Figure 7b), but are smaller for Urban Tree Shift, with only a range of 20 W m⁻² (Figure 7e). In the case of Urban Tree Expansion, LE changes are directly linked to the larger tree canopy area increasing the transpiring footprint. Urban Tree Shift changes are non-linear: LE increases until 26% of the domain contains tree over pavement, and then decreases. Finally, Downspout Disconnection increases peak LE by 11 W m⁻² by increasing available water and has negligible impact on H (2 W m⁻²). Outside of arid or semi-arid climates, we would not expect major changes in LE and H due to more available soil water, as increased soil water does not enhance LE at the expense of H during the daytime unless drought conditions occur (Miller et al., 2020; Shields & Tague, 2015; Voter & Loheide, 2021).

Urban Tree Expansion and Urban Tree Shift both reduce H during the daytime, with this change relating to both increased ET and changes in effective surface thermal properties. The most marked change occurs near midday, when peak H reduces by 47 W m⁻² for Urban Tree Expansion (Figure 7b) and 89 W m⁻² for Urban Tree Shift (Figure 7e). Most of this reduction is likely due to more energy partitioning to LE, though hints of another mechanism of H reduction—changing the effective emissivity and albedo in simulations—lie in the variability (shading in Figure 7). H variability in Urban Tree Expansion and Urban Tree Shift remain nearly constant at the daily scale across simulations, but LE becomes more variable. Tree canopy shades the pavement in both Urban Tree Expansion and Urban Tree Shift, resulting in peak H reductions with a nearly constant interquartile range. At the same time, more of the tree canopy is over a warmer surface (pavement surface temperatures are warmer than the vegetated surface by an average of 2 K during the daytime), which induces more variable LE (a widening of the interquartile range shading).

3.5 Warm Season Energy Balances

Diurnal energy balances and environmental factors like rainfall depth and time between rain events change season long LE/ET and H patterns, especially when vegetation is water limited. We investigate changes in warm season scale energy patterns and their links to sub-grid lateral water transfers by examining total daily LE (Figure 8) and H (Figure 9) across every simulation for the 2019 warm season. Results for 2018 and 2020 warm seasons are provided in Supplemental Material.

Urban Tree Expansion, Urban Tree Shift, and Downspout disconnection all convert more available radiation (net radiation minus ground heat flux storage) into LE during the warm season when more sub-grid lateral water transfer is included (Figure 8). This corresponds to a reduction in seasonal H totals (Figure 9). All scenarios include banding of higher-than-average (lower than average) LE (H) days during and directly after days with rainfall, representing the effects of enhanced infiltration and interception on energy partitioning. In Urban Tree Expansion (Figure 8a & b, Figure 9a & b) and Downspout Disconnection (Figure 8e & f, Figure 9e & f) increases LE and corresponds to nearly identical decreases H as sub-grid lateral water transfer increases. In the Urban Tree Shift scenario, however, a drying effect occurs where LE suddenly drops when 25% or more of the simulated area is tree over pavement (Figure 8c). This drying creeps earlier into the warm season as tree over pavement fraction increases, coincident with earlier onset of soil water
stress. Though there is a large reduction in LE due to drying—on the order of 2 GJ in some extreme cases—the same magnitude of increase in H is not observed, tied to changes induced by modified radiative and thermal properties like albedo, emissivity, and heat capacity.

**Figure 8:** Daily integrated LE from the entire simulated domain over the 2019 warm season and difference from baseline heatmaps, both in GJ. Within heatmaps, rows are individual days and...
columns are the different simulated scenarios. Panels a) and b) are Urban Tree Expansion simulations, Panels c) and d) are Urban Tree Shift, and Panels e) and f) are Downspout Disconnection. A hyetograph of daily precipitation on the left and select integrated total energy on the top of each heatmap is provided for reference.

Figure 9: As in Figure 8, but for H.
4 Discussion

4.1 Implications for Land Surface Modeling in Urban Regions

Current LSM frameworks are not generally able to represent the highly heterogeneous hydrologic processes that exist in urban environments. The usage of a single dominant land type (or even a mosaic of land types within a single grid) that do not interact with other surface types is not supported by recent work showing the impact of lateral transfers on the water balances of single home parcels (Voter & Loheide, 2018), city blocks (Avellaneda et al., 2017; Wang et al., 2022), and city-scale responses of runoff and storm water systems (Arjenaki et al., 2021). LSMs are somewhat distinct from models developed for purely hydrologic prediction, in that they primarily aim to provide boundary conditions for coupled atmospheric models. The increasing complexity and resolution of atmospheric models, however, has driven LSM development to include more processes from other scientific disciplines (Fisher & Koven, 2020). The need to correctly quantify the urban energy balance—even in relatively coarse atmospheric and earth system simulations—requires the inclusion of these complex, fine-scale lateral water transfers, since they directly impact water and energy cycling at multiple scales (Oke et al., 2017). Our results indicate that current LSMs that neglect lateral water transfers generally create too much runoff and too little ET in urban areas, which could affect simulated atmospheric processes and their impacts. Noah-MP HUE presents a first step in bridging this gap by adding new physics that allows for sub-grid sharing of water and energy.

The changes brought by sub-grid lateral water transfers in urban regions are complex and provide nuanced results that would be missed without explicit integration into a physically-based model. Adding lateral water transfer in Urban Tree Expansion and Urban Tree Shift scenarios increased ET and decreased runoff, but created surprising, opposing trends in terms of changes in deep drainage and seasonal water balances. These subtle differences carried over into the daily and seasonal energy balances, where the effects of increased ET and subsequent reduction in H did not align across scenarios. Furthermore, while Downspout Disconnection increased runoff from vegetated areas, this increase was less than the amount of runoff that would have been generated from the rooftops, highlighting the complex interactions among diverse physical processes in cities (Miles & Band, 2015). Our results align with other recent studies of urban tree effects (Meili et al., 2021) and high-resolution urban hydrologic simulations (Arjenaki et al., 2021; Voter & Loheide, 2018), but with the added benefits of limited incurred computational cost and easy integration into regional climate and earth system simulations.

The interplay between rainfall characteristics and traditional hydrologic considerations, like antecedent soil moisture, are a key driver of variability among our simulations. While storm depth is inversely related to runoff reduction (Figure 2), it alone does not explain the variability seen across storms. Second-order rainfall characteristics are particularly important in urban regions due to the limited spatial scale of the regions themselves (Emmanuel et al., 2012) and highly connected impervious areas (Jacobson, 2011). Characteristics like time between events can generate complex top layer soil conditions (Sun et al., 2018) that further change runoff generation and are especially important drivers of hydrologic heterogeneity at urban and vegetation interfaces (Yao et al., 2016). Particularly important is timing between storms, as it impacts the not only the amount of ET and the duration of dry-down periods (Figure 6), but also the runoff generation mechanisms during...
subsequent storm (e.g., saturation excess vs. infiltration excess). Timing between storms also influences partitioning of energy into H and LE (Figure 8 and Figure 9), with drier conditions reducing ET due to soil water stress. ET rates within Urban Tree Expansion and Urban Tree Shift simulations are further linked to the “urban oasis effect,” where ET from vegetation in urban areas—in this case over pavement—are large compared to similar vegetation not in urban areas due to greater thermal loading and atmospheric demand due to less atmospheric water overall in urban areas (Yang et al., 2015; Ziter et al., 2019). When ET is reduced due to insufficient soil water, like in Urban Tree Shift, a reduction in H is still present due to radiative and thermal property changes, akin to the behavior in other studies (Meili et al., 2021; Ryu et al., 2016; Schwaab et al., 2021; Zipper et al., 2017).

4.2 Implications for Urban Water and Heat Management Solutions

A key management takeaway from this study is that the specific placement of trees, impervious surface disconnections, and permeable pavements—often termed green infrastructure or nature-based solutions but in reality are intrinsic features of the urban environment—can dramatically influence large scale hydrology. Simulations presented in this study are representative of idealized probable distributions of land-cover interactions in a city resolved at different scales. For example, one could expect to find that 35% of pavement is covered by tree canopy at a small scale, e.g. single household, and is likely near the right side of both subplots of Figure 3. If we increase the scope of the region of interest to include a full neighborhood, we will likely smaller fractions of pavements covered by trees falling into the ranges on the leftmost sides of Figure 3. By applying similar reasoning to Downspout Disconnection and Permeable Pavement, the smaller scales of interest like a single house or roadway approach larger fractions of disconnection, which fall on the left of Figure 4 and move to the right as the region of interest increases. Careful consideration on the placement of many small-scale interventions can help reduce runoff generation “hotspots”, though not every intervention may be appropriate for an area. For example, enhanced deep drainage may not desired in a location due to potential negative effects including inundation of aging infrastructure (Peche et al., 2019), enhanced contaminant transport to groundwater (Andres et al., 2018), and “basement flooding” in areas with shallow or perched water tables.

Tree cover not only offers runoff reduction benefits to a city (Selbig et al., 2022), but also offers co-benefits of temperature reduction that could be of service to cities’ adaptation to climate warming. The initial placement of tree cover (i.e., Urban Tree Shift results) reduce runoff via interception. The runoff reduction will likely increase with tree age due to both a larger canopy enhancing interception and more root water uptake enhancing infiltration. At the same time, trees that overlap pavement provide shade, altering the albedo, emissivity, and other radiative properties (Meili et al., 2021; Ziter et al., 2019). These changes can enhance ET and cool air temperature in a wide range of climates (Schwaab et al., 2021). Urban trees offer a wide variety of ecosystem services in urban regions, such as increasing thermal comfort for humans (Sanusi et al., 2016), increasing human health benefits (McDonald et al., 2016), reducing water pollution (Denman et al., 2016; Livesley, Ossola, et al., 2016), and even reducing urban air pollution when specific tree species are selected (Livesley, McPherson, et al., 2016; Park & Schade, 2016). A way to include community members in tree placement, and to help avoid repeating past urban management practices that have increased extreme heat exposure in historically marginalized communities, is through engagement programs like community-owned trees, solicitation of shade location
priorities, and post rainfall event interviews to identify runoff hotspots (Azizi et al., 2022; Guardaro et al., 2020; Hoffman et al., 2020; Wilson, 2020).

4.3 Limitations of this Study

Generally, we do not examine different parameters in this study, which affect both vegetation energy cycles and hydrological processes (Cuntz et al. 2016). We examined a single soil texture class in this study—silt loam—using meteorology from a single location (Milwaukee, Wisconsin) in a cool continental climate. Soil texture affects surface and subsurface processes in LSMs and regional climate simulations (Dennis & Berbery, 2021), especially for processes relating to surface runoff and ET. Soil texture impacts surface runoff as well as the percentage of tree canopy cover at which peak ET in Urban Tree Shift scenarios occurs within Noah-MP HUE. We provide examples of changes in results for Urban Tree Expansion and Urban Tree shift with a clay loam soil texture in SI. We also neglected other common aspects of urban soil, such as compaction, which increases surface runoff through a reduction in porosity and hydraulic conductivity (Herrmann et al., 2017; Jian et al., 2021; Shuster et al., 2014; C. B. Voter & Loheide, 2018). Finally, our study does not consider the potential effects of groundwater. A high water table would likely result in a reduced soil volume available for infiltration, as well as reduced infiltration capacity (Bhaskar et al., 2015).

Underlying climate also influences the effects of lateral transfers. Voter & Loheide (2021) examined the effects of downspout disconnection across the United States and found that runoff reduction partitioning between deep drainage and ET is strongly correlated with aridity index. Similarly, the type of urban vegetation and rates of ET vary with underlying climate (Mazrooei et al., 2021). Instead, our work presents an in-depth look at a single location to give insights into how fractional incrementation of the amount of lateral transfer changes the local water balance. Furthermore, we do not investigate differences brought about by strictly defining realistic representations of local or regional vegetation or landscaping, but instead use the concept of plant functional types. This approach is common in LSMs within earth system models (Duckworth et al., 2000).

Finally, our work only looks a small selection of low impact development practices (green infrastructure). Green infrastructure encompasses a wide variety of practices (Fletcher et al., 2015), and the ones that we selected make up a majority of the regional green infrastructure plan within Milwaukee, WI (Milwaukee Metropolitan Sewerage District, 2013). This work allows for further development of other green infrastructure practices, like bioretention swales and green roofs, but such measures may only make up a small fraction of an urban landscape.

5 Conclusions

While lateral transfers of water, and therefore energy, are ubiquitous within complex urban environments and are increasingly recognized for the impact they have on water and energy cycles, they have been overlooked in land surface models (LSMs) to date. We presented a new version of a widely used LSM that integrates 1) land type mosaicking capabilities to address sub-grid heterogeneity in land cover/land use, and 2) the ability to transfer water between certain paired land types, to better represent urban processes in a way that is usable and computationally efficient within coarse-scale regional climate and earth system models. We investigated the effects that incremental changes in the amount of lateral transfer have on both water and energy budgets. In
terms of hydrologic impacts, disconnecting impervious surfaces and adding permeable pavement generated the largest decreases in runoff. There are more modest runoff benefits to adding tree canopy, as tree canopy overlying pavement causes interception and enhances infiltration due to increased drying of soils. The addition of trees that overhang pavements offers the substantial co-benefit of increasing latent heat flux throughout the day while decreasing the sensible heat flux, which would translate to reduced air temperature. To our knowledge, these effects cannot be captured by other contemporary LSMs. The effects illustrated in this study are important due to implications for the potential regional feedbacks that urban water and energy fluxes have within the local and regional climate, as well as providing guidance for planners and communities seeking to reduce runoff and heat—important steps towards greater climate justice and equity in urban areas—through widespread but small-scale green infrastructure intervention.

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Data Availability Statement

NLDAS data for simulations is available for download through NASA’s Goddard Earth Sciences data and Information Services Center (GES DISC) (https://disc.gsfc.nasa.gov/datasets?keywords=NLDAS). Noah-MP HUE, summary code data, and code used in the creation of this manuscript is available through a Zenodo repository (https://doi.org/10.5281/zenodo.8019119) (A. Alexander, 2023).
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