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Surface Runoff Discrepancy in Urban-PLUMBER Land Surface Models

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Key Points:

- Large discrepancies in simulated urban surface runoff appear between urban land surface models (ULSMs)
- Not all ULSMs capture the effect of the impervious fraction on surface runoff
- Simplified ULSMs produce less surface runoff compared to their sophisticated peers across various climates and impervious fractions

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Abstract

Enhanced surface runoff in urban environments reduces water availability and limits the evaporative cooling potential. We evaluate surface runoff in 18 urban land surface models (ULSM) in Urban-PLUMBER for 6,570 rainfall events across 21 urban sites. Surface runoff occurs when rainfall exceeds the infiltration, saturation, or interception capacity. Ten models omit at least one of these processes, while seven fail to increase runoff with increasing imperviousness. Surprisingly, some models lack any runoff during intense (>50mmh^{-1}) or prolonged (>20 mm) rainfall. Urban land surface models (ULSMs) turn 0%–86% rainfall into runoff. Most models produce runoff in agreement with an empirical comparison offered by the CN method, especially for high imperviousness. However, ULSM runoff exceeds CN runoff estimates for low impervious fraction, particularly by models with incomplete process description and for low-intensity rainfall. The large discrepancy between ULSMs calls for advancing the urban hydrology representation in ULSMs, which is essential for correct simulation of evaporative cooling in cities.

Plain Language Summary

Precipitation that is lost as surface runoff is not stored to evaporate and thus to cool the environment at a later time. Urban areas are characterized by many impervious surfaces like roads and buildings, which promote runoff and reduces water availability for evaporation. This decreased water availability can exacerbate heat in cities. This study examines how ULSM predict runoff, which is crucial for simulating energy exchange between the surface and the atmosphere. We find that many models perform well for high impervious fraction and heavy rainfall events, but substantial discrepancy in modeled runoff appears for low-intensity events and at green sites. Improving these models will enhance estimation of water availability and evaporation, and enabling more effective urban cooling and water management strategies.

1. Introduction

Urban dwellers are exposed to elevated temperatures compared to rural areas, which may increase sleep disorder, morbidity, and mortality (Fan et al., 2022; Ho et al., 2023; Masselot et al., 2023). Water can cool urban areas by using roughly half of the surface available energy for evaporation (Qiu et al., 2023; Trenberth et al., 2009). Water availability for evaporation is relatively low in urban areas, as impervious surfaces produce more runoff than natural areas (Gurnell et al., 2007; Jacobson, 2011; Leopold, 1968; McGrane, 2016; Paul & Meyer, 2001; Shuster et al., 2005). Unfortunately, dry conditions limit vegetation's cooling potential (Kraemer & Kabisch, 2022; Nimac et al., 2022). Future cooling demand will coincide with dry conditions more frequently, as compound drought and heatwaves are projected to occur more often (Mukherjee & Mishra, 2021). Urban evaporation recession revealed that water storage available for urban evaporation is considerably lower than in natural vegetation and crops (Jongen et al., 2022). The low water storage capacity challenges heat stress mitigation, especially during

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compound events. The design effective greening solutions requires understanding and quantification of water lost through runoff and available for evaporation.

Currently, models simulating land–atmosphere interaction in urban environments contain relatively straightforward runoff schemes. These urban land surface models (ULSMs) focus on representing the surface energy balance that affects the local urban climate and the overlying atmosphere and are typically used as lower boundary conditions in numerical weather prediction and climate models (Grimmond et al., 2011; Lipson et al., 2024). Recently, the Urban-PLUMBER project evaluated the full water balance representation for a large set of ULSMs (Jongen et al., 2024; Lipson et al., 2024). The evaluation highlighted that runoff was the most poorly simulated water flux with likely feedbacks on evaporation through its impact on water availability. The poor performance is illustrated by the missing relation between modeled surface runoff and the impervious fraction in almost half of the ULSMs in that study (Jongen et al., 2024). The failure of ULSMs to capture this relation emphasizes the need to improve these models' surface runoff parameterization. Therefore, rather than finding the best models for urban surface runoff, we evaluate how ULSMs trigger runoff induced by precipitation events, and how this could be improved.

Surface runoff parameterization evaluation requires consideration of the runoff processes at play. Traditionally, surface runoff in natural environments is hypothesized to originate from infiltration excess (Horton, 1933) or saturation excess (Dunne & Black, 1970). Impervious surfaces produce surface runoff by preventing infiltration, similar to infiltration excess and provide small storage that quickly overflows, similar to saturation excess. Hereafter, this combination is called interception excess. Surface runoff from impervious surfaces may partly drain to pervious areas where water is buffered in the soil or causes additional saturation excess (Hopkins et al., 2015). Moreover, pervious areas themselves are affected by urbanization as soil layers are removed (Herrmann et al., 2018) and soils are compacted (Shuster et al., 2015). This increases surface runoff through infiltration excess from pervious surfaces. The high urban surface runoff can be caused by interception, infiltration, or saturation excess (Stewart et al., 2019). Yet, not all models include all three processes in their conceptualization (McDonnell, 2013).

We first examine the modeled surface runoff from 18 ULSMs from the Urban-PLUMBER project that contains a range of surface runoff parameterizations (Lipson et al., 2024). We demonstrate how current models capture runoff processes and how this affects modeled surface runoff, and hypothesize that ULSMs generate discrepancies in surface runoff because they might not reflect all urban runoff physics processes. Second we explore "archetype events," that is, low- and a high-intensity precipitation event at sites with a low (0.31) and a high (0.96) impervious fraction (F_I) for a better understanding of the model behavior. Moreover we compare the modeled surface runoff to the CN method as zeroth order estimate. Based on the high-intensity event at the most impervious site, we demonstrate the impact of including or excluding runoff processes from the models.

2. Methods

This study analyzes the surface runoff parameterization in 18 Urban-PLUMBER ULSMs (Table 1). The models represent an area of ~1 km^2 as a single grid cell. While observations were not provided to the participating modelers to preventing model tuning, sanity checks were undertaken to eliminate human errors. The model output covers 20 sites with a range of climates, impervious fractions, and observational periods described in detail by Lipson et al. (2022b). At all sites, eddy-covariance systems provide evaporation observations. Depending on site data availability, model resolution is 30- or 60-min for periods of 148–1,827 days (average 912 and median 748 days). Most models operate with 30 or 60 min timesteps, while a minority using shorter timesteps.

We first consider surface runoff response to site characteristics for varying total precipitation given differences in observational periods and local climate. This relation is examined over the whole model simulation based on accumulated surface runoff and precipitation. Water fluxes are normalized by the inflow accumulated over the whole model simulation. Inflow is defined as the left-hand side and negative fluxes on the right-hand side of the urban water balance (Grimmond et al., 1986):

$$P + I = R_s + R_{ss} + \mathrm{ET} + \Delta S \quad (1)$$

Table 1
Characteristics of the 18 Urban Land Surface Models in This Study

Model	Urban geometry	Vegetation	Soil hydrology	Snow accumulation	Infiltration excess runoff	Saturation excess runoff	Interception excess runoff	Irrigation	Reference
ASLUMv2.0	Canyon	Grass	Multi-layer[1]	No	Yes	Yes	Yes	No[2]	Wang et al. (2013) Wang et al. (2021)
ASLUMv3.1	Canyon	Grass + trees	Multi-layer[1]	No	Yes	Yes	Yes	No[2]	Wang et al. (2013) Wang et al. (2021)
CABLE	Non-urban	Separate tile	Multi-layer	Veg.	No	Yes	No	No	Kowalczyk et al. (2006) Wang et al. (2011)
ECLand	Non-urban	Separate tile	Multi-layer	Veg.	Yes	No	No	No	Boussetta et al. (2021)
ECLand-U	Two-tile	Separate tile	Multi-layer	Veg.+urban	Yes	No	No	No	McNorton et al. (2021) Boussetta et al. (2021)
CLMU5	Canyon	Grass + shrubs	Multi-layer	Urban	Yes	Yes	Yes	No	Oleson and Feddema (2020)
JULES 1T	One-tile	Separate tile	Multi-layer	Veg.+urban	Yes	Yes	Yes	No	Best et al. (2011)
JULES 2T	Two-tile	Separate tile	Multi-layer	Veg.+urban	Yes	Yes	Yes	No	Best et al. (2011)
JULES MOR	Two-tile	Separate tile	Multi-layer	Veg.+urban	Yes	Yes	Yes	No	Best et al. (2011)
Manabe 1T	One-tile	Manabe bucket	One-layer	Veg.+urban	No	Yes	Yes	No	Best et al. (2011) Manabe (1969)
Manabe 2T	Two-tile	Manabe bucket	One-layer	Veg.+urban	No	Yes	Yes	No	Best et al. (2011) Manabe (1969)
NOAH-SLAB	One-tile	Separate tile	Multi-layer	Veg.+urban	Yes	No	Yes	No	Kusaka et al. (2001) Ek et al. (2003)
NOAH-SLUCM	Canyon	Separate tile	Multi-layer	Veg.+urban	Yes	No	Yes	No	Kusaka et al. (2001) Ek et al. (2003)
SNUUCM	Canyon	Separate tile	Multi-layer	Veg.	Yes	No	Yes	No	Ryu et al. (2011) Ek et al. (2003)
SUEWS	Two-tile	Separate tile	One-layer	Veg.+urban	Yes	Yes	Yes	No[2]	Järvi et al. (2011) Ward et al. (2016)
TERRA 4.11	One-tile	LSM	Multi-layer	Veg.	No	Yes	Yes	No	Wouters et al. (2015) Schulz and Vogel (2020)
UCLEM	Canyon	Grass + shrubs	One-layer	Veg.+urban	No	Yes	Yes	Yes	Thatcher and Hurley (2012) Lipson et al. (2018)
UT&C	Canyon	Grass + shrubs + trees	Multi-layer	No	Yes	Yes	Yes	Yes	Meili et al. (2020)

Note. All models are part of the Urban-PLUMBER project (Lipson et al., 2024). Two models did not provide soil moisture output ([1]). Three models capable of simulating irrigation did not include it in their Urban-PLUMBER runs ([2]). Of the three models missing snow accumulation, two ignore snowfall (ASLUMv2.0 and ASLUMv3.1) and one converts it to rainfall (UT&C).

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where P is precipitation, I irrigation, R_s surface and R_{ss} subsurface runoff, ET evapotranspiration and ΔS water storage change. As the ULSMs ignore effects of rivers or streams, surface runoff is interpreted as overland flow leaving the model domain.

While summarizing metrics assist model comparison, analyzing "archetype events" reveals additional differences between models (de Boer-Euser et al., 2016). Characteristic rainfall events are studied to distinguish all three runoff generation processes: infiltration, saturation, and interception excess. We select a long low- and a high-intensity precipitation event at two sites with contrasting F_I. While saturation and interception excess are likely during prolonged low-intensity rainfall, infiltration and interception excess are more likely during a high-intensity precipitation event. Contrasting F_I reveal how models handle interception runoff. Rainfall events were selected without dry periods longer than 1 hr. Where low-intensity events should exceed 20 mm with an average intensity of maximally 2 mm h^{-1}, high-intensity events should exceed 50 mm with an average intensity of at least 10 mm h^{-1}. The precipitation events are selected with the same criteria at both sites to eliminate the precipitation regime influences on the results. However, the least impervious site (US-Minneapolis2, 5%) data set does not include precipitation events meeting the criteria, so US-Baltimore (31%) is used for the low F_I with KR-Jungnang (96%) for the most impervious. Vegetation and soil characteristics will differ between sites and impact surface runoff, but details beyond plan areas fractions were not provided to the modelers.

Unfortunately, direct model evaluation is hampered by lacking urban runoff observations. Occasionally available observations do not reflect the spatial scales considered in ULSMs (Berthier et al., 1999; Grimmond et al., 1986, 2011; Lipson et al., 2024; Walsh et al., 2005). Hence we use the Curve Number (CN) method for comparison to ULSM results, as the method is a widely used first order empirical approach for runoff estimates based on urban and natural site characteristics such as F_I (Bhaduri et al., 2000; Chin, 2022; Cronshey et al., 1985; NRCS, 2004a; Panigrahi & Ramadas, 2025; Williams et al., 2012; Wu et al., 2024; Xu et al., 2020). Pervious–impervious surfaces interactions are simplified or partially captured given the bulk approach of the empirically derived CN values (Alivio et al., 2024). As the method is not intended for hydrograph generation (Eli & Lamont, 2010), we instead compare on long-term runoff ratios. The CN method therefore offers a practical, empirical comparison to ULSMs.

The CN requires the site characteristics relevant for runoff generation (Rawls et al., 1981). Here, CN values are linearly interpolated for the F_I giving composite CNs (NRCS, 2004b). CN-based surface runoff estimates ignore subsurface properties beyond soil type, overlooking soil depth and bedrock permeability influencing (sub-)surface runoff partitioning (Weedon et al., 2015, 2023). As urban soil properties are often not mapped (Van De Vijver et al., 2020), we undertake sensitivity tests considering CNs belonging to the hydrological soil group with the highest and lowest infiltration capacity. Water storage is assumed to be empty at the beginning of the event. The relation between total event surface runoff (R_e) and CN is:

$$R_e = \frac{(P_e - 0.05S)^2}{P_e + 0.95S} \text{ with } S = \frac{1000}{\text{CN}} - 10 \text{ assuming } I_a = 0.05S \quad (2)$$

where P_e is the total event precipitation, S the potential maximum retention, and I_a the initial abstraction (all in inches). CN estimates are based on P_e and are thus independent from rainfall intensity. I_a represents intercepted rainfall before runoff starts, and (Chin, 2023) found $I_a = 0.05$ S suits the urban setting.

3. Results

Since more surface runoff is expected from impervious than from pervious surfaces, a misrepresentation of F_I leads to surface runoff underestimation. Hence, we evaluate whether the F_I positively correlates with the surface runoff ratio. Most models yield this correlation (Figure 1). This is consistent with the general trend of lower observed evaporation at more impervious sites (Figure 1a). Two models generate surface runoff ratios with an almost perfect correlation with the F_I and nearly no surface runoff at low F_I (0.95 and 0.98, Figures 1g–1s). This suggests these models only generate surface runoff from impervious surfaces.

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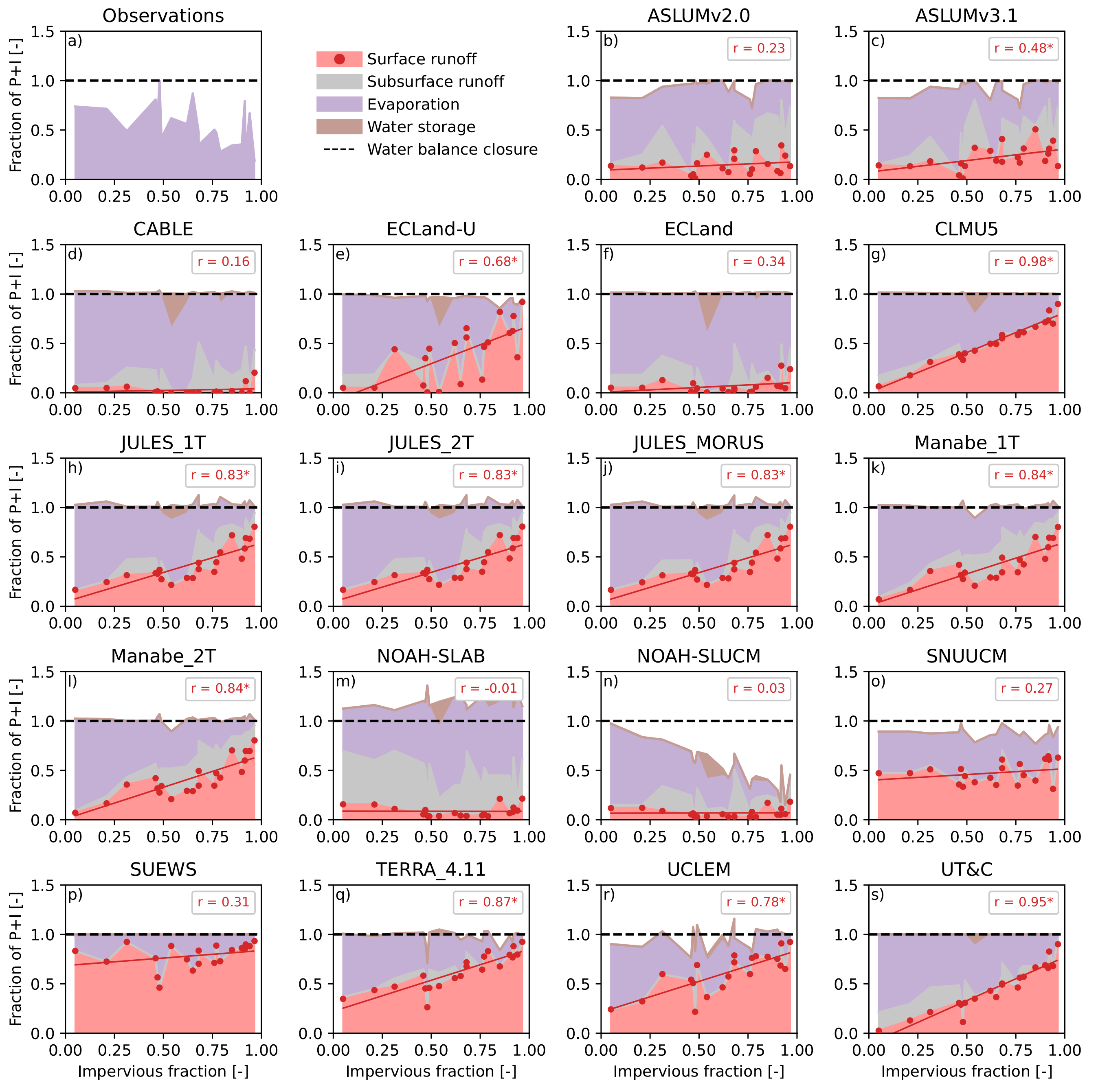

Figure 1. Modeled average water balance partitioning (shading) for all 21 Urban-PLUMBER sites (red dots) sorted by F_I for (a) observations and (b–s) the 18 models. Evaporation observations are available from eddy-covariance data sets with original sources referenced within Lipson et al. (2022b). The red lines show linear regression between scaled surface runoff and the F_I. Significant correlations are indicated with an asterisk ($p < 0.05$, Wald (1943) test). Results are based on in total 6,570 precipitation events. The number of rainfall events per site is listed in Table A1.

In contrast, no significant correlation between modeled surface runoff ratios and F_I was found for seven models ($p < 0.05$, Wald (1943) test, Figures 1b, 1d, 1f, and 1m–1p), while one model ignores snowfall and four models produce little surface runoff regardless of F_I (Figures 1d, 1f, 1m, and 1n). Two of these four models are not developed for urban areas, instead representing the impervious areas as bare soil (Figures 1d–1f). One other of the four fails to partition all the incoming water (Figure 1n). This deficiency seems related to the impervious scheme

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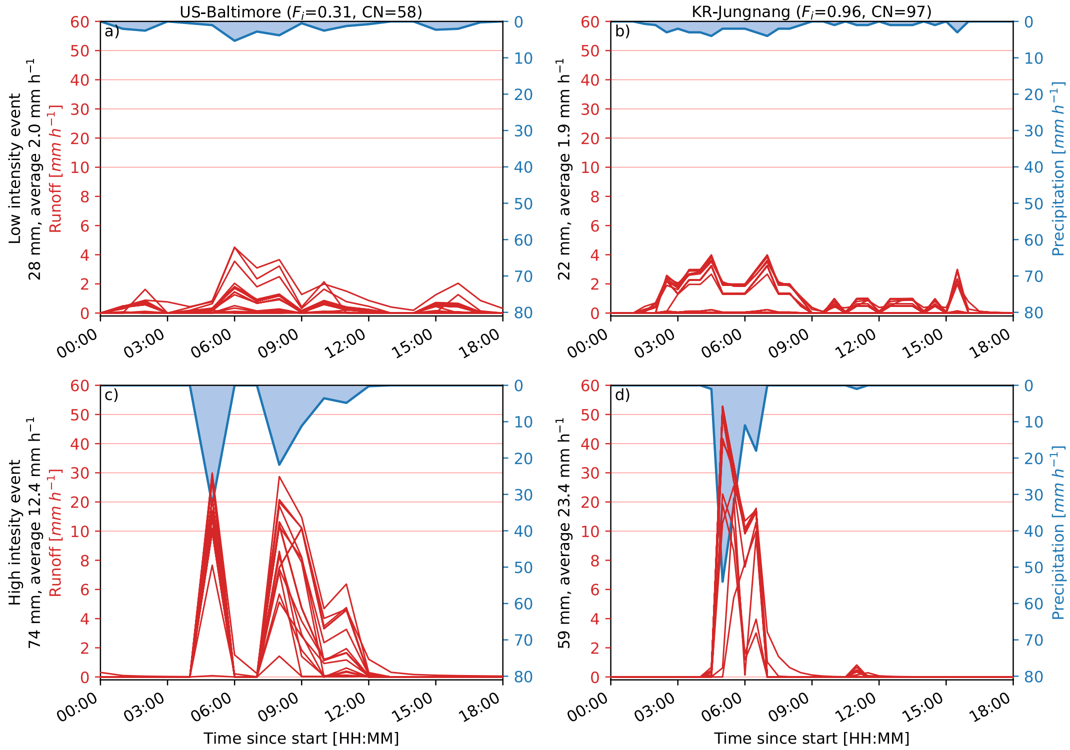

Figure 2. Modeled surface runoff (one line per model) for (a, b) low- and (c, d) high-intensity precipitation events (shading) at sites with (a, c) low (US-Baltimore) and (b, d) high (KR-Jungnang) F_I.

as the unexplained fraction increases with F_I. Given the low surface runoff ratios in the models missing the correlation, the missing correlation cannot be explained by other factors affecting this ratio like the rainfall distribution. Misrepresented impervious surfaces seem to cause underestimation of surface runoff, as not all models produce the correlation between modeled surface runoff ratios and impervious surfaces. Apart from two models, rainfall intensity does not correlate significantly with the surface runoff ratio, and neither with annual rainfall or soil texture for all models (not shown).

To raise insight in the modeled mechanisms, we consider the four identified archetype events (Section 2) to assess the model response to different rainfall intensities at two sites with contrasting F_I values (Figure 2). Modeled surface runoff closely mimics rainfall dynamics in most models during all four events. However, the amount of modeled surface runoff differs among the ULSMs ranging from no surface runoff to almost all precipitation for the low-intensity event at the less impervious site (Figure 2a). At the more impervious site, model results are more clustered with six models yielding no or negligible surface runoff and 12 following the rainfall intensity pattern (Figure 2b). During the high-intensity events, modeled surface runoff directly responds to rainfall in all but two models, yet the peak surface runoff rates differ by a factor of four (Figures 2c and 2d). Surprisingly, precipitation rates above 10 mm h^{-1} for 2 hrs do not trigger runoff in some models despite that nearly the entire surface is impervious. Many models fail to produce the surface runoff volumes expected given the rainfall volume and intensity. Overall the model variation of median fraction rainfall that turns into runoff varies between 0% and 86% (Appendix A).

Per event, ULSMs are compared to CN surface runoff estimates. For the most impervious site, the ULSMs yield runoff, that is, in general consistent and close to the CN method estimate (Figure 3). However, for the low intensity event six models to not trigger runoff, while for the high-intensity event five ULSMs generate substantially lower runoff than 50–60 mm as triggered by the majority of the models. These five models also miss the correlation between F_I and modeled surface runoff ratio. The other models are relatively close to the CN expected

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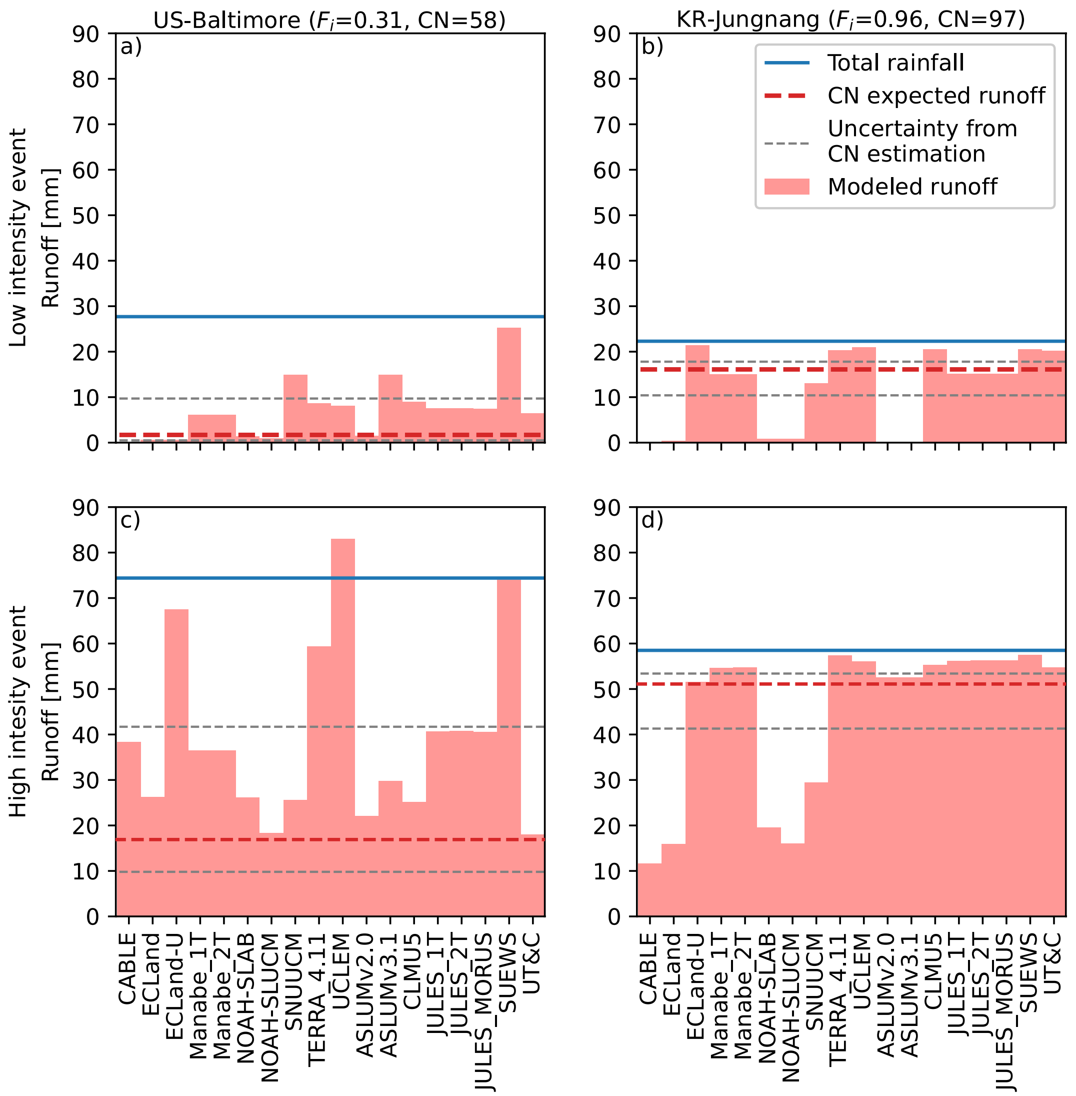

Figure 3. Comparison of modeled surface runoff with the corresponding Curve Number reference (dashed line) for (a, b) low- and (c, d) high-intensity precipitation events (Figure 2) at sites with (a, c) low (US-Baltimore) and (b, d) high (KR-Jungnang) impervious fractions with total event precipitation (solid line). The uncertainty is based on the range of CNs without information on the soil composition (US-Baltimore: 46–86; KR-Jungnang: 92–98). Models are sorted by the number of runoff processes included (increasing from left to right).

runoff. At the least impervious site, modeled surface runoff is more variable and more often exceeds CN estimates than at the more impervious site (Figure 3). One outlier model produces more runoff than the observed rainfall while no irrigation is modeled during the event.

To reveal the separate runoff processes, we examine the differences between models that include or exclude infiltration, saturation, and interception excess. Missing runoff processes cause unlikely hydrographs with delayed or low surface runoff peaks (Figure 4). Most models missing infiltration excess still follow the rainfall pattern, as the site is mainly impervious. However, one model includes only saturation excess, and thus surface runoff lags behind even with precipitation rates of more than 50 mm h^{-1}. All models missing saturation excess simulate lower peak surface runoff than models with saturation excess (except the model missing interception excess). The three models missing interception excess produce less and delayed surface

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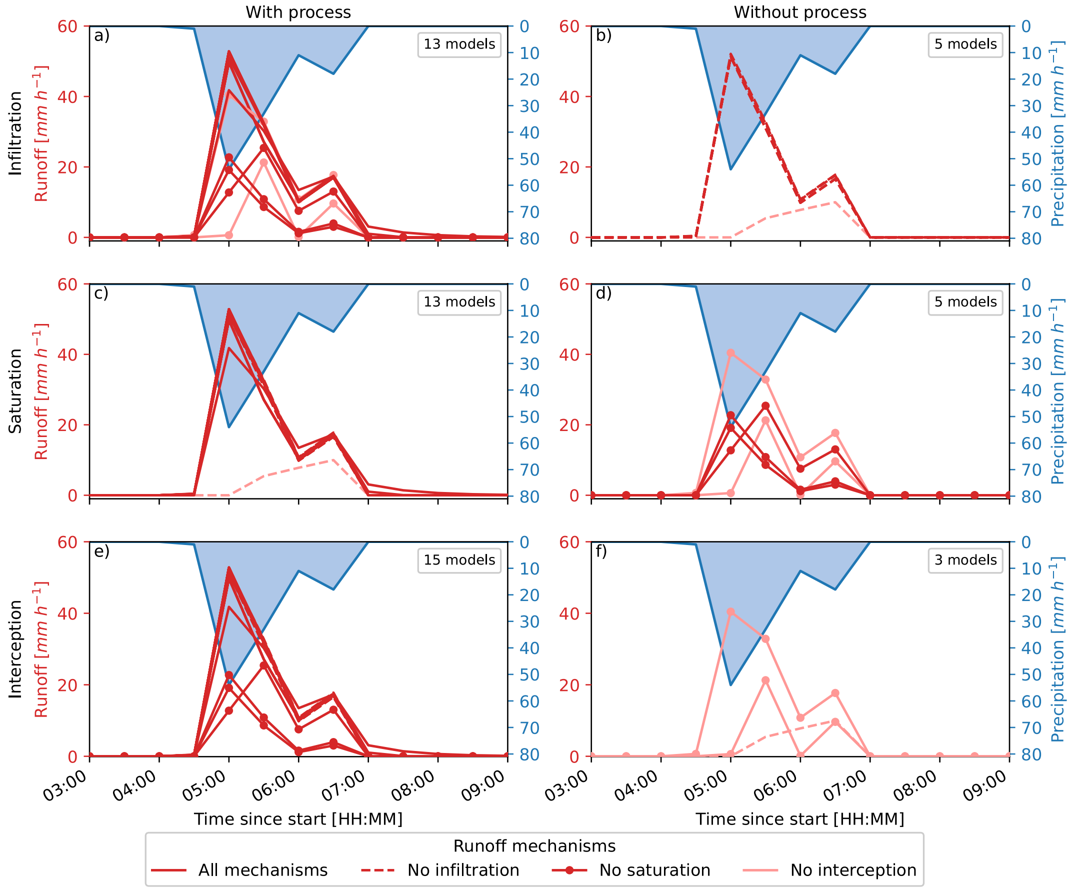

Figure 4. Dependence of modeled surface runoff response to model runoff parameterization illustrated with high-intensity precipitation at a highly impervious site ($F_I = 0.96$, KR-Jungnang) for 18 Urban-PLUMBER models (Table 1) including (a) infiltration, (c) saturation, and (e) interception excess; and missing (b) infiltration, (d) saturation, and (f) interception excess. The indicated time since the start corresponds with Figure 2. The number of models is indicated in each panel.

runoff missing impervious surfaces. The models missing runoff processes illustrate all processes are necessary to capture surface runoff correctly. Missing interception delays surface runoff and missing saturation lowers peak surface runoff.

4. Discussion and Conclusion

Examining the surface runoff parameterization of 18 ULSMs revealed not all models include surface runoff generation processes important in urban areas. Modeled surface runoff shows substantial variation between ULSMs, and ULSMs substantially exceed CN runoff estimates for low F_I, indicating further model evaluation and developments should focus on relatively green sites. The low model runoff is pronounced during low-intensity rainfall, possibly due to inadequate saturation excess or poorly estimated soil parameters. The variation in modeled runoff may result from missing processes, as models accounting for infiltration, saturation, and interception excess generate more surface runoff and higher surface runoff peaks. Additionally, seven models fail to simulate increased surface runoff for higher impervious fractions. We suspect the impervious surface parameterization in these models is inadequate and most likely fails to produce sufficient runoff.

As none of the 18 models represent slope and drainage systems, their effects are not considered. Yet, topography is a key factor in surface runoff generation (Hudson, 1985). Even gentle slopes increase surface runoff; a 1% slope may double while a 2.5% slope may triple surface runoff (Haggard et al., 2005). While topography from grid cell to grid cell is part of numerical weather prediction and climate models, the influence of sub-grid topography is parameterized for other processes like radiation (Helbig & Löwe, 2012) and drag (Sützl et al., 2021) but not always for runoff. TOPURBAN (Valeo & Moin, 2000) is a variable source area model adapted for the urban environment based on TOPMODEL (Beven et al., 1995). This model includes the sub-grid slope effect with the topographic index based on the slope and upstream drainage area. These are the only two parameters required for the TOPURBAN approach, which is compatible with ULSM concepts.

Most of the studied models do not separate drainage and piped water flows from surface runoff. As the models were run offline rather than coupled, it is not relevant for our conclusions whether water leaves the model as surface runoff, streamflow, or drainage. When ULSMs are spatially distributed or coupled to atmospheric models, it would be useful to separate these fluxes. For this separation and runoff routing, it is crucial to know how impervious surfaces are connected with streams or drainage systems (Baruch et al., 2018).

The surface runoff and evaporation shown here are calculated with observations at the temporal model resolution without sub-timestep information. Without sub-timestep information, models assume an average rainfall intensity for the sub-timesteps within the relatively long (half-) hourly resolution. The consequential loss of rainfall intensities detail changes the modeled runoff response, which has prolonged effects through the moisture conditions (Ward et al., 2018).

Currently, ULSMs miss runoff generation processes leading to biases in surface runoff. Moreover, seven models do not generate more surface runoff as the impervious fraction increases. Improvements could be made by at least including all three runoff generation processes and potentially extending the models to account for slope and drainage. Extra focus is warranted on the performance at greener sites and during low-intensity rainfall given higher intermodel spread in these circumstances. Improved surface runoff parameterization will provide more accurate water availability for evaporation. As evaporation from vegetation is a commonly proposed strategy to lower temperature in cities, the ULSMs will be better suited to predict the cooling benefits of vegetation. This enhanced predictive capability is also critical for supporting integrated climate adaptation strategies including storm water management, blue-green infrastructure design, and urban heat mitigation. Together these can contribute to making cities more livable and resilient.

Appendix A

Table A1 summarizes the key modelling results for all sites.

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Table A1
Overview Per Site of the Number of Precipitation Events Analyzed, the Accumulated Rainfall Over the Entire Modeled Period $\left(\sum P\right)$ *in mm, and the Accumulated Runoff Over the Same Period* $\left(\sum R\right)$ *as the Percentage of* $\sum P$ *(%)*

Site	Number of precip events	Precipitation (mm)	ASLUMv2.0	ASLUMv3.1	Cable	ECLand	ECLand-U	CLMU5	JULES_1T	JULES_2T	JULES_MORUS
AU-Preston	196	886	11	41	0	51	4	50	29	29	29
AU-SurreyHills	62	1,217	25	32	0	1	0	43	22	22	22
CA-Sunset	876	5,004	21	18	0	66	5	61	38	38	37
FI-Kumpula	225	1,789	4	4	1	7	1	40	35	35	34
FI-Torni	225	1,789	10	17	1	48	1	65	47	47	46
FR-Capitole	292	643	8	19	0	62	7	71	52	53	52
GR-HECKOR	65	421	6	26	0	64	7	74	67	67	67
JP-Yoyogi	673	7,122	34	31	12	78	28	83	69	69	69
KR-Jungnang	146	2,572	13	13	21	93	24	90	81	82	81
KR-Ochang	169	1,313	6	17	2	36	11	43	39	39	39
MX-Escandon	302	728	24	39	0	36	5	70	71	71	71
NL-Amsterdam	352	1,678	29	41	0	57	3	56	44	44	44
PL-Lipowa	541	2,389	5	22	0	14	1	60	36	36	36
PL-Narutowicza	540	2,389	8	23	0	9	1	52	31	31	30
SG-TelokKurau	147	1,281	16	51	2	83	15	74	81	81	81
UK-KingsCollege	340	1,371	28	31	0	51	6	61	55	55	54
UK-Swindon	433	1,607	16	13	0	45	5	40	27	27	27
US-Baltimore	530	6,057	17	18	6	44	13	31	31	31	31
US-Minneapolis1	212	1,921	13	15	5	5	5	20	28	28	28
US-Minneapolis2	212	1,921	16	16	5	5	5	8	19	19	19
US-WestPhoenix	32	111	2	2	0	1	0	35	46	46	46

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Manabe_1T	Manabe_2T	Noah-SLAB	Noah-SLUCM	Snuucm	Suews	TERRA_URB	Uclem	UT&C	CN	Observed
29	29	7	6	42	76	56	46 (57)	44 (270)	14	70
21	21	4	4	38	88	48	37 (40)	35 (88)	8	62
49	49	4	3	55	84	68	72 (0)	50 (371)	21	69
44	44	5	5	26	76	60	62 (0)	31 (375)	18	79
49	49	5	8	41	89	78	83 (0)	56 (171)	30	77
52	52	7	5	62	86	80	75 (0)	69 (58)	38	76
65	65	8	5	64	87	84	68 (45)	66 (75)	58	32
69	70	12	11	60	90	88	91 (0)	83 (50)	71	86
81	81	22	18	62	93	94	92 (0)	90 (4)	79	87
33	33	10	7	50	59	55	51 (0)	29 (369)	14	66
70	71	9	6	31	88	80	65 (38)	68 (112)	47	44
34	35	4	3	52	70	74	79 (0)	49 (140)	16	73
35	35	4	3	28	72	72	62 (0)	46 (583)	18	64
29	29	4	3	28	64	64	60 (0)	37 (798)	13	33
77	77	21	17	40	86	84	77 (0)	67 (168)	37	69
42	43	4	3	44	73	83	78 (0)	57 (39)	34	80
34	34	3	3	43	0	46	69 (0)	31 (104)	20	66
36	36	11	9	48	92	47	61 (0)	21 (390)	14	78
17	17	16	13	38	72	50	37 (0)	13 (355)	8	85
7	7	16	13	38	83	40	28 (0)	3 (405)	5	88
32	32	5	3	33	47	45	22 (184)	12 (201)	14	−81

Note. For the models, the accumulated runoff is the sum of all simulated surface runoff. For CN, accumulated runoff is derived by summing the runoff estimated per event over the entire period. For observations $\sum R$ is estimated through $\left(\sum P - \sum E\right)$. for the models with irrigation (UCLEM and UT&C), the accumulated irrigation is provided in mm in brackets, which is added to $\sum P$ before calculating the percentage.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All rainfall and evaporation observation data from this study are openly available at Zenodo (Lipson et al., 2022a). Model results are visualized at https://urban-plumber.github.io/sites and will be published together with Urban-PLUMBER Phase 2.

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