Focus Article

Testing the impact of at-source stormwater management on urban flooding through a coupling of network and overland flow models

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In many urban catchments, stormwater flooding is a serious problem. Low-impact development and the use of stormwater control measures (SCMs) have the potential to mitigate such flooding, but this potential is highly context specific and remains largely untested. In this study, we tested the potential of SCMs to impact stormwater flooding in a peri-urban catchment by coupling a one-dimensional 1D stormwater drainage model with a two-dimensional (2D) overland flow model. We predicted consequent flood dynamics for a range of storm events and management scenarios. We found that realistically extensive application of rain tanks and infiltration trenches is most effective in mitigating stormwater flooding for common-to-rare storm events [5- to 20-year annual recurrence interval (ARI)] with short durations, such that the events have rainfall depths that are similar to the retention (or storage) capacity of commonly used small-scale SCMs. Retention of stormwater also has the ability to mitigate overland flow intensity, positively impacting pedestrian safety and reducing potential building damage for rare events with ARIs above 20 years. In addition, SCMs also provide benefits to alternative options such as pipe upgrades, through their protection of receiving waters and enhancement of urban landscape amenity.

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INTRODUCTION

With the growth in population, flood risk is growing at an alarming rate, globally, with economic exposure concentrated in urbanized areas.[1] While riverine and coastal flood threats are critical considerations for flood risk management systems, urban stormwater flooding is also important.[2] In Victoria, Australia, alone (with a population of around 5.8 million),[3] stormwater-related flooding costs the community ~ $175,000,000 in damages annually.[4] Damages include those that are tangible (e.g., damage to building and contents, infrastructure, disruption to services) and intangible (e.g., loss of life and physical and psychological effects on human health and well-being, as well as damage to receiving waters through erosion and scouring of channels).[5]

Urban stormwater flooding is caused by runoff flow rates (primarily from impervious surfaces) that exceed the capacity of urban drainage systems (e.g., gulleys, pits, and storm sewers), and is relatively frequent because of limited drainage system capacity (e.g., 5- to 10-year ARI) and the potential for blockages.[2]

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Urban stormwater flooding can be alleviated (and potentially mitigated) in a number of ways. Possibly, the most common approach involves stormwater infrastructure augmentation and/or duplication.[6] Replacing existing stormwater pipes with larger ones is a typical strategy in this approach, albeit with high cost and disruption to the public during construction.[7] An alternative flood management approach is low-impact development (LID),[8–11] which also delivers benefits to receiving waters and landscape amenity.

In the LID approach, the aim is to restore the natural flow regimes through the infiltration and retention of impervious runoff. The underlying principle is to try to maintain the site water balance as close as possible to its natural state. To achieve this aim, impervious runoff is managed at-source using stormwater control measures (SCMs)—e.g., rain tanks, rain-gardens. By restoring natural flow regimes, the frequency and volume of impervious runoff (i.e., stormwater) delivered to receiving waters (via stormwater drainage systems) can be greatly reduced[10,12,13]—a prerequisite for the restoration of aquatic ecosystems.[14] In addition, the use of SCMs such as rain-gardens can improve the visual amenity of urban areas.[15]

At small scales (e.g., land parcel), recent research has found that SCMs can be designed to deliver effective stormwater infiltration and retention performance. For example, Gilroy and McCuen[10] developed a microwatershed model of suburban land parcels in Baltimore, MD, USA, and found that rain tanks were capable of controlling rooftop runoff from small storms. Burns et al.[16] predicted that a LID strategy comprising a rain tank overflowing to a rain-garden could mimic the hydrology of pervious land. At larger scales (e.g., streetscape and catchment), modeling studies are pointing to the potential for modest reductions in peak flows using rain tanks that capture runoff at residential land parcels, with diminishing results for more extreme events and in cases of uncontrolled impervious surface runoff (e.g., from the road network, car parks).[12]

Expecting diminishing flood hazard reductions with decreasing flood frequency, and a site-specific response to the implementation of SCMs based on land cover, topography, and climate, our goal is to test a framework that measures the site-specific impact of a limited range of SCMs on stormwater-related flooding. We test this approach on a peri-urban catchment in Southeast Australia where we predict flood dynamics for a range of theoretical storm events and management scenarios—e.g., current land use versus current land use with application of SCMs. A commonly used one-dimensional (1D) stormwater drainage model is coupled with a powerful 2D hydrodynamic overland flow model applied at the 'microwatershed scale' to pinpoint hot spots of potential flood risk. Results provide further evidence that LID, exemplified in this case by a combination of rain tanks and infiltration trenches, is a viable flood management approach. The LID strategy tested can effectively increase the design capacity of local drainage systems while simultaneously providing additional benefits through the protection of receiving waters and enhancement of landscape amenity. Furthermore, results suggest that the microwatershed scale overland flow model can successfully pinpoint localized flood hazards.

STUDY AREA AND METHODS

Our study site was a small peri-urban catchment in the eastern suburbs of Melbourne, Australia (Figure 1). The catchment has an area of 2.84 ha and is dominated by pervious land. Urban development in the catchment is characterized by low-to-medium density housing. There are 0.67 ha of impervious surfaces in the catchment (meaning that the catchment is 23.4% impervious), mainly composed of roof areas with some roads. Most impervious surfaces in the catchment drain to a (separate) stormwater drainage system. There are three side-entry (or open) stormwater pits in the road reserve, which drain 0.07 ha of road. All other stormwater pits in the catchment are junctions (and covered by lids). The drainage system conveys impervious runoff to a large stormwater pipe (750 mm) to the north of the catchment.

MANAGEMENT SCENARIOS AND STORM EVENTS

We conjectured two stormwater management scenarios: (1) developed and (2) developed with SCMs. In (1), we assumed current land use and stormwater infrastructure. The second scenario was the same as (1), but with SCMs draining *all impervious surfaces in the catchment*. Roof areas drained to rain tanks and all other impervious surfaces drained to infiltration trenches, which are made up of a gravel soil–based substrate, through which water infiltrates.

We considered design storm events ranging in duration (1 to 30 min) and magnitude (ARI; 1 to 100 years). We sourced design rainfall estimates specific to the study area (Australian Bureau of Meteorology, www.bom.gov.au) and used a suitable temporal pattern[17] to derive 84 synthetic storm events. The temporal pattern used was representative

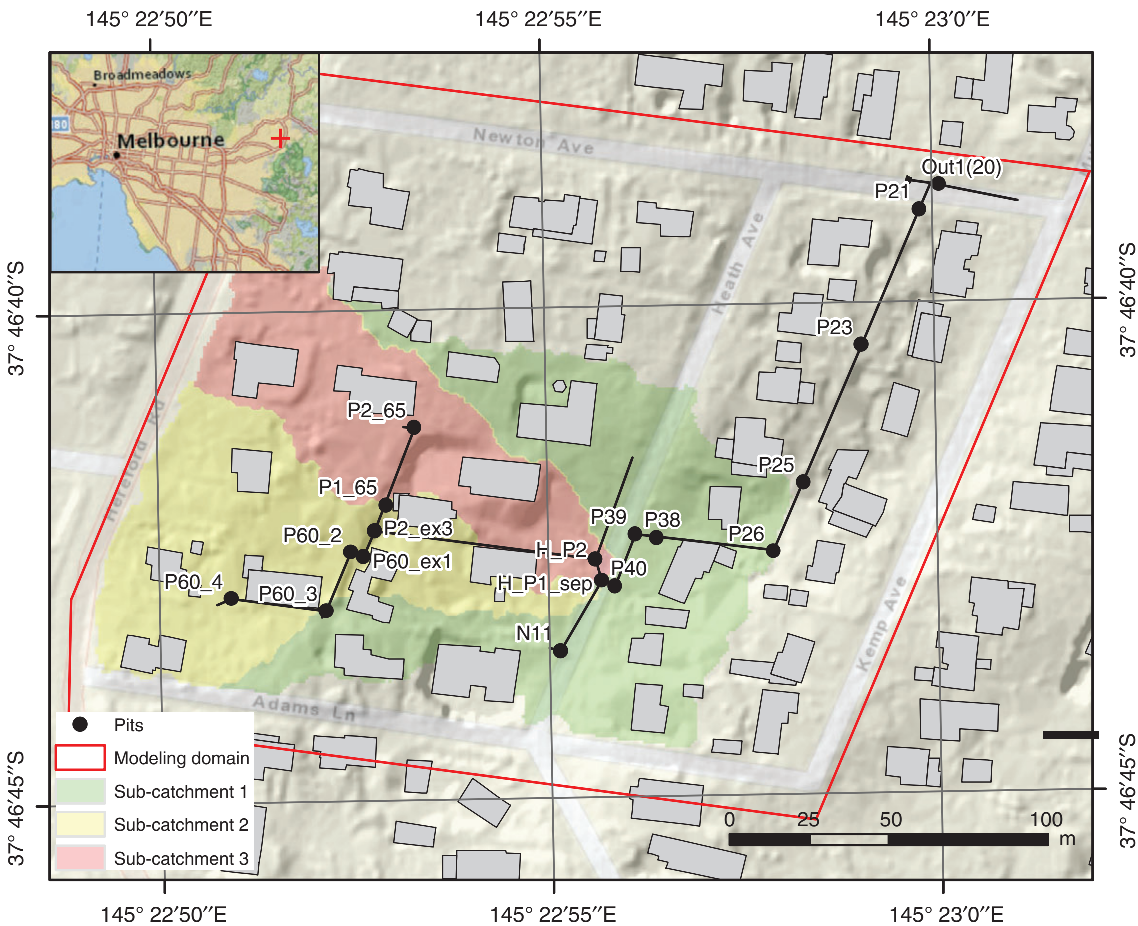

FIGURE 1 | The study site showing locations of stormwater pipes (black lines) and pits (dots). Two pervious subcatchments (shaded in red and yellow) drain to a side-entry pit (H_P1_sep). Thus, some pervious surface runoff flows into the stormwater drainage system. The other pervious subcatchment (shaded in green) flows near the closed pit P25.

of a short-duration thunderstorm event. We then combined all the storm events into one time series of rainfall and this became input to the modeling (described in detail below).

FLOOD MODELING

We tested the impact of SCMs on stormwater flooding through a coupling of network and overland flow models (Figure 2). The network model was used to predict stormwater-related flooding—i.e., flow that escapes (or surcharges) from the stormwater drainage system via pits. These flows became input to a hydrodynamic overland flow model, which predicted flood dynamics. Details on the network and overland flow modeling are described below.

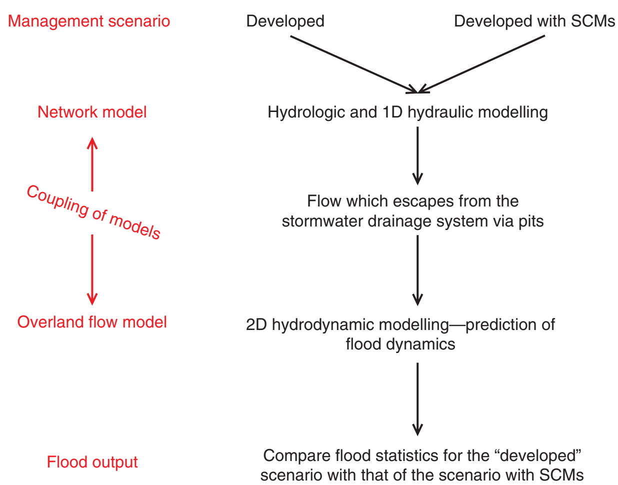

FIGURE 2 | Modeling flow chart.

Network Modeling

We used the SWMM model (USEPA, Cincinnati, OH) to carry out network modeling.[18] SWMM is a widely used hydrology-hydraulic-water quality simulation model. An SWMM model for the study catchment was built using various input data—e.g., land use data (impervious and pervious surface coverage; derived from aerial imagery) and stormwater drainage system information (sourced from local municipal design records). The input data were validated using field survey; any errors were corrected accordingly. The SWMM model was then calibrated to 20 small-to-moderate storm events recorded during 2014. Because none of these storm events were large enough to initiate pervious surface runoff in the catchment, we considered only *impervious surfaces* in model calibration. We do, however, account for pervious surfaces when modeling the large synthetic storm events (described below). Calibration data included 1-min rainfall [recorded at a nearby (600 m) pluviograph] and 1-min flow (recorded inside the catchment outlet stormwater pipe using a Sigma Hach 950 Submerged AV flow meter). The calibration approach involved sampling the space of four SWMM parameters—width of overland flow, Manning's n roughness coefficient for overland flow over impervious surfaces, slope, and pipe roughness. We ran the SWMM model 1925 times for calibration, each time with a different model parameter set. Using two objective functions (Nash-Sutcliffe model efficiency coefficient and a metric that measured the absolute percentage change between measured peak flow and modeled peak flow), we derived a well-calibrated SWMM model.

We then built variations of the calibrated SWMM model for each stormwater management scenario. For the 'developed' scenario, we added three pervious subcatchments to the calibrated model (Figure 1). Two of these subcatchments drained to a side-entry pit and the other drained near a closed pit in the northeast of the catchment. Soil properties of the pervious subcatchments were representative of the clay soils found in the study area (Table 1). The SWMM model for the 'developed with SCMs' scenario was the same as the 'developed' scenario, but with rain tanks and infiltration trenches deployed throughout the catchment. All roof areas drained to rain tanks (sized to 5000 L per 200 m^2 of roof area) and all other impervious surfaces drained to infiltration trenches (sized to 5% of their impervious catchment). Other infiltration trench properties included thickness (500 mm), void ratio (0.75), seepage (or exfiltration) rate (1 mm h^{-1}; identical to the minimum infiltration rate of the underlying soils), and no underdrain. We set all SCMs to be empty prior to each synthetic storm event.

SWMM models for the 'developed' and 'developed with SCMs' scenarios were run using the synthetic time series of storm events. For each scenario and storm event, we extracted time series of pit flooding (see pit location in Figure 1). These time series represented stormwater flooding and thus became input to the overland flow model.

Overland Flow Modeling

To predict flooding dynamics for each management scenario, we applied the hydrodynamic overland flow model BreZo (University of California, Irvine, CA), which solves the two-dimensional shallow-water equations.[19] BreZo flooding predictions are based on SWMM-predicted flow rates associated with surcharging at pits and pervious runoff, which were input to BreZo as time-dependent point sources positioned at pit locations and subcatchment outlets, respectively. Details on the coupling of SWMM and BreZo are presented by Kim et al.[20] To simulate flooding at the microwatershed scale, BreZo was run on a metric resolution unstructured mesh with an average cell size of 1.0 m in areas of inundation, based on the square root of the average cell area. Ground elevations were assigned to each mesh vertex by nearest-neighbor interpolation from a 1 m resolution Digital Terrain Model (DTM) derived from an aerial lidar survey with a root-mean-squared-error (RMSE) vertical accuracy better than 0.2 m (Department of Environment and Primary Industries; www.depi.vic.gov.au). A spatially distributed Manning's n parameter was used to model bottom shear and assigned to each cell in accordance with the landcover ($n = 0.012\ m^{-1/3}\ s$ for paved areas, $n = 0.02\ m^{-1/3}\ s$ for graveled drive ways, $n = 0.025\ m^{-1/3}\ s$ for grassy areas, and finally $n = 0.04\ m^{-1/3}\ s$ for areas with shrubs and tree canopy). The effect of buildings on flood propagation was resolved using the building-hole method[21,22] that assumes that building walls completely block overland flow, which is a good approximation at this site because buildings are constructed on concrete foundations and flood depths are relatively shallow. Previous research suggests that when the volume of flood water is known, BreZo predicts flood extent in suburban catchments with an accuracy approaching 80% using a metric resolution mesh that is parameterized with aerial lidar ground elevation data, a spatially distributed Manning's n based on landcover and the building-hole method.[22,23]

Presentation of Flood Results

We compare the maximum water depth (across storm durations) for the 'developed' scenario with that of the scenario with SCMs, for given storm magnitudes (1-, 5-, 20-, and 100-year ARI). In addition, we make a similar comparison with the maximum flow intensity.

TABLE 1 | SWMM Model Parameters for the Pervious Subcatchments in the Study Site

SWMM Parameters	Pervious Subcatchment 1	Pervious Subcatchment 2	Pervious Subcatchment 3
Outlet	By covered pit P25	Side-entry pit H_P1_sep	Side-entry pit H_P1_sep
Area (ha)	0.9386	0.6911	0.5482
Width of overland flow path (m)[1]	39.11	22.88	18.84
Slope (%)	13	13	13
% Imperv	0	0	0
N-Perv (Manning's n; $m^{-1/3}$ s)	0.1	0.1	0.1
Dstore-Perv (mm)	5	5	5
Maximum infiltration rate ($mm\,h^{-1}$)[2]	25.4	25.4	25.4
Minimum infiltration rate ($mm\,h^{-1}$)[2]	1	1	1
Decay constant (h^{-1})[2]	4	4	4
Drying time (days)[2]	2	2	2

[1]Estimated by dividing catchment area by the longest overland flow path.
[2]Horton infiltration parameters (representative of clay soils).

Differences in these flood statistics underscore the impact of at-source stormwater management on urban flooding.

RESULTS

Predicted flood depths for the 'developed' and 'developed with SCMs' scenarios are shown in Figure 3 for selected storm magnitudes (1-, 5-, 20-, and 100-year ARI), while Table 2 shows predicted flooded area for the full range of storm magnitudes. It can be seen in Table 1 that the deployment of SCMs has the biggest impact on infrequent storm events with return periods between 10 and 20 years, reducing the flooded area by around 40%. Figure 3 shows the locations where flooding from the 20-year storm is mitigated, especially in the vicinity of pit H_P2, eliminating a potentially 10- to 20-cm deep flood zone disturbing three structures. The effects of SCMs on rare storms, such as the 100-year event, is not as marked in terms of flood area reduction, although a shallow flood zone near pit P1_65 is eliminated. Flow depths are only spot-wise marginally reduced inside the primary flow path from pit H_P2 to the model downstream boundary. Figure 3 also shows that for frequent events with 1- to 5-year return periods, flooding is minimally affected by SCMs with the flood areas for these events being quite small even in the case without SCMs. We note that in this study, pervious runoff, generated in subcatchment 1 (Figure 1), is added to the overland flow model in the vicinity of pit P25; hence the flooded areas shown for the 1-year and 5-year return periods (Figure 3) are primarily a product of pervious runoff, and thus not affected by SCMs.

Figure 4 shows the effect of SCMs on the safety hazard presented by overland flow as measured by the flow intensity, defined as the depth-velocity product (hv). Flow intensity has been used as an indicator of the threat to public safety[24–26] as well as damage to buildings.[23,27,28] Jonkman and Penning-Rowsell[29] provide a review of established thresholds of flow intensity for pedestrian safety, indicating that adults experience a loss of stability between 0.5 and 2 $m^2\,s^{-1}$, depending on the person's height and mass.[30,31] In this study, predicted flow intensities within the primary flow path, regardless of the presence of SCMs, are generally far below the danger threshold of 0.5 $m^2\,s^{-1}$. The 100-year event attains an intensity of 0.1 $m^2\,s^{-1}$, which is unlikely to destabilize an adult but could threaten the safety of children. Return periods < 20 years yield proportionally smaller flow intensities (0–0.05 $m^2\,s^{-1}$). The ability of the SCMs to retain some of the impervious flow results in slightly reduced flow depths and in turn marginally reduced flow intensities for events with return periods of 20 years and larger. One exception exists for scenarios with return periods of 5 years and above, where a steep slope along the building in the vicinity of manhole P25 allows for faster flow velocities generating flow intensities above 0.5 $m^2\,s^{-1}$ and escalating flood hazard locally. Here, deployment of SCMs does not mitigate flood hazard below the potential danger level.

DISCUSSION

Our results suggest that flood mitigation by SCMs is effective when the cause of such flooding is

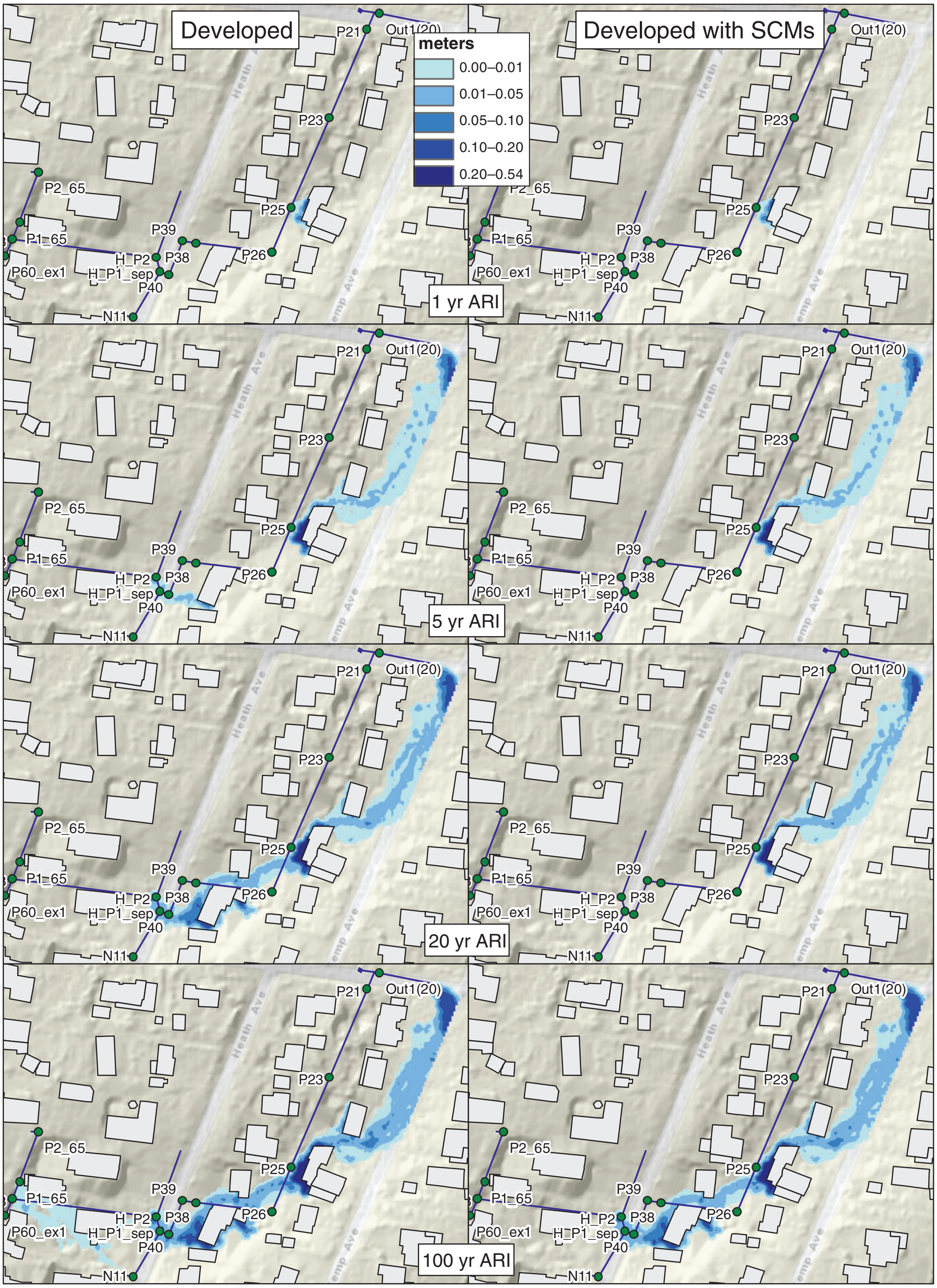

FIGURE 3 | Predicted flood depths from aggregate storm durations for selected return periods.

short-duration storm events, which have rainfall depths that are of a similar magnitude as the available retention (or storage) capacity of commonly used small-scale SCMs such as rain tanks and infiltration trenches. For our study site, it was short-duration storm events (≤18 min) with moderate rainfall depths (≤20.4 mm; ≤ 20-year ARI) that caused considerable stormwater flooding. The SCMs had a substantial impact on this flooding because they could retain much of the impervious runoff (25 mm for rain tanks

TABLE 2 | The Effect of SCMs on Flooded Area

ARI (X years)	Scenario: Developed (m^2)	Scenario: Developed with SCMs (m^2)	Reduction of Flooded Area (%)
1	185	185	0
1.5	1284	1284	0
5	2004	1729	14
10	2835	1795	37
20	3071	1850	40
50	3886	2973	23
100	4564	3211	30

and 11 mm for infiltration trenches). It should be noted that we assumed that the SCMs were empty prior to each storm event. To ensure that this is a realistic assumption, the SCMs need to be designed appropriately. For example, the rain tanks must be either connected to demands, which regularly drawdown the storage (e.g., use for toilet flushing, hot water, and clothes washing), or designed to release water prior to storm events. Such a release may either occur passively (with a controlled trickle flow released either to the stormwater network or to passively irrigated garden or open space areas) or through real-time-control, such that a controlled release from the tank is initiated remotely by a server using predicted rainfall. In the latter situation, the tank may release enough volume to retain the predicted rainfall over the next 24 or 48 h. Control of infiltration systems is more difficult, although theoretically similar principles could apply, with a piped release back to the stormwater network, based on predicted rainfall. In addition, such SCMs must be regularly maintained. A future improvement in this work would be to consider the stochastic behavior of SCMs, perhaps using Monte Carlo Simulation.

Predictions of flood dynamics show that channelized flows along natural depressions can be obstructed by building foundations, causing a deflection of the flow path and relatively deeper ponding at the face of the building (e.g., Figure 3). Hydrodynamic overland flow models require an explicit treatment of buildings to resolve this effect at the point scale, such as the building-hole method used here or the building-block method whereby building geometries are extruded from the computational mesh.[22] Alternative building treatments such as the building resistance method and the building porosity method[22,32] are not recommended in this situation. With the building resistance method, there is no model capacity to completely block flow, which is essential to compute ponding at the building face, while the building porosity method is designed to predict flooding dynamics at the land parcel scale (not the point scale) and involves a mesh resolution comparable to the building size (typically 10 m). Furthermore, none of the preceding methods are designed to account for transmissive building foundations, such as the pier and beam type that includes a crawlspace, or for flows through open doors and windows. Hydrodynamic overland flow models generally do not resolve this level of detail, and these limitations should be kept in mind when flood depth predictions are applied for flood hazard analysis and mitigation purposes. It is possible to extend flood inundation models to account for these details, but any such model would demand extensive building geometry data that are unlikely to be accessible for modeling studies. Overland flow predictions from this case study show that flow intensities are below the thresholds for adult pedestrian safety and building damage, but microwatershed flood hazard data such as this could help to substantially improve flood preparedness and mitigation, for example, by providing household-level guidance on where flood mitigation measures such as flood proofing are needed and by mapping the location of both danger and safety zones within a community.

CONCLUSION

This study shows the ability of SCMs to reduce urban stormwater flooding in a peri-urban catchment, which has been fitted with rain tanks and infiltration trenches at small scales. The tested SCMs are able to retain stormwater runoff reducing flooded area, and as expected function best for medium frequency events with average recurrence interval of 10–20 years. For those events, a flood area reduction of up to 40% is observed, while less frequent and more severe events with 50- to 100-year average recurrence interval are attenuated by up to 30%. The difference in performance is attributable to the produced rainfall depth, which in the case of medium frequency events is more similar to the magnitude of the available capacity of the tested SCMs. Impervious runoff retained by SCMs has also shown to reduce flow depth, which in turn reduces flow intensity. This is true for medium to even rare storm events, where flood hazard along streets is mitigated, positively impacting pedestrian safety, while reduced intensities surrounding buildings mitigate damages to buildings. SCMs appear less beneficial for frequent storm events with 1- to 5-year average recurrence intervals. Here, pervious runoff, which is not treated by SCMs, is still able to produce

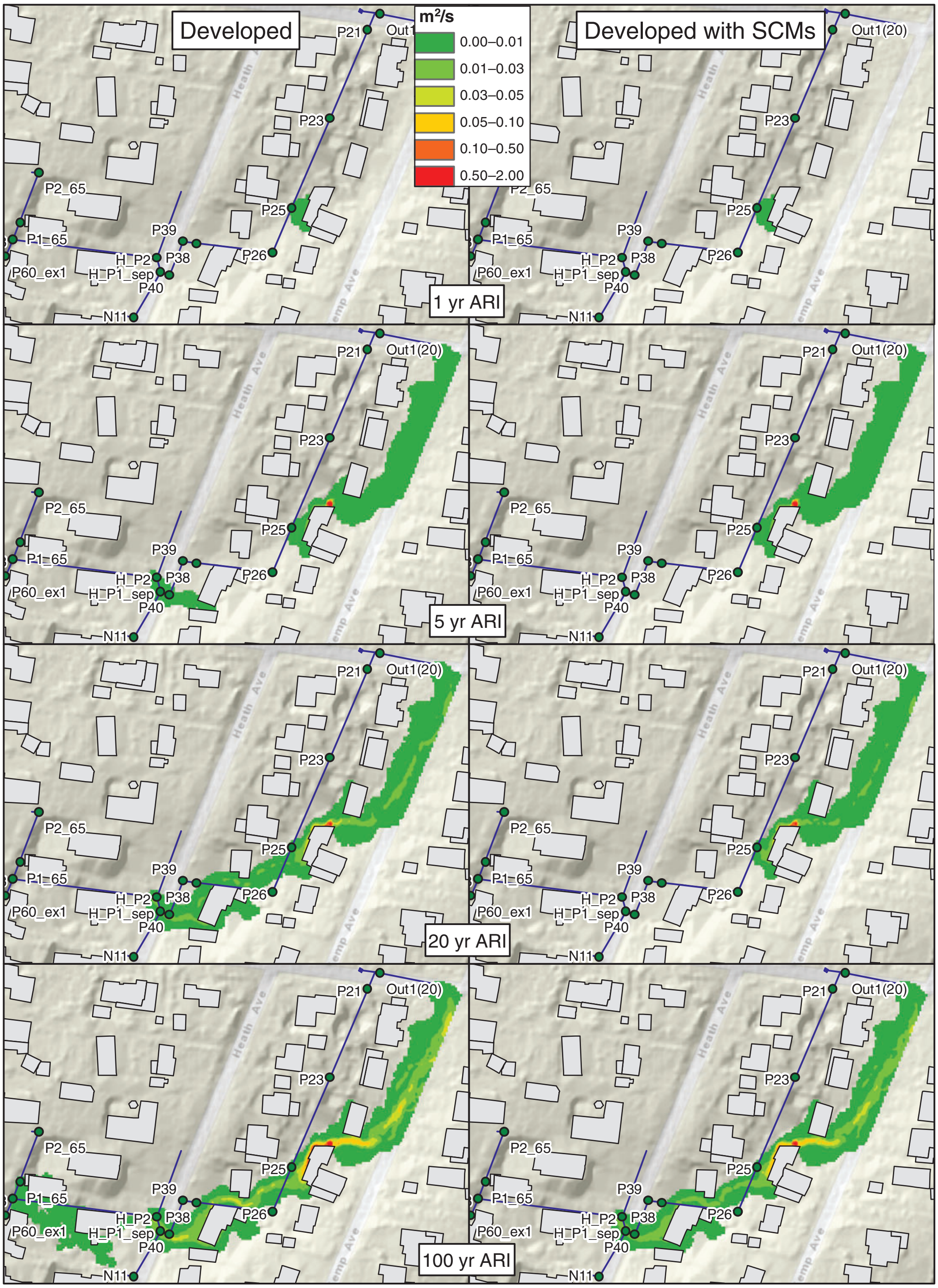

FIGURE 4 | Predicted depth-velocity product from aggregate storm durations for selected return periods.

flooding that on steep slopes can result in hazardous yet localized conditions.

Adding to the existing arguments for LID (water quality improvement, restoration of more natural flow regimes, improvement of the urban microclimate and urban amenity), this work provides further evidence that at-source stormwater management is a viable option for localized flood hazard mitigation. In developed catchments that are prone to stormwater flooding, the use of SCMs could offset the need for infrastructure augmentation (e.g., pipe upgrades). In urbanizing catchments, their use could substantially reduce the amount of stormwater infrastructure required. An economic analysis of using LID for flood management versus alternative approaches warrants further study. Importantly, this analysis should consider the additional benefits of LID, including the protection of receiving waters and enhancement of the urban landscape amenity. In doing so, LID could present a particularly attractive option, not only for flood management but also for catchment management more generally.

An important direction for future research is to explore the impact of SCMs at larger scales (e.g., whole-of-catchment). The use of SCMs could help alleviate riverine urban flooding—i.e., urban streams bursting their banks and inundating nearby buildings, although such potential remains to be thoroughly explored. In doing this work and thus propagating floods into stream channels, the geomorphic impacts of SCMs could be assessed. By using SCMs to reduce the frequency and volume of urban stormwater runoff delivered to streams, the shear stresses applied to the channel might be lowered, thus leading to reduced stream erosion.

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