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The effect of Sustainable Urban Drainage Systems on outdoor comfort and runoff

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Abstract. Cities are facing numerous challenges such as Urban Heat Island Effect (UHIE) and more frequent flooding events, due to the increasing soil sealing. Greenery and water implemented in urban outdoor spaces have been promoted as effective strategies to counteract UHIE while Sustainable Urban Drainage Systems (SUDS) have been identified as convenient solutions to increase resilience to flooding. However, since many SUDS are green-based, they also benefit urban microclimate and outdoor thermal comfort. In this work, the effectiveness of SUDS as passive strategies to simultaneously improve outdoor thermal comfort and reduce stormwater runoff is assessed. The analysis is carried out on a neighbourhood in Ostia (Rome), selected as representative of Mediterranean climate. The case study area is modelled on ENVI-met in three different scenarios: the current condition is compared with two future developments in which green and water-based mitigation strategies are implemented or in which soil sealing continues based on current trend. Moreover, for each scenario, stormwater runoff has been determined using the Soil Conservation Service curve number method. Results show that the implemented mitigation strategies allow achieving improved thermal comfort conditions and at the same time they can reduce runoff.

1. Introduction

This study estimates to what extent urban mitigation strategies can help to reduce the negative effect of anthropization on the urban environment and human wellbeing in the Mediterranean climate. More in detail, the paper considers two crucial challenges that cities face, the urban heat island effect (UHIE) and urban flooding (UF), to decrease their negative impact on urban areas. The positive effect of greenery and water in the mitigation of both challenges is widely known [1–3]and here we evaluate greenery and water presence in cities under the light of outdoor thermal comfort and runoff risk reduction, combining the two aspects towards a wider comprehension of the coupled effects of such solutions. Urban form, thermal properties of buildings and urban materials, and anthropogenic heat sources modify the urban energy balance in comparison to the rural one, determining an increase in air temperature in urban areas. This phenomenon, namely the urban heat island effect (UHIE) implies a significant impact on the outdoor comfort in urban areas, worsening citizens' wellbeing, especially during summer [4]. A strategy to face UHIE is to increase evapotranspiration and provide shadowed areas employing greenery and water, still controlling for humidity caused by such solutions. The same strategies are also beneficial towards flooding risk reduction and are among the most diffused solutions in Sustainable Urban Drainage Systems (SUDS), with particular respect to surface water drainage [1, 5]. While the effect of greenery and water on urban temperatures and citizens' thermal comfort has been widely investigated, as well as the effect of green/water-based SUDS on flooding risk reduction, the two aspects have not been studied together. Here we considered situations where the use of green areas and water allow to pluvial water to percolate through soil, partially restoring the water-cycle in urban impervious areas and, thus, reducing runoff by pluvial flooding. A neighborhood in Ostia (Rome) is presented and analyzed as a significant case study of the Mediterranean climate, under different scenarios.

2. Method

The effectiveness of Sustainable Urban Drainage Systems (SUDS) mitigation strategies with respect to both runoff reduction and microclimate were evaluated by means of numerical analyses. More specifically, we selected a case study urban area; then, we hypothesized different scenarios for the future and modelled the reference case study and the other scenarios on ENVI-met. On the same case study and scenarios, runoff was calculated. Finally, both the results are compared, to obtain a comprehensive view on SUDS performance in urban areas. In the next sub-sections, the method that we employed is more in depth described.

2.1 Mitigation strategies

Research on outdoor thermal comfort and studies on flooding risk reduction both promote strategies aiming at reducing the negative consequences of soil sealing in urban areas. Indeed, the extensive use of impermeable materials, often characterized by low albedo and large thermal admittance and capacity, increases sensible heat within urban boundaries, thus contributing to the Urban Heat Island Effect (UHIE) [6]. At the same time, it also has a great influence on soil hydrology, exacerbating the risk of flash floods from intense rain events [6]. The mitigation strategies include the implementation of greenery and water in urban outdoor spaces and the application of specific stormwater control measures characterized by vegetation or permeable paving, which are able to improve the outdoor thermal comfort and to reduce stormwater runoff through shading, evaporation, evapotranspiration, retention and infiltration mechanisms [7]. Sustainable Urban Drainage Systems (SUDS) are flood mitigation strategies specifically designed to bring the flow of runoff in urban landscape closer to pre-development natural level [8] and since many of them are green-based, they also have benefits on urban microclimate and outdoor thermal comfort.

In the improved simulation scenario presented in this paper, the implemented strategies include permeable pavements in existing parking lots, green areas and water ponds in public outdoor spaces and trees in streetscapes and squares. Permeable pavements (PPs) are made of impermeable modular elements, but voids between elements allow water infiltration and soil-atmosphere gas exchange [6]. Their hydraulic efficiencies are comparable with the efficiencies of vegetated SUDS: indeed, it was demonstrated that PPs allow the reduction of the generated runoff volume and of the peak flow with efficiencies over 80% and 95% respectively, slow flow velocities and increase the water residence time around 70% [8]. Even when built over low-conductivity, clay soils, PPs can considerably improve long-term hydrology especially if they include an internal water storage zone [9]. Referring to thermal benefits, PPs are effective in mitigating the UHIE via evaporative cooling [10]. Among the vegetated SUDS that can be implemented in the green areas designed in the Ostia case study, there are bioretention cells, raingardens, infiltration trenches and tree pits. Bioretention and raingardens have been demonstrated to be the most effective runoff mitigation strategies in low-density residential watersheds [11]. More specifically, bioretention cells are biologically-based media filters designed to temporarily store and treat a prescribed water volume from highly impervious catchments: the inclusion of an internal water storage zone allows these systems to significantly reduce runoff and peak flow, even in areas characterized by low permeability soils [12]. Vegetated raingardens - garden beds designed to capture and filter rainwater using a permeable soil substrate and plants [13] - have been proved to be effective in reducing the total volume of runoff, its frequency and peak flow [13]. Instead, infiltration trenches can be used to retain stormwater runoff directing it from roads to passively irrigate established urban trees: they show significant potential for high runoff retention but their performance is lower compared with alternative stormwater control measures such as raingardens [14]. Finally, tree pits are particularly suitable in dense urban areas due to their small size and have been proved to be effective in reducing annual runoff volume and frequency [15].

Referring to thermal benefits, all these different types of stormwater control measures contribute to mitigate UHIE because they include vegetation layer: trees and grassland in cities are proved to guarantee lower air and mean radiant temperatures (T_a, T_{mr}) mitigating human heat stress related to UHIE and thus improving outdoor thermal comfort indices such Predicted Mean Vote (PMV) or MOCI, which was specifically tailored on Mediterranean population [16]. Indeed, vegetation decrease solar radiation absorption by shading and evapotranspiration [7]: trees and bushes are able to decrease T_{mr} due to the reduction of radiative exchanges (longwave radiation) [17]; moreover, greenery also controls incident and reflected direct shortwave radiation thanks to evapotranspiration and it permits to decrease PMV [17].

Finally, water ponds have been proved to have positive effects on urban microclimate, improving the quality of the outdoor thermal environment and pedestrian comfort: it was demonstrated that the implementation of a water pond in a built-up area, indeed, decreases air and radiant temperatures throughout the day mainly through evaporation, creating urban cool islands [18].

2.2 Case study and scenarios
The case study area chosen for the analysis is a public square in Ostia Lido, Municipality of Rome, central Italy. The case study has been chosen due to the local climate, very hot during summer, and since it is subject to pluvial flooding, due to insufficient sewer drainage system. The height of the flooding does not represent a direct risk for human life but indeed it negatively affects the commercial and regular activities in the area. The modelled area is 140x140 m wide, mainly composed by urban paving and asphalt roads and sidewalks. Three green areas are also present, but the soil is not irrigated. The trees in the area are mainly palm trees, while buildings are 2 to 4 floors high.

The current situation is referred to as "Ref" scenario. Then, SUDS are hypothetically applied in the "Strat" scenario: green, irrigated areas are added (for a total of 2900 m^2), as well as trees and permeable paving for the parking lots (1900 m^2) and 250 m^2 of water ponds in the green areas. Finally, a "Dev" scenario following land consumption trends in Ostia [19] was modelled, where the existing green areas have been covered by impermeable paving. The pluviometry data are derived from [20], where all the main flooding events in the area are collected. For the runoff analysis, the selected value is referred to the event of the 20 October 2011, characterized by a rainfall height of 96,7 mm and a return period of 5 years.

2.3 Outdoor microclimate simulation
For the microclimate simulation, Ref, Strat and Dev scenarios were modelled and simulated on ENVI-met software. The dimension of the grid cell was 2mx2m, and simulations were conducted for 24 hours, from 7 am of the 7th August to 7 am of the 8th August, one of the hotter days in the specific local climate, by considering the "Lido di Ostia" climate file. ENVI-met allows to compute, throughout maps and data on specific grid cells, all the microclimate variables, such as mean radiant temperatures, surface and air temperatures, wind speed and relative humidity [21]. All these values are then employed to evaluate the MOCI [22], a specific comfort index tailored on the Mediterranean population: while 0 represents thermal neutrality, negative values indicate cold sensation and positive ones hot sensation. MOCI was calculated for different points in the case study area, as indicated in Figure 1.

2.4 Runoff estimation: the SCS Curve Number Method
The runoff reduction has been estimated through the Soil Conservation Service Curve Number (SCS) curve number method [23], a simple and efficient method to quantify the approximate amount of runoff from a rainfall event in a specific area. The inputs to carry out the analysis with this method are rainfall amount and curve number (*CN*). The curve number is based on the area's hydrologic soil group, land use, land cover type and hydrologic condition. The value of *CN* varies according to the land use and the kind of soil.

The empirical equation in reference is reported in Eq.1, where: Q = runoff (mm); P= rainfall (mm); S= potential maximum retention after runoff begins (mm); I_a= initial abstractions is calculated as in Eq. 2.

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \quad (1)$$

$$I_a = 0.2\,S \rightarrow Q = \frac{(P-0.2\,S)^2}{(P+0.8\,S)} \rightarrow S = \frac{25400-254\,CN}{CN} \quad (2)$$

3. Results

3.1 SUDS effect on microclimate

The numerical analyses demonstrated that the considered SUDS are able to improve microclimate conditions. Indeed, as can be noticed from the maps below, Dev scenario has higher temperatures than Ref, and on its turn, Strat has lower temperatures than Ref. More precisely, on the square and sidewalks, Dev reaches around 40°C and above as surface temperature (T_{surf}), and 68°C and above as mean radiant temperature (T_{mr}); in Ref, temperatures on the sidewalks are similar to Dev, but much lower T_{surf} are visible in the squares (32-34°C) as well as slightly lower T_{mr}, equal to 66°C. Strat displays even lower T_{surf}, 28-35°C in the green squares, while the water ponds reach even lower temperatures. T_{mr} is lower especially in the squares (64°C, and as low as 42°C close to the trees), where trees are present.

With respect to MOCI, comfort levels are comprised between -0.5 and 0.5. A walking pedestrian is considered for MOCI calculation, wearing typical summer clothes, equal to 0.54 clo, i.e., short trousers, short-sleeved t-shirt and sandals. Considering midday hours, MOCI rarely goes below 1.9, which means strong thermal discomfort for pedestrians. Therefore, mitigation strategies that could also positively affect microclimate are of fundamental importance to reduce thermal stress on citizens walking or resting in public areas. The impact of the application of SUDS, especially green and trees in the squares (PT1 from Figure 1), is visible in the MOCI. Indeed, Ref scenario shows -0.2 MOCI points with respect to Dev, between 10 am and 6 pm. Strat significantly improves thermal comfort sensation, being 1.0 lower than Dev and 0.8 lower than Ref, especially around 2 pm – 5 pm.

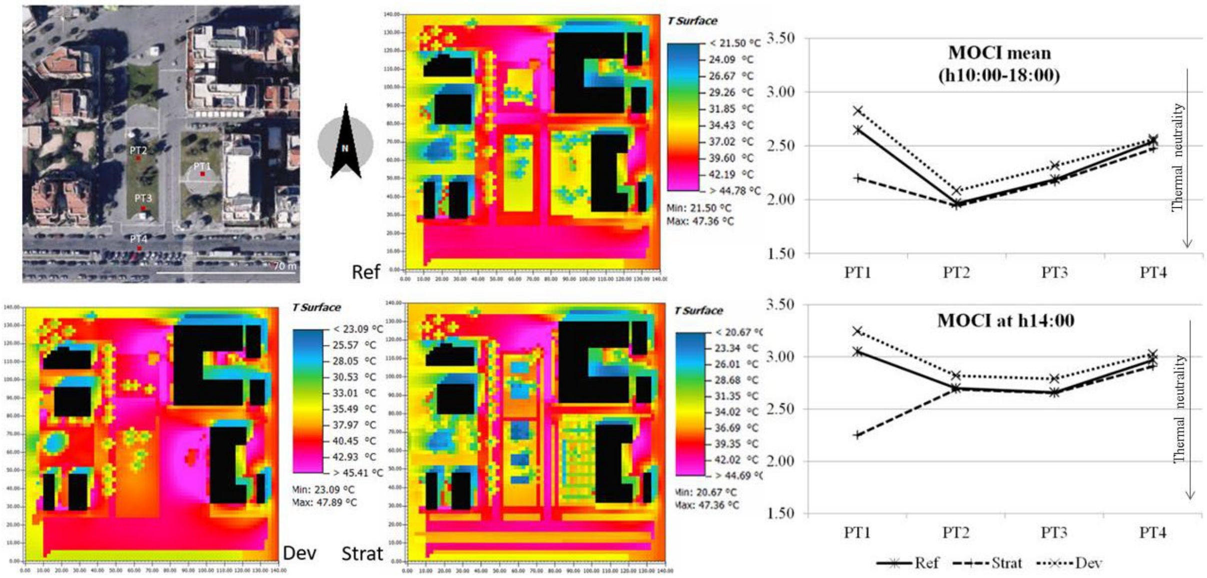

Figure 1. Case study area and maps of surface temperatures for each scenario.

3.2 SUDS effect on runoff

The three scenarios have been evaluated also with respect to runoff reduction through the implementation of SUDS. More precisely, in terms of input characteristics for the different scenarios, the following have been considered: (i) Ref: the analysis is based on the case study in the current situation; the examined area has a mixed distribution of activities, mainly residential and commercial with high land consumption. The green areas lack any irrigation system and the soil is sandy. Consequently, the considered CN refers to "urban district" with soil group "A" and a curve number equal to 89. According to the equations listed above, the assumed value for P is equal to 96.7 mm in 24 hours for the event considered with a return period of 5 years [20], as that one of a severe event in 2011, which caused a minor pluvial flooding in the whole area.; (ii) Dev: for the second case we considered the higher imperviousness of the urban area, with more paved areas; so, the CN for this case is equal to 98, since the drainage is ensured only by the sewer system and not by the infiltration; (iii) Strat: for the third scenario, where the SUDS were implemented in order to reduce stormwater runoff, the total area is 19.600 m^2, the green areas are 4.801 m^2 with the addition of 250 m^2 of water ponds, increasing the percentage of non-consumed soil to approximately the 24.5% of the total area so that the imperviousness of the area is reduced and we can assume a value of CN equal to 77.

Therefore, using the SCS Curve Number method the results are, for Ref, 67.11 mm; for Dev, 90.84 mm and for Strat, 42.21 mm. The results obtained through the SCS Curve number method show a significant reduction of the runoff in Strat scenario, confirming the effectiveness of the adopted strategies also under this point of view.

4. Conclusions

In this preliminary work, the effectiveness of sustainable urban drainage systems (SUDS) was evaluated by means of numerical methods. The SUDS considered in the Strat scenario are the addition of green areas, water ponds, and trees. Such simple solutions could be further enhanced, in terms of results in runoff reductions, by successive steps, by also more specifically modelling tree pits, infiltration trenches and bioretention to the strategies applied in Strat. The case study area, in Ostia, close to Rome (central Italy) was modelled in three different scenarios, Ref, Dev and Strat, being the latter the more effective in reducing runoff and improving microclimate (lower MOCI). Indeed, while Dev heightened T_{surf} (+6-8 °C) and T_{mr} (+2°C), the strategies applied in Strat were able to lower T_{surf} up to 6°C and T_{mr} up to 10°C in the considered area, especially in PT1, where trees were added. Such results are in line with existing literature [7], describing reductions of around 10°C both in T_{surf} and T_{mr} due mainly to the shading effect of trees. Also pedestrians' comfort was improved in Strat scenario up to 0.6 point with respect to Dev and 0.4 with respect to Ref, in accordance with previous research [24]. Runoff reductions for Strat scenario, equal to -25/50 mm, are in line with literature [8].

This work aims to highlight the need for an integrated analysis with respect to strategies to mitigate extreme events, such as pluvial flooding and heat-waves. Future studies could validate such numerical analysis by means of in-field measurements and could consider wider urban areas and a wider variety of SUDS.

References

[1] Pappalardo V, La Rosa D, Campisano A, et al. The potential of green infrastructure application in urban runoff control for land use planning: A preliminary evaluation from a southern Italy case study. Ecosyst Serv 2017; 26: 345–354.
[2] Tong S, Wong NH, Tan CL, et al. Impact of urban morphology on microclimate and thermal comfort in northern China. Sol Energy 2017; 155: 212–223.
[3] Cascone S, Coma J, Gagliano A, et al. The evapotranspiration process in green roofs: A review. Build Environ 2019; 147: 337–355.
[4] Coccolo S, Kämpf J, Mauree D, et al. Cooling potential of greening in the urban environment, a step further towards practice. Sustain Cities Soc. Epub ahead of print 2018. DOI: 10.1016/j.scs.2018.01.019.
[5] Galderisi A, Trecozzi E. Green strategies for flood resilient cities:The Benevento case study. Procedia Environ Sci 2017; 37: 655–666.
[6] Fini A, Frangi P, Mori J, et al. Nature based solutions to mitigate soil sealing in urban areas: Results from a 4-year study comparing permeable, porous, and impermeable pavements. Environ Res 2017; 156: 443–454.
[7] Duarte DHS, Shinzato P, Gusson S, et al. The impact of vegetation on urban microclimate to counterbalance built density in a subtropical changing climate. Urban Clim 2015; 14: 224–239.

[8] Rodríguez-Rojas MI, Huertas-Fernàndez F, Moreno B, et al. A study of the application of permeable pavements as a sustainable technique for the mitigation of soil sealing in cities : A case study in the south of Spain. J Environ Manage; 205. Epub ahead of print 2018. DOI: 10.1016/j.jenvman.2017.09.075.
[9] Braswell AS, Winston RJ, Hunt WF. Hydrologic and water quality performance of permeable pavement with internal water storage over a clay soil in Durham , North Carolina. J Environ Manage 2018; 224: 277–287.
[10] Wang J, Meng Q, Tan K, et al. Experimental investigation on the influence of evaporative cooling of permeable pavements on outdoor thermal environment. Build Environ 2018; 140: 184–193.
[11] Eaton TT. Approach and case-study of green infrastructure screening analysis for urban stormwater control. J Environ Manage 2018; 209: 495–504.
[12] Winston RJ, Dorsey JD, Hunt WF. Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. Sci Total Environ 2016; 553: 83–95.
[13] Richards PJ, Farrell C, Tom M, et al. Vegetable raingardens can produce food and reduce stormwater runoff. Urban For Urban Green 2015; 14: 646–654.
[14] Szota C, Coutts AM, Thom JK, et al. Street tree stormwater control measures can reduce runoff but may not benefit established trees. Landsc Urban Plan 2019; 182: 144–155.
[15] Grey V, Livesley SJ, Fletcher TD, et al. Tree pits to help mitigate runo ff in dense urban areas. J Hydrol 2018; 565: 400–410.
[16] Rosso F, Golasi I, Castaldo VL, et al. On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban canyons. Renew Energy 2018; 118: 825–839.
[17] Salata F, Golasi I, Vollaro ADL, et al. How High Albedo and Traditional Buildings' Materials and Vegetation Affect the Quality of Urban Microclimate. a Case Study. Energy Build 2015; 99: 32–49.
[18] Imam Syafii N, Ichinose M, Kumakura E, et al. Thermal environment assessment around bodies of water in urban canyons: A scale model study. Sustain Cities Soc 2017; 34: 79–89.
[19] ISPRA. Consumo di suolo, dinamiche territoriali e servizi ecosistemici. Edizione 2018, http://www.isprambiente.gov.it/it/pubblicazioni/rapporti/consumo-di-suolo-dinamiche-territoriali-e-servizi-ecosistemici.-edizione-2018 (2018).
[20] Giandonato A, Garcia C, Laudiero F. Studio per il risanamento idraulico dei bacini delle acque medie e basse dell ' area di Roma Sud e individuazione degli interventi per la mitigazione del rischio idraulico nelle aree oggetto di studio.
[21] Coccolo S, Kämpf J, Scartezzini JL, et al. Outdoor human comfort and thermal stress: A comprehensive review on models and standards. Urban Clim 2016; 18: 33–57.
[22] Salata F, Golasi I, de Lieto Vollaro R, et al. Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy. Build Environ 2016; 96: 46–61.
[23] Ara Z, Zakwan M. Estimating Runoff Using SCS Curve Number Method. Int J Emerg Technol Adv Eng 2018; 8: 195–200.
[24] Salata F, Golasi I, Vollaro E de L, et al. Evaluation of different urban microclimate mitigation strategies through a PMV analysis. Sustain 2015; 7: 9012–9030.