



# Scenario-Based Hydraulic Assessment of Sustainable Urban Drainage in an Allotment from Northeastern Portugal <sup>†</sup>

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## Abstract

Urbanization and climate change increase stormwater runoff and pressure on conventional drainage systems. This study compared six drainage-design scenarios in a 2.1 ha allotment in northeastern Portugal, combining pitched, flat, and extensive green roofs with conventional or sustainable pavements. Using weighted runoff coefficients, the rational method, and Portuguese design criteria, effects on runoff, peak discharge, downstream pipe sizing, and public drainage-network construction cost were estimated. The most sustainable scenario reduced the runoff coefficient from 0.70 to 0.50, the estimated peak discharge by 29.31%, and the estimated public drainage-network construction cost by 10.65%. Results support source-control solutions in allotment-scale drainage design.

**Keywords:** sustainable urban drainage; green roofs; sustainable pavements; stormwater runoff; drainage network design

## 1. Introduction

Climate change and ongoing urban growth are increasing stormwater-management challenges in cities. Conventional stormwater management has often followed a linear approach, aiming to collect and discharge runoff as quickly as possible to prevent local flooding. However, more frequent intense rainfall events and the progressive sealing of urban surfaces can increase runoff and peak discharges beyond the capacity of conventional drainage systems. These conditions reinforce the vulnerability of urban areas to flooding and highlight the need for more integrated and resilient approaches to stormwater management [1,2]. In this context, source-control and nature-based solutions are increasingly relevant because they can retain, infiltrate, delay, or temporarily store stormwater before it reaches the public drainage network [1–3]. Among these solutions, green roofs and permeable pavements are particularly relevant at the scale of urban allotments: green roofs can reduce and delay runoff from buildings, while permeable pavement systems can promote infiltration, subsurface storage, and attenuation of overland flow [3–7]. However, their performance is case-specific and depends on factors such as design characteristics, substrate or sub-base configuration, antecedent moisture conditions, soil infiltration capacity, rainfall



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characteristics, clogging, and long-term maintenance [5–7]. Despite their potential, the integration of green roofs and sustainable pavements into the hydraulic design of public stormwater drainage systems remains underexplored, particularly at the allotment scale.

Therefore, scenario-based drainage-design studies can provide a practical way to estimate how alternative surface configurations may influence hydraulic demand on public stormwater drainage networks. A previous study in the same urban allotment focused on green roofs [8], while the present proceeding extends that analysis by considering six practical scenarios combining roof typologies and pavement solutions within the same regulatory drainage-design framework. The aim was to assess their potential influence on runoff coefficients, estimated peak discharge, downstream pipe sizing, and public drainage-network construction cost.

## 2. Materials and Methods

This study was developed as a scenario-based hydraulic design assessment. No field rainfall–runoff monitoring was carried out; instead, alternative surface configurations were compared using regulatory design criteria, adopted runoff coefficients, and standard hydraulic calculation procedures.

### 2.1. Study Area

The study was conducted in a 2.1 ha urban allotment located in Macedo de Cavaleiros, northeastern Portugal (41°32′11″ N, 6°57′22″ W; 572 m a.s.l.). The area includes streets, parking areas, pavements, green spaces, and residential plots. Although the 2.1 ha correspond to the physical area of the allotment, the downstream collector CP11 also receives additional upstream inflows from external contributing areas connected to manholes P1, P3, and P5, as considered in the drainage-network design. The local climate is continental with Mediterranean influence, characterized by irregular rainfall, mainly concentrated in autumn and winter, with an annual mean precipitation of around 700 mm [9]. Further information concerning the study area can be found in [10].

### 2.2. Criteria for Sizing the Public Stormwater Drainage System

The public stormwater drainage system was designed as a separate network, in accordance with Portuguese Regulatory Decree no. 23/95 of 23 August [11] and complementary technical guidance [12]. The system comprises connection pipes, stormwater inlets, manholes, and main drainage collectors. In the layout, collectors are identified as CP<sub>i</sub> and manholes as Pi. A minimum pipe cover of 1.00 m was considered, and the network was designed so that the depth did not exceed 4.00 m.

The hydraulic sizing required the determination of the effective drainage area, concentration time, rainfall intensity, and design discharge. Drained areas were measured from the allotment drawing using AutoCAD® software (2025.1.1). The individual runoff coefficients assigned to the different surface types were selected from Portuguese regulatory and technical references [11–13] and from the detailed assessment previously developed for the same allotment [10]. Since the allotment includes surfaces with different hydrological characteristics, a weighted-average runoff coefficient,  $C_m$ , was calculated for each scenario according to Equation (1) [12].

$$C_m = (\sum_{i=1}^N S_i \times C_i) / (\sum_{i=1}^N S_i) \quad (1)$$

where  $S_i$  is the area of surface  $i$  (m<sup>2</sup>),  $C_i$  is the runoff coefficient of surface  $i$  (dimensionless), and  $C_m$  is the weighted average runoff coefficient (dimensionless).

Site-specific runoff coefficients derived from local rainfall–runoff monitoring were not available; therefore, the adopted coefficients were used as design values within a regulatory,

scenario-based hydraulic sizing exercise. The six drainage scenarios and the resulting weighted-average runoff coefficients are presented in Table 1.

**Table 1.** Drainage scenarios considered in the hydraulic analysis and corresponding weighted average runoff coefficients.

| Scenario | Roof Typology         | Pavement Type           | C <sub>m</sub> |
|----------|-----------------------|-------------------------|----------------|
| 1        | Pitched roofs         | Conventional pavements  | 0.70           |
| 2        | Pitched roofs         | Sustainable pavements * | 0.61           |
| 3        | Flat roofs            | Conventional pavements  | 0.65           |
| 4        | Flat roofs            | Sustainable pavements * | 0.55           |
| 5        | Extensive green roofs | Conventional pavements  | 0.59           |
| 6        | Extensive green roofs | Sustainable pavements * | 0.50           |

\* Sustainable pavements included porous asphalt roads, permeable concrete sidewalks, and grass-grid parking areas. The surface areas and individual runoff coefficients used to calculate C<sub>m</sub> were: roads, 3535.83 m<sup>2</sup> (C = 0.80 for conventional pavements and C = 0.60 for sustainable pavements); sidewalks, 4535.10 m<sup>2</sup> (C = 0.80 or 0.60); parking areas, 1857.72 m<sup>2</sup> (C = 0.80 or 0.60); green areas, 3428.55 m<sup>2</sup> (C = 0.20); roof/building footprint area, 5769.85 m<sup>2</sup> (C = 0.90 for pitched roofs, C = 0.70 for flat roofs, and C = 0.50 for extensive green roofs); paved plot yards, 955.66 m<sup>2</sup> (C = 0.80); and green plot yards, 955.66 m<sup>2</sup> (C = 0.20). The total area was 21,038.37 m<sup>2</sup>.

The concentration time was calculated as the sum of inlet time and travel time. Since the drainage basin was considered sloping (1.5% to 8%) and more than 50% impermeable, an inlet time of 7.5 min was adopted [11]. Rainfall intensity was estimated for a return period of 10 years using the intensity–duration–frequency relationship for rainfall region B, Portugal,  $I = 232.21 \times t^{-0.549}$ , based on the calculated concentration times [10,11]. Maximum design discharges were then estimated using the rational method (Equation (2)) [11]. Minimum design discharges were taken as 30% of the maximum values, with a lower limit of 5 L/s.

$$Q = C \times I \times A \quad (2)$$

where Q is the design flow rate (L/s), I is the average rainfall intensity (mm/h), C is the runoff coefficient (dimensionless), and A is the drained area (m<sup>2</sup>).

Hydraulic performance under free-surface flow was assessed with the Manning–Strickler equation (Equation (3)) [12]:

$$Q = A_m \times K_s \times R_h^{2/3} \times i^{1/2} \quad (3)$$

where Q is the flow rate (m<sup>3</sup>/s), A<sub>m</sub> is the wetted cross-sectional area (m<sup>2</sup>), K<sub>s</sub> is the roughness coefficient, taken as 110 m<sup>1/3</sup>/s [11], R<sub>h</sub> is the hydraulic radius (m), and i is the pipe slope (m/m).

Corrugated polypropylene pipes were adopted for the drainage network. Commercial pipe diameters were selected to convey the estimated design discharges while complying with Portuguese regulatory criteria for minimum nominal diameter, velocity, slope, pipe cover, and self-cleansing conditions. The minimum nominal pipe diameter was 200 mm, and the admissible flow velocity ranged from 0.9 to 5.0 m/s [11]. Pipe slopes ranged from 0.3% to 15.0%. The hydraulic verification also considered the maximum pipe capacity, with flow depth limited to the pipe diameter, and a minimum drag tension of 4 N/m<sup>2</sup> [11,14].

Finally, a comparative cost estimate was prepared for the different drainage scenarios. This estimate was limited to the construction cost of the designed public stormwater drainage network, including earthworks, pipes and fittings, network structures, and miscellaneous works, based on 2025 market prices. The construction, maintenance, and replacement costs of the surface solutions themselves, namely green roofs and sustainable pavements, were not included.

### 3. Results and Discussion

#### 3.1. Estimated Hydraulic Response of the Analyzed Scenarios

The detailed collector-by-collector results for drained area, effective area, concentration time, and rainfall intensity are provided in Appendix A as Table A1 for Scenarios 1–3 and Table A2 for Scenarios 4–6, while the main hydraulic differences among the six scenarios are summarized in Table 2. As expected, the effective area decreased as lower runoff coefficients were assigned to the roof and pavement types considered in each scenario, whereas concentration time and rainfall intensity varied only slightly among scenarios. The estimated peak discharges obtained at the downstream collector CP11 were 380.06, 328.49, 350.62, 298.67, 320.53, and 268.68 L/s for Scenarios 1, 2, 3, 4, 5, and 6, respectively. Although the analyzed allotment has a physical area of 2.1 ha, CP11 also receives three additional upstream external contributions of 2000 m<sup>2</sup> each, connected to manholes P1, P3, and P5, resulting in a total drained area of 27,038.4 m<sup>2</sup> at this collector [10]. These external contributions were kept constant in all scenarios.

**Table 2.** Summary of the main hydraulic results for the six scenarios.

| Scenario | Roof Typology | Pavement Type           | Peak Discharge (L/s) | Peak-Flow Reduction (%) |
|----------|---------------|-------------------------|----------------------|-------------------------|
| 1        | Pitched roofs | Conventional pavements  | 380.06               | —                       |
| 2        | Pitched roofs | Sustainable pavements * | 328.49               | 13.57                   |
| 3        | Flat roofs    | Conventional pavements  | 350.62               | —                       |
| 4        | Flat roofs    | Sustainable pavements * | 298.67               | 14.82                   |
| 5        | Green roofs   | Conventional pavements  | 320.53               | —                       |
| 6        | Green roofs   | Sustainable pavements * | 268.68               | 16.18                   |

\* Sustainable pavements included porous asphalt roads, permeable concrete sidewalks, and grass-grid parking areas. Peak-flow reduction values refer to the replacement of conventional pavements within each roof typology; the global reduction between Scenarios 1 and 6 was 29.31%.

Under the adopted design assumptions, the highest estimated peak discharge was observed for Scenario 1, representing the conventional configuration, whereas the lowest was observed for Scenario 6, which combined extensive green roofs with sustainable pavements. Overall, peak discharge decreased by 29.31% between Scenarios 1 and 6. The comparison between paired scenarios highlights the influence of pavement type within each roof typology: replacing conventional pavements with sustainable pavements reduced peak discharge by 13.57% in pitched-roof scenarios, 14.82% in flat-roof scenarios, and 16.18% in green-roof scenarios. In addition, under conventional pavements, using extensive green roofs instead of pitched roofs reduced peak discharge by 15.66%, whereas under sustainable pavements, the corresponding reduction was 18.21%.

Additional details on the hydraulic calculations and drainage-network design are presented in [10]. The minimum (0.90 m/s) and maximum (5.00 m/s) flow velocities were verified in all scenarios, as were the minimum (0.3%) and maximum (15.0%) slopes. Drag tensions also complied with the minimum criterion of 4 N/m<sup>2</sup>. Across the six scenarios, the collector diameter remained unchanged up to CP6 (200 mm). Diameter variations were observed in collectors CP7, CP8, CP9, CP10, and CP11, with smaller diameters in the more sustainable solutions. The maximum diameter was 500 mm in the last collector for Scenarios 1, 2, 3, and 5, and decreased to 400 mm for Scenarios 4 and 6. From a design perspective, this pattern suggests that, under the adopted assumptions, reducing runoff at source through green roofs and sustainable pavements may reduce the required dimensions of downstream collectors. By contrast, ref. [2] noted that, in conventional drainage systems without such measures, urban flooding problems have often been addressed by increasing pipe diameters to convey stormwater as quickly as possible.

These findings build on previous results for the same urban allotment, where a roof-focused study showed that extensive green roofs reduced the estimated maximum flow by 15.9% relative to pitched impermeable roofs [8]. By jointly considering roof typologies and pavement solutions across six combined scenarios, the present paper extends that analysis and indicates the potential added value of combining source-control solutions in drainage-network design. However, the results should be interpreted as deterministic, scenario-based hydraulic design estimates rather than as demonstrated hydrological performance. No observed rainfall–runoff data were available for calibration or validation, and the estimated discharges depend on the adopted runoff coefficients, design rainfall assumptions, and regulatory hydraulic criteria. In addition, the performance of green roofs and permeable or semi-permeable pavements may vary with rainfall characteristics, antecedent moisture conditions, substrate or sub-base properties, clogging, soil infiltration capacity, and maintenance [4–7]. Under the rational method, the estimated peak discharge varies linearly with the weighted runoff coefficient and rainfall intensity, whereas the effects on pipe sizing and construction costs are not strictly linear because they depend on commercial pipe-diameter thresholds, regulatory criteria, excavation depth, and unit-cost assumptions. Therefore, the 29.31% reduction obtained for Scenario 6 should be understood as a case-specific, indicative estimate under the selected design assumptions, not as a universal performance value.

### 3.2. Comparative Cost Estimate of the Public Stormwater Drainage System

The estimated construction costs of the designed public stormwater drainage network are presented in Table 3.

**Table 3.** Estimated construction costs of the public stormwater drainage network for each scenario (€ + VAT).

| Description of Works         | Scenario 1       | Scenario 2       | Scenario 3       | Scenario 4       | Scenario 5       | Scenario 6       |
|------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Earthworks                   | 9687.62          | 8752.69          | 9041.29          | 8857.79          | 8482.15          | 7381.06          |
| Pipes and fittings           | 9785.00          | 9448.00          | 8806.00          | 8769.50          | 8436.00          | 8364.50          |
| Network structures           | 15,100.00        | 15,100.00        | 15,100.00        | 15,000.00        | 15,000.00        | 15,000.00        |
| Miscellaneous works          | 1347.20          | 1347.20          | 1347.20          | 1347.20          | 1347.20          | 1347.20          |
| <b>Total value (€ + VAT)</b> | <b>35,919.82</b> | <b>34,647.89</b> | <b>34,294.49</b> | <b>33,974.49</b> | <b>33,265.35</b> | <b>32,092.76</b> |

The comparative cost estimate included four main categories related to the public stormwater drainage network: earthworks, pipes and fittings, network structures, and miscellaneous works. The total estimated costs were EUR 35,919.82, 34,647.89, 34,294.49, 33,974.49, 33,265.35, and 32,092.76 (+VAT) for Scenarios 1 to 6, respectively. The lowest value was obtained for Scenario 6, whereas the highest corresponded to Scenario 1. This difference, EUR 3827.06, represents a reduction of about 10.65% in the estimated construction cost of the public drainage network. The more sustainable scenarios tended to reduce costs mainly for earthworks and pipes and fittings, while network structures and miscellaneous works varied only slightly. This pattern is consistent with the hydraulic results, since lower peak discharges generally translated into less demanding drainage-network dimensions. However, this reduction should not be interpreted as an overall economic benefit of green roofs or sustainable pavements, since the construction, maintenance, and replacement costs of these surface solutions were not included. Compared with the previous study for the same allotment, which focused only on roof typologies, the present analysis indicates that including pavement solutions further reduced hydraulic demand and the estimated construction cost of the public drainage network.

## 4. Conclusions

This study indicated that alternative roof and pavement scenarios could reduce the hydraulic demand on the public stormwater drainage network of the analyzed urban allotment. Under the adopted design assumptions, the combination of extensive green roofs and sustainable pavements resulted in the lowest weighted runoff coefficient and estimated peak discharge, with a 29.31% reduction in peak flow relative to the conventional scenario. These results suggest that source-control solutions can contribute to more efficient allotment-scale drainage design and may reduce downstream pipe dimensions and the estimated construction cost of the public drainage network. However, the results should be interpreted as scenario-based hydraulic design estimates rather than as experimentally validated hydrological performance. The analysis depends on adopted runoff coefficients, a single design rainfall relationship, a 10-year return period, regulatory assumptions, and unit-cost estimates. Moreover, the cost comparison only includes the estimated construction cost of the public stormwater drainage network and does not account for the implementation, maintenance, or replacement costs of green roofs and sustainable pavements. Future work should include local experimental assessment of runoff coefficients, sensitivity analysis, additional return periods, climate-adjusted rainfall scenarios, and broader life-cycle economic assessment of sustainable drainage solutions.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

**Table A1.** Drained area, effective area, concentration time, and rainfall intensity for Scenarios 1–3.

| Drainage Pipe | Drained Area (m <sup>2</sup> ) | Effective Area (m <sup>2</sup> ) |        |        | Concentration Time (min) |     |     | Rainfall Intensity (mm/h) |      |      |
|---------------|--------------------------------|----------------------------------|--------|--------|--------------------------|-----|-----|---------------------------|------|------|
| Scenarios:    |                                | (1)                              | (2)    | (3)    | (1)                      | (2) | (3) | (1)                       | (2)  | (3)  |
| CP1           | 2712.3                         | 1905.1                           | 1649.1 | 1756.3 | 7.5                      | 7.5 | 7.5 | 76.8                      | 76.8 | 76.8 |
| CP2           | 3579.8                         | 2514.4                           | 2176.5 | 2318.0 | 7.8                      | 7.8 | 7.8 | 75.3                      | 75.3 | 75.3 |
| CP3           | 4789.2                         | 3363.9                           | 2911.9 | 3101.2 | 7.5                      | 7.5 | 7.5 | 76.8                      | 76.8 | 76.8 |
| CP4           | 5914.5                         | 4154.3                           | 3596.1 | 3829.9 | 7.6                      | 7.6 | 7.6 | 76.2                      | 76.1 | 76.2 |
| CP5           | 2854.0                         | 2004.6                           | 1735.3 | 1848.1 | 7.5                      | 7.5 | 7.5 | 76.8                      | 76.8 | 76.8 |

Table A1. Cont.

| Drainage Pipe | Drained Area (m <sup>2</sup> ) | Effective Area (m <sup>2</sup> ) |          |          | Concentration Time (min) |     |     | Rainfall Intensity (mm/h) |      |      |
|---------------|--------------------------------|----------------------------------|----------|----------|--------------------------|-----|-----|---------------------------|------|------|
| Scenarios:    |                                | (1)                              | (2)      | (3)      | (1)                      | (2) | (3) | (1)                       | (2)  | (3)  |
| CP6           | 5350.2                         | 3757.9                           | 3253.0   | 3464.5   | 7.9                      | 7.9 | 7.9 | 74.8                      | 74.6 | 74.7 |
| CP7           | 14,069.9                       | 9882.6                           | 8554.6   | 9110.8   | 7.7                      | 7.7 | 7.7 | 75.8                      | 75.6 | 75.7 |
| CP8           | 18,135.7                       | 12,738.4                         | 11,026.6 | 11,743.6 | 8.0                      | 8.0 | 8.0 | 74.4                      | 74.2 | 74.3 |
| CP9           | 20,340.4                       | 14,286.9                         | 12,367.1 | 13,171.2 | 8.1                      | 8.1 | 8.1 | 73.5                      | 73.6 | 73.7 |
| CP10          | 22,396.4                       | 15,731.0                         | 13,617.1 | 14,502.5 | 8.3                      | 8.3 | 8.3 | 72.7                      | 72.6 | 72.8 |
| CP11 *        | 27,038.4                       | 18,991.5                         | 16,439.5 | 17,508.4 | 8.4                      | 8.5 | 8.4 | 72.0                      | 71.9 | 72.1 |

Note: (1) Scenario 1; (2) Scenario 2; (3) Scenario 3. (\*) Collector CP11 includes additional upstream inflows connected to manholes P1, P3, and P5.

Table A2. Drained area, effective area, concentration time, and rainfall intensity for Scenarios 4–6.

| Drainage Pipe | Drained Area (m <sup>2</sup> ) | Effective Area (m <sup>2</sup> ) |          |          | Concentration Time (min) |     |     | Rainfall Intensity (mm/h) |      |      |
|---------------|--------------------------------|----------------------------------|----------|----------|--------------------------|-----|-----|---------------------------|------|------|
| Scenarios:    |                                | (4)                              | (5)      | (6)      | (4)                      | (5) | (6) | (4)                       | (5)  | (6)  |
| CP1           | 2712.3                         | 1500.3                           | 1607.6   | 1351.6   | 7.5                      | 7.5 | 7.5 | 76.8                      | 76.8 | 76.8 |
| CP2           | 3579.8                         | 1980.2                           | 2121.7   | 1783.8   | 7.8                      | 7.8 | 7.8 | 75.3                      | 75.3 | 75.2 |
| CP3           | 4789.2                         | 2649.2                           | 2838.5   | 2386.5   | 7.5                      | 7.5 | 7.5 | 76.8                      | 76.8 | 76.8 |
| CP4           | 5914.5                         | 3271.6                           | 3505.5   | 2947.2   | 7.6                      | 7.6 | 7.6 | 76.1                      | 76.1 | 76.1 |
| CP5           | 2854.0                         | 1578.7                           | 1691.5   | 1422.2   | 7.5                      | 7.5 | 7.5 | 76.8                      | 76.8 | 76.8 |
| CP6           | 5350.2                         | 2959.5                           | 3171.0   | 2666.0   | 7.9                      | 7.9 | 8.0 | 74.5                      | 74.6 | 74.3 |
| CP7           | 14,069.9                       | 7782.8                           | 8339.1   | 7011.1   | 7.7                      | 7.7 | 7.8 | 75.5                      | 75.6 | 75.4 |
| CP8           | 18,135.7                       | 10,031.8                         | 10,748.8 | 9037.1   | 8.0                      | 8.0 | 8.0 | 74.2                      | 74.1 | 74.0 |
| CP9           | 20,340.4                       | 11,251.4                         | 12,055.6 | 10,135.7 | 8.1                      | 8.1 | 8.2 | 73.5                      | 73.5 | 73.2 |
| CP10          | 22,396.4                       | 12,388.6                         | 13,274.1 | 11,160.2 | 8.3                      | 8.3 | 8.3 | 72.8                      | 72.9 | 72.5 |
| CP11 *        | 27,038.4                       | 14,956.4                         | 16,025.4 | 13,473.3 | 8.5                      | 8.4 | 8.5 | 71.9                      | 72.0 | 71.8 |

Note: (4) Scenario 4; (5) Scenario 5; (6) Scenario 6. (\*) Collector CP11 includes additional upstream inflows connected to manholes P1, P3, and P5.

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