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Innovative methodology to prevent and mitigate diffuse pollution from urban water runoff

WATERUN

Deliverable D3.4

Manual of the planning tool to model the reduction of pollution runoff, CSO and pollution discharge to water bodies.

Work Package 3

Modelling tools for UWR Management

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Executive Summary

Abstract	This manual documents the application of the MUST-B block-based planning toolkit, developed under WATERUN Task 3.4, to support preliminary planning and screening of decentralised stormwater and CSO mitigation measures. The toolkit addresses two complementary objectives: Subtask 3.4.1: Screening urban pollution runoff at the block scale to identify priority locations and approximate sizing needs for decentralised measures such as Low-Impact Development (LID) and Nature-based Solutions (NbS). Subtask 3.4.2: Assessing how block-scale interventions influence downstream drainage behaviour, including combined sewer overflow (CSO) or stormwater discharge, using data-reduced hydraulic modelling. The workflow relies exclusively on open and widely available geospatial data and does not require surveyed sewer infrastructure. It integrates two open-source software components: UrbanWaterBlocks for block generation, attribute mapping, and decentralised intervention pre-sizing, and pysewer for synthetic drainage network generation and hydraulic simulation using EPA SWMM. Rather than replacing detailed engineering design, the MUST-B toolkit is intended as a planning-level decision-support tool. It enables consistent scenario comparison, identification of priority intervention areas, and evaluation of cost–performance trade-offs at an early stage, when data availability is limited and strategic flexibility is highest. The approach is demonstrated through three contrasting case studies—Santiago de Compostela (Spain), Aarhus (Denmark), and Amman (Jordan)—covering combined and separated sewer systems, retrofit and greenfield development, and both data-rich and data-scarce environments. Together, these applications illustrate how block-based planning can support urban water

	management decisions across diverse European and international settings.
Keywords	Preliminary stormwater planning; block-based urban drainage modelling; decentralised stormwater management (LIDS/NbS); data-reduced hydraulic modelling; urban runoff reduction

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1 INTRODUCTION

1.1 Purpose of the MUST-B Planning Toolkit

Increasing urbanisation, ageing drainage infrastructure, and climate change are intensifying stormwater runoff and pollution pressures on receiving water bodies. More frequent and intense rainfall events, combined with declining infiltration and retention capacity in dense urban areas, are fundamentally altering the urban water cycle.

Achieving progress toward zero-pollution cities requires early, spatially explicit planning tools that can account for the complexity of real urban environments. Urban form, infrastructure, topography, regulatory constraints, land ownership, and societal acceptance all influence which interventions are feasible. Planning workflows must therefore be both consistent in method and adaptable to local conditions. Because these conditions vary widely among cities, effective implementation depends not on a single solution, but on approaches that integrate spatial, regulatory and social constraints.

The **M**anagement of **U**rban **S**tormwater at Block-level Planning **T**oolkit, hereafter called MUST-B Planning Toolkit, was developed within the WATERUN project to support this need by enabling scenario-based, planning-level assessment of decentralised[1] stormwater management strategies at the urban block scale. Urban blocks—defined as areas enclosed by surrounding streets—serve as modular planning units in which on-site retention, infiltration, storage, and evapotranspiration measures can be evaluated (Despot et al., 2026; Dev Roy et al., 2026; Friesen et al., 2025; Khurelbaatar et al., 2021). The overarching objective is to reduce runoff and pollutant transport beyond block boundaries before flows enter the sewer system.

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[1] Terminology note: In this manual, the terms Nature-based Solutions (NbS) and Low Impact Development (LID) are used together where appropriate. NbS reflects the terminology adopted in the WATERUN proposal and policy context, while LID is the standard term used within the Stormwater Management Model (SWMM) framework. In the context of this manual, both terms refer to decentralised stormwater interventions designed to manage runoff close to its source and may include nature-based, hybrid, or low-impact grey solutions.

A key advantage of the block-based approach is its scalability. Analyses can be performed at the neighbourhood scale and extended to entire cities by aggregating blocks, allowing consistent comparison across spatial scales. The workflow is designed for transferability, relying on open and widely available datasets so that applications to other municipalities require only city-specific input data.

Key information provided by the toolkit includes:

- Planning-level estimates of the potential for decentralised stormwater and pollution management
- Identification and prioritisation of urban blocks with high runoff contribution and intervention potential
- Comparison of alternative decentralised intervention scenarios under different rainfall conditions
- Support for identifying short- and medium-term implementation priorities in urban transformation strategies

1.2 Scope of the Manual and Relation to WATERUN Subtasks

This manual documents the implementation of the MUST-B Planning Toolkit developed under WATERUN Task 3.4—Development of the planning tool. It explicitly focuses on the two subtasks defined in the project proposal and clarifies how they are operationalised within the toolkit and this manual.

Subtask 3.4.1 – Modelling the Reduction of Urban Pollution Runoff

This subtask addresses the estimation and reduction of surface runoff and associated pollution loads at the urban block scale using decentralised green infrastructure. Within this manual, Subtask 3.4.1 is implemented through:

- Automated urban block generation
- Block-scale runoff estimation based on imperviousness and rainfall inputs
- Identification of priority blocks for decentralised intervention

- Pre-sizing of decentralised green infrastructure (LID/NbS) for runoff retention and infiltration
- Scenario-based comparison of runoff reduction strategies

These elements are documented in Section 3 of this manual.

Subtask 3.4.2 – Modelling the Reduction of CSO and Pollution Discharge

This subtask addresses the hydraulic performance of urban drainage systems and the reduction of combined sewer overflows through decentralised and network-based interventions. Within this manual, Subtask 3.4.2 is implemented through:

- Generation of synthetic gravity-driven sewer networks from open data
- Block-to-network connection and flow routing
- Dynamic hydraulic simulation using EPA SWMM
- Evaluation of CSO volumes, peak flows, and contributing areas
- Scenario-based comparison of CSO mitigation strategies

These elements are documented in Section 4 of this manual.

1.3 Core Functionalities of the MUST-B Planning Toolkit

Rather than requiring detailed sewer inventories or parcel-level surveys, the toolkit uses open, widely available datasets, enabling rapid screening of intervention strategies across neighbourhoods and entire catchments.

Core functionalities include:

- Automated urban block generation
  Delineates urban blocks from road networks (e.g. OpenStreetMap or cadastral data), producing spatial units that align with planning practice and represent coherent hydrological response units.

- Block-scale runoff and pollution potential assessment

Estimates imperviousness, runoff generation, and population-related loads at the block level using raster-based land-cover and population datasets

- Pre-sizing of decentralised green infrastructure (LID/NbS)

  Identifies suitable blocks for decentralised interventions (e.g. bioretention cells and infiltration shafts) and estimates the area or volume required to achieve target runoff or water-quality control levels.

- Scenario-based exploration of intervention strategies

  Enables comparison of alternative planning scenarios, such as different levels of LID coverage, connectivity assumptions, or rainfall return periods.

- Synthetic sewer network generation for data-scarce context

  Generates gravity-driven stormwater or combined sewer networks from topography and block geometry when surveyed sewer data are unavailable.

- Hydraulic and CSO performance modelling using SWMM

  Exports block-based subcatchments and synthetic networks to EPA SWMM for dynamic simulation of flows, surcharge, and combined sewer overflow behaviour.

- Identification of priority areas and critical infrastructure.

  Supports prioritisation using performance indicators such as retained runoff, decentralisation potential index, contributing area impact (CAI), and hydraulic stress.

The toolkit integrates two main open-source software components.

- UrbanWaterBlocks handles block generation, attribute mapping, and decentralised intervention pre-sizing (Dev Roy et al., 2026; Lippera et al., 2025); and
- pysewer generates synthetic sewer networks, sizes pipes, and prepares hydraulic models for simulation (Despot et al., 2026; Sanne et al., 2024).

Together, these components support early-stage planning, screening, and comparison of stormwater and CSO mitigation strategies. Figure 1 illustrates how open geospatial datasets (e.g., roads, elevation, land cover, rainfall) are transformed into spatially aligned planning units (blocks), synthetic drainage networks, and simulation-ready SWMM models via an integrated Python workflow.

The MUST-B Planning Toolkit is implemented as a structured Python workflow that builds upon earlier, stable versions of the UrbanWaterBlocks (in review) and pysewer libraries (https://git.ufz.de/despot/pysewer). The current implementation reflects ongoing development and integration and is documented here as a reproducible methodological framework.

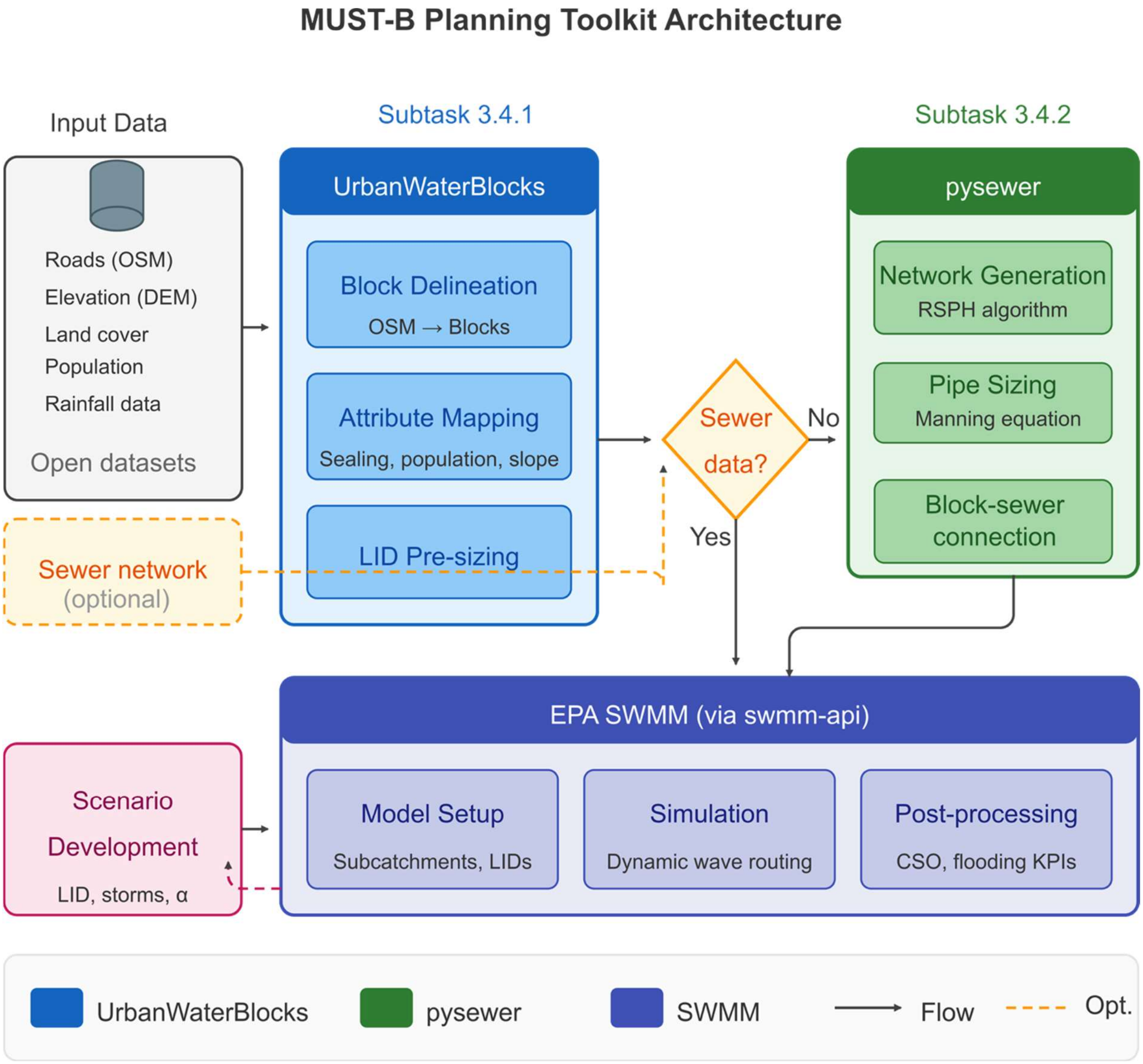

Figure 1: MUST-B planning tool architecture. Integration of the core tools and workflow developed with T3.4.

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1.4 Who Should Use This Toolkit–and When

The MUST-B Planning Toolkit is intended for early-stage planning and strategic screening of decentralised stormwater and CSO mitigation options. It is designed to support decision-making when detailed infrastructure data are limited, and multiple intervention strategies need to be compared efficiently.

The MUST-B Planning Toolkit is intended for (Who):

- Urban planning offices
- Drainage and stormwater engineers
- Water utilities and water boards
- Infrastructure strategy teams
- Consultants supporting early-stage drainage planning
- Research teams supporting municipal planning processes

The toolkit is designed for (When):

- Early-stage planning or pre-feasibility stage
- Detailed sewer network data are unavailable, incomplete, or restricted
- You need to screen multiple decentralised intervention scenarios
- The objective is to prioritise locations for LID/NbS rather than to design them
- You need to compare relative performance across neighbourhoods or catchments
- Strategic targets (e.g. runoff reduction, CSO reduction) are more important than exact hydraulic optimisation.

Typical planning questions this toolkit can answer include:

- Which urban blocks contribute most to runoff or CSO generation?
- Where would decentralised green infrastructure have the greatest impact?
- What level of runoff or CSO reduction is realistically achievable at the block or catchment scale?
- How does partial connectivity between impervious areas and LID affect performance?
- How do decentralised interventions interact with sewer network capacity?
- Which areas should be prioritised for further detailed investigation?

This section defines the decision-support role of the toolkit and should be read before applying the workflows in Sections 3 and 4.

1.5 Planning Scope and Application Conditions

Data scarcity challenge:

Many cities, particularly in parts of the Global South case study, lack digitised sewer infrastructure data due to security restrictions, data fragmentation, or incomplete digitisation. The Amman, Jordan case study (Section 5.3) illustrates this context. This tool addresses that gap by generating synthetic networks from open data.

Planning vs. design:

Early-stage screening requires simpler, faster tools than detailed hydraulic design. Block-based models provide a planning-relevant scale for scenario comparison and intervention prioritisation.

Regulatory context:

The EU Urban Wastewater Treatment Directive (2024) sets strategic targets to limit combined sewer overflows, including a benchmark of ≤ 2 % of the annual dry-weather load for bigger cities. At the same time, several EU Member States are reviewing and expanding regulatory approaches for stormwater discharges, moving beyond traditional wastewater permitting toward more integrated runoff management (Jensen et al., 2020). In this context, planning-level screening tools are needed to explore the feasible range and limits of decentralised interventions, identify where regulatory targets may be challenging to meet, and prioritise locations for more detailed follow-up analysis

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1.6 Required Data

The data required to use the tool are presented in Table 1:

Table 1: Required input data used in the MUST-B Planning Toolkit.

Data Type	Source
City boundary	OpenStreetMap
Road network	OpenStreetMap
Digital Elevation Model (DEM)	National/regional providers, SRTM
World Settlement Footprint (WSF)	DLR GeoService
Population data	GHSL (global) or Urban Atlas (EU)
Rainfall data (preferred: sub-hourly, e.g., 10-min)	National meteorological service

1.7 How This Manual is Organised

This manual is organised into five sections:

- Section 2 – Conceptual Framework: Explains the urban block concept, block generation workflow, synthetic network generation, and the theoretical basis for the approach
- Section 3 – Subtask 3.4.1: Guidance on modelling urban pollution runoff reduction at block scale
- Section 4 – Subtask 3.4.2: Guidance on modelling CSO and pollution discharge reduction at network scale
- Section 5 – Case Studies: Real-world applications in Amman, Aarhus, and Santiago de Compostela
- Section 6 – Conclusion: Summary and key takeaways

2 CONCEPTUAL FRAMEWORK

2.1 The Urban Block Concept

Urban blocks are defined as the areas enclosed by bordering streets. They represent the essential intermediate scale of urban form that aligns closely with how cities organise land use and plan local infrastructure.

In this tool, urban blocks serve a dual role:

1. **Hydrological response units:** Blocks act as relatively uniform runoff units that contribute discretely to the larger catchment
2. **Network generation basis:** Block boundaries provide the geometric outlines for generating synthetic, gravity-driven sewer networks

This alignment with urban planning units (parcels, districts) makes blocks a practical spatial unit for managing runoff near its source and planning decentralised interventions. Key terms used throughout the manual are summarised in Table A.1.

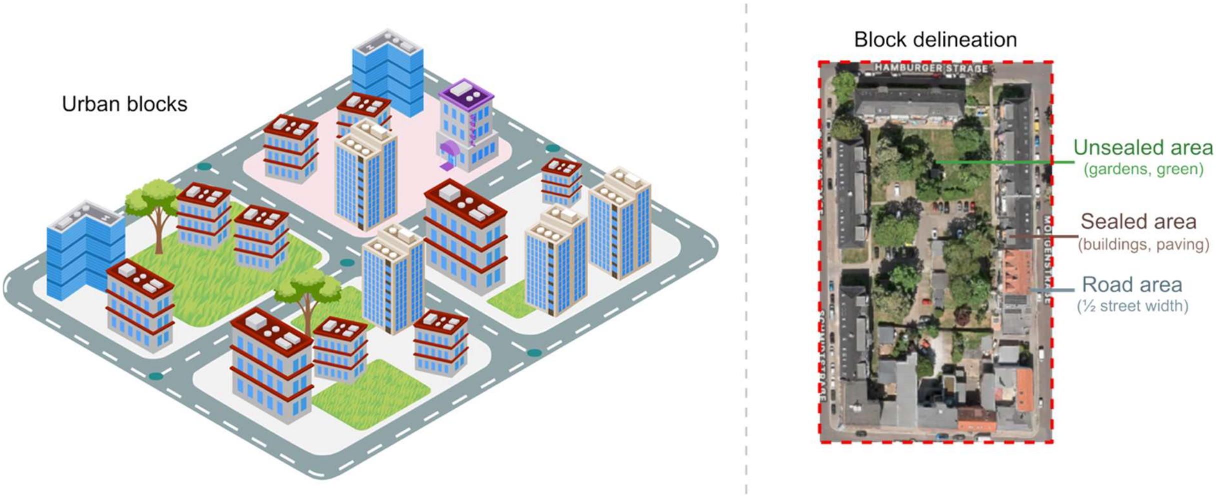

Figure 2: Derivation of urban blocks from OpenStreetMap street centrelines. Street geometries are cleaned and topologically corrected to form closed polygons representing urban blocks, which serve as the basic spatial units for runoff attribution and LID placement.

2.2 Block Generation Workflow (UrbanWaterBlocks)

The UrbanWaterBlocks tool generates blocks through a two-stage pipeline (Dev Roy et al., 2026):

Stage 1: Block Consolidation

Converts street networks into closed urban block polygons. These block polygons are the backbone of the planning tool as they discretise the urban area into blocks and provide the block outlines for further geospatial operations.

Stage 2: Block Mapping

Adds land cover attributes and LID/NbS potential to existing blocks. This stage runs after block consolidation. Block outlines created from other GIS tools or workflows can also be used in this step. Additionally, different population data sources (e.g., GHSL, Urban Atlas) can be used once a specified rasterised input is provided.

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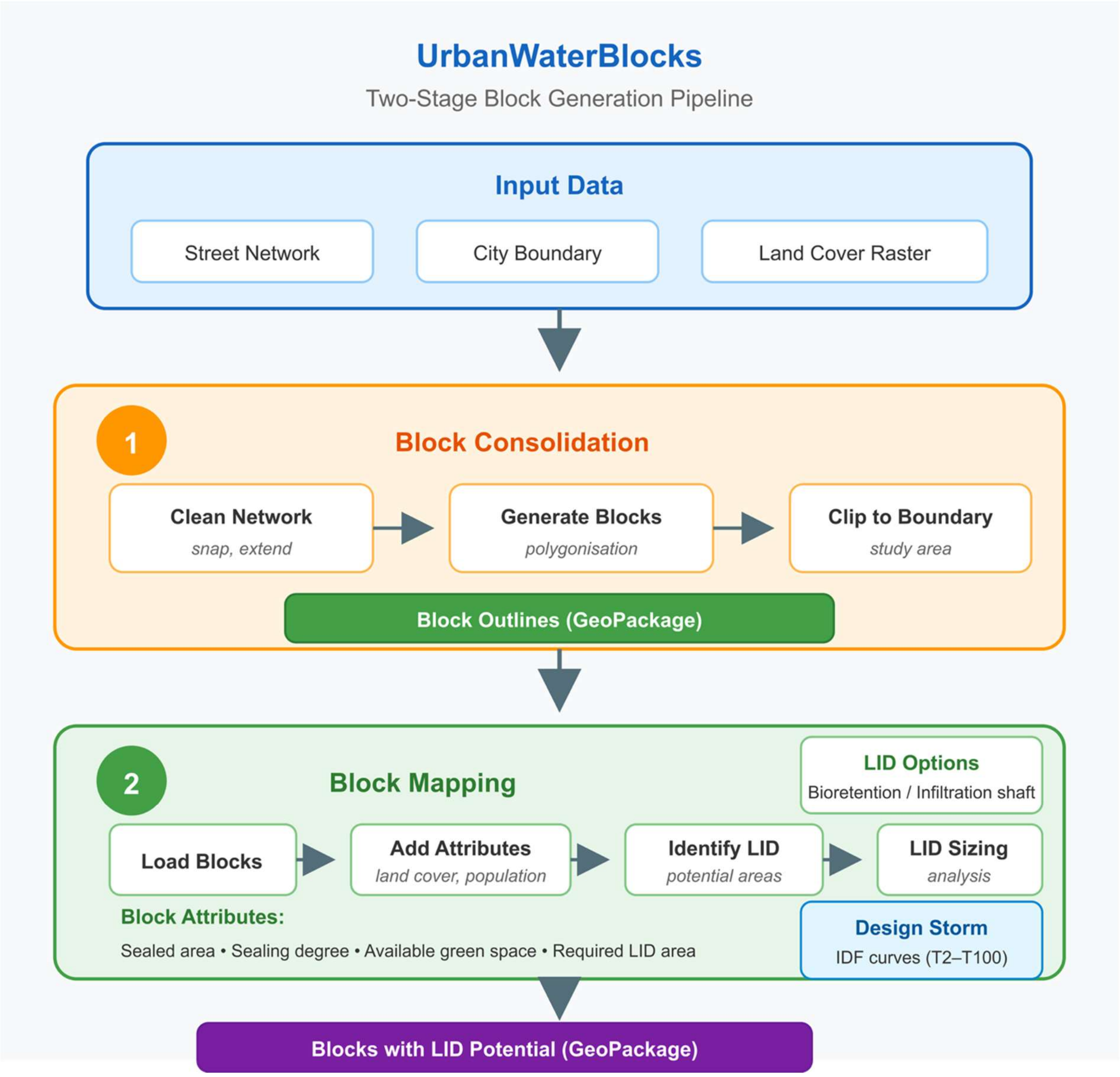


Figure 3: UrbanWaterBlocks two-stage pipeline for block generation and LID/NbS sizing. Stage 1 consolidates street network data into block polygons; Stage 2 maps land cover attributes and calculates LID requirements based on design storm parameters.

2.3 Block Attributes

Each urban block is enriched with a set of attributes that support runoff estimation, decentralised intervention planning, and network coupling. These attributes are deliberately limited to variables that are observable from open data or robustly derived, ensuring transferability across cities and data contexts.

At a conceptual level, block attributes fall into four groups:

- **Geometric attributes**, describing block extent and spatial identity
- **Land-cover attributes**, capturing imperviousness (sealing degree) and runoff potential
- **Population attributes**, supporting dry-weather flow estimation where required
- **Intervention-related attributes**, used to assess decentralised mitigation potential and prioritisation

These attributes enable blocks to function as self-contained planning units that can be analysed individually or aggregated across neighbourhoods and catchments. A complete overview of block attributes, their data sources, default assumptions for missing data, and their usage across workflow components is provided in Appendix A (Table A-1). Readers interested in implementation details or data handling rules are referred there.

2.4 Synthetic Sewer Network Generation (pysewer)

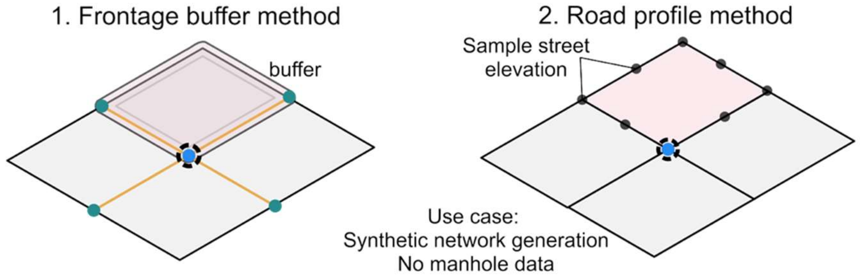
When surveyed sewer infrastructure data is unavailable, the pysewer tool generates synthetic, gravity-driven networks using a data-reduced workflow:

- **Block connection points:** Sample road elevations at regular intervals around each block perimeter, then select the lowest point as the drainage inlet (road profile method). Where sewer network data is available, and pysewer is not applied, a frontage buffer method is used to identify connection points (Figure 4).

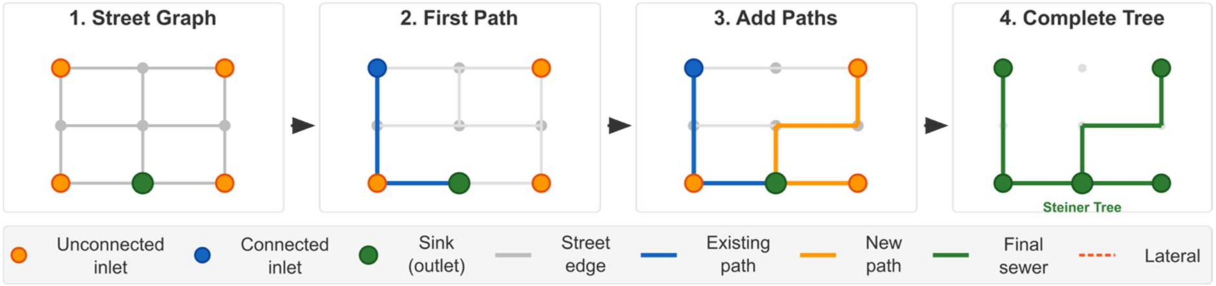
1. **Network routing:** Apply the Repeated Shortest Path Heuristic (RSPH) to route flows toward the outlet, creating a directed Steiner arborescence (Hwang and Richards, 1992).
2. **Gravity enforcement:** Orient edges based on DEM elevation profiles to ensure gravity-driven flow.
3. **Pipe sizing:** Apply the Modified Rational Method with regional IDF curves to determine required pipe diameters.

Key Equations:

- **Rational Method:** $Q = C \times I \times A / 360$, where Q ($m^3/s$) is the peak runoff discharge, C (–) is the runoff coefficient, I (mm/h) is rainfall intensity corresponding to the time of concentration (Tc) and A (ha) is the block area.
- **Time of Concentration (Tc):** Calculated as the combined travel time of overland flow from contributing blocks and in-pipe flow along the critical drainage path, identified using a Dijkstra-based shortest-path search through the generated network.
- **Manning's equation:** Used for diameter selection based on slope and required capacity.



(a) Block connection strategies



(b) Repeated Shortest Path Heuristic (RSPH)

Iterative network construction connecting block inlets to outlet via shortest paths

Figure 4: Conceptual representation of block-to-sewer network connection and runoff routing. Block-scale runoff is assigned to sewer network nodes using rule-based spatial connections, after which flow routing is computed along the network graph toward downstream control points or outfalls.

2.5 Block-Network Connection

A central premise of the MUST-B Planning Toolkit is that urban blocks can act as hydrological response units while also forming a coherent basis for synthetic sewer network generation. This dual role enables surface runoff processes and subsurface conveyance to be represented consistently within a planning-scale framework.

During toolkit development, this block-to-network concept was evaluated using real urban configurations and observed system behaviour (Despot et al., 2026). These studies showed that:

- Block-based representations preserve the spatial relevance required for decentralised intervention;
- Predictive performance at planning level is comparable to conventional reference setups, despite reduced data requirements;
- Synthetic networks generated from open data reduce structural complexity while retaining key hydraulic drivers of surcharge and CSO occurrence.

This framework underpins the workflows described in Sections 3 and 4 and the application case studies in Section 5, which illustrate its use across different urban forms, drainage systems, and data-availability contexts.

2.6 Scenario Analysis and Exploration

The primary value of the MUST-B Planning Toolkit lies in its ability to explore intervention opportunities at the planning stage, where decisions have the greatest influence on long-term system performance and cost, yet uncertainty is still high Figure 5.

At this stage, simplified representations are advantageous: they allow rapid comparison of alternatives before committing to detailed design or implementation. The toolkit, therefore, supports scenario-based exploration, focusing on relative performance rather than absolute prediction.

Typical scenario groups are outlined in Table 2

Table 2: Overview of scenario types considered for planning-level assessment of decentralised stormwater management strategies.

Scenario Type	Description
Baseline	Current conditions without decentralised interventions
LID deployment	Increasing levels of decentralised intervention coverage
Targeted intervention	Measures applied only to high-priority blocks

Scenario Type	Description
Climate stress	Increased rainfall intensities representing future conditions

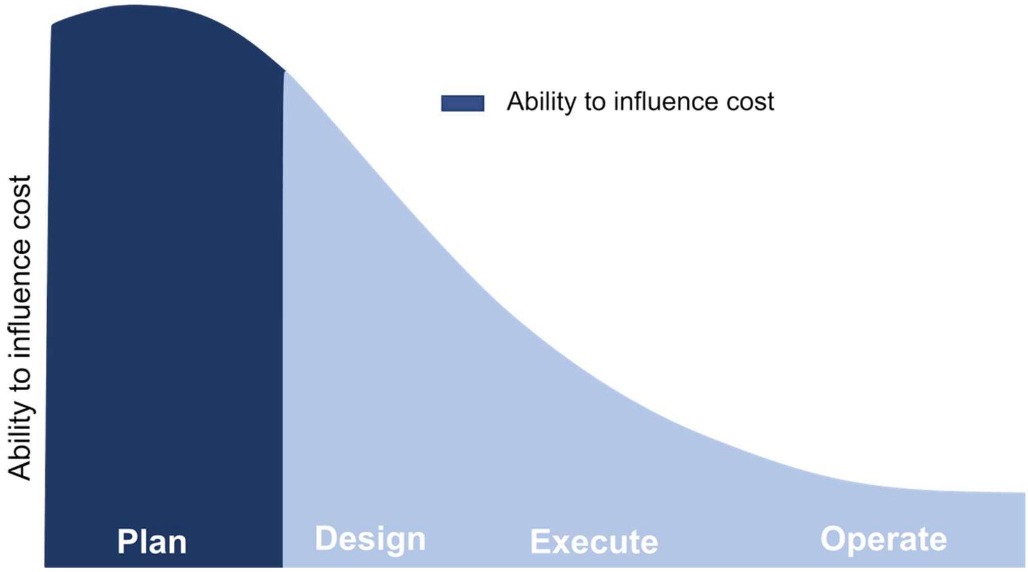


Figure 5: Potential for influencing project cost as a function of the project stage. Modified following (ATV-A 200, 1997)

The specific scenarios explored for each application are described in Section 5.

Based on the conceptual framework presented in this section, the following sections describe the practical implementation of the toolkit for (i) block-scale runoff reduction and (ii) network-scale overflow assessment.

3 SUBTASK 3.4.1 – MODELLING THE REDUCTION OF URBAN POLLUTION RUNOFF

Subtask 3.4.1 addresses the planning-level reduction of urban runoff and associated pollution loads through decentralised, block-scale interventions. The objective is to systematically screen and prioritise urban areas where local retention and infiltration can most effectively reduce runoff before it enters the sewer system.

Within the MUST-B Planning Toolkit, this subtask is implemented through the block mapping workflow, which integrates:

- Urban block geometry derived from street networks

- Land-cover and population attributes derived from raster data
- Design rainfall events derived from IDF analysis
- Pre-sizing of decentralised LID/NbS measures at block scale

The outputs of this workflow provide spatially explicit indicators of runoff generation, retention potential, and intervention feasibility. These results form the basis for both standalone planning assessments and optional downstream hydraulic analysis in Subtask 3.4.2.

3.1 Step-by-Step Workflow

3.1.1 Step 0: Prepare Spatial and Rainfall Inputs

The analysis begins with preparing spatial datasets and defining the rainfall input to be used consistently across all subsequent steps. In addition to block geometry and land-cover data, a design rainfall representation is required for runoff estimation and scenario comparison.

Design rainfall inputs are derived using an IDF analysis consistent with (DWA-A 531, 2025). The toolkit supports two common workflows:

1. Direct derivation of IDF curves from user-defined rainfall time series, and
2. Use of standardised KOSTRA-DWD[2] IDF values for general planning applications (Germany only).

The selected rainfall definition forms a common basis for block-scale LID pre-sizing (Subtask 3.4.1) and network-based simulations (Subtask 3.4.2), ensuring consistency across scenarios.

At this stage, the required inputs are limited to open and commonly available datasets, enabling application in data-scarce environments. At this step, the following data is required:

1. Obtain city boundary (from OpenStreetMap or local cadastral data)

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[2] KOSTRA-DWD is the German Weather Service's national intensity–duration–frequency (IDF) atlas, providing statistically derived design rainfall values on a gridded (raster) basis. For applications outside Germany, equivalent national IDF datasets or IDF curves derived directly from local rainfall time series should be used (Deutscher Wetterdienst (DWD), 2022).

2. Obtain World Settlement Footprint (WSF) raster, which is used to calculate the sealed, unsealed, and largest connected unsealed areas and the sealing degree per block (expressed as the imperviousness parameter in the preceding SWMM model setup)
3. Prepare IDF rainfall data or rainfall time series
4. Configure parameters (coordinate reference system (CRS), thresholds)

Caution: Ensure all spatial data use the same coordinate reference system (CRS). Misalignment causes incorrect attribute calculations.

3.1.2 Step 1: Block Consolidation (Generate Block Polygons)

Urban blocks are generated by converting the road network into closed polygons ("block consolidation"). This step produces the spatial units used throughout the toolkit and ensures consistent block boundaries across the city.

Figure 6: Visual inspection of block consolidation, e.g. using QGIS. Inspection at this stage ensures that the blocks are cleanly delineated. Parameter tuning may be required to achieved desired result.

If blocks are already available from local GIS workflows (e.g., cadastral blocks or manually curated polygons), this step can be skipped, and the existing block layer can be used as input to block mapping. Block attributes generated during this step are summarised in Appendix B.

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3.1.3 Step 2: Generate Block Attributes and Potential Planning Area

Following block consolidation, each block is enriched with a limited set of attributes derived from open spatial datasets. These attributes describe block geometry, imperviousness, population, and available unsealed space, and form the basis for all subsequent analyses.

A key outcome of this step is the identification of the largest connected unsealed area within each block. For planning purposes, the largest connected unsealed area within each block is defined as the potential planning area for decentralised interventions. This area represents the most contiguous and practically usable green space available for Nature-based Solutions or LID implementation. While smaller or disconnected unsealed areas may also contribute in practice, planners are typically constrained to work within predefined, continuous spaces. Defining the planning boundary in this way provides a consistent and conservative basis for block-scale intervention sizing and comparison.

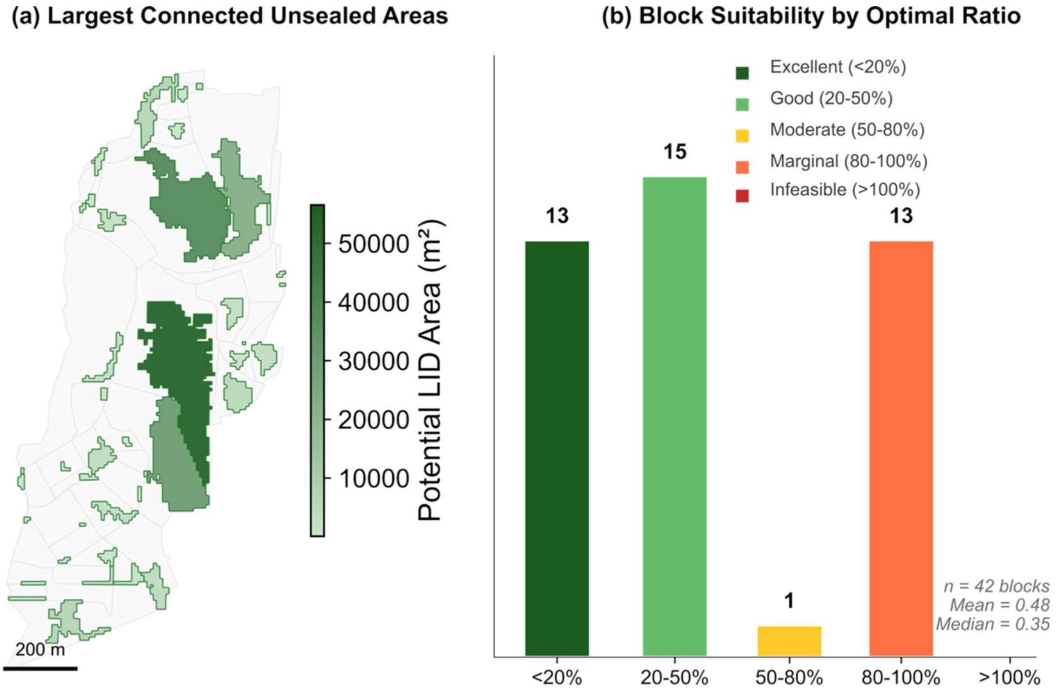

Figure 7: LID Potential Assessment for Santiago de Compostela. (a) Largest connected unsealed areas within each urban block, representing potential sites for Low Impact Development (LID) infrastructure. (b) Distribution of blocks by optimal ratio, defined as the fraction of available LID area required to achieve full retention under the design storm.

3.1.4 Step 3: Pre-size Decentralised LID Using Design Storms

Decentralised LID measures are pre-sized at block scale using design storms derived from the IDF analysis described above. For each block, runoff generated on sealed surfaces during the design event is compared against the available LID placement area identified in Step 2.

The sizing procedure determines the minimum LID area required to fully retain the design storm runoff, subject to spatial constraints (Dev Roy et al., 2026; Lippera et al., 2026, 2025). Where the available unsealed area is insufficient, the resulting retention is reported as partial, allowing realistic assessment of implementation limits. Sizing is repeated across multiple design storms or return periods to support scenario-based comparison and sensitivity analysis at the planning stage.

LID Technologies Considered

The MUST-B Planning Toolkit currently supports two decentralised LID technologies for block-scale pre-sizing: bioretention cells and infiltration shafts. These technologies were selected because they represent contrasting space requirements and performance characteristics commonly encountered in urban retrofit planning.

- Infiltration shafts represent compact, subsurface infiltration systems with a small surface footprint and high storage capacity per unit area.
- Bioretention cells represent surface-based systems combining detention, infiltration, and evapotranspiration, requiring more space but offering broader hydrological and urban co-benefits.

Both technologies are implemented using simplified, planning-level parameterisations and are configured as infiltration-only systems (no underdrains). A conceptual cross-section of both LID types is shown in Figure 8. LID design parameters follow standard ranges reported in the referenced guidelines and literature used throughout the manual (Dev Roy et al., 2026; Lippera et al., 2025).

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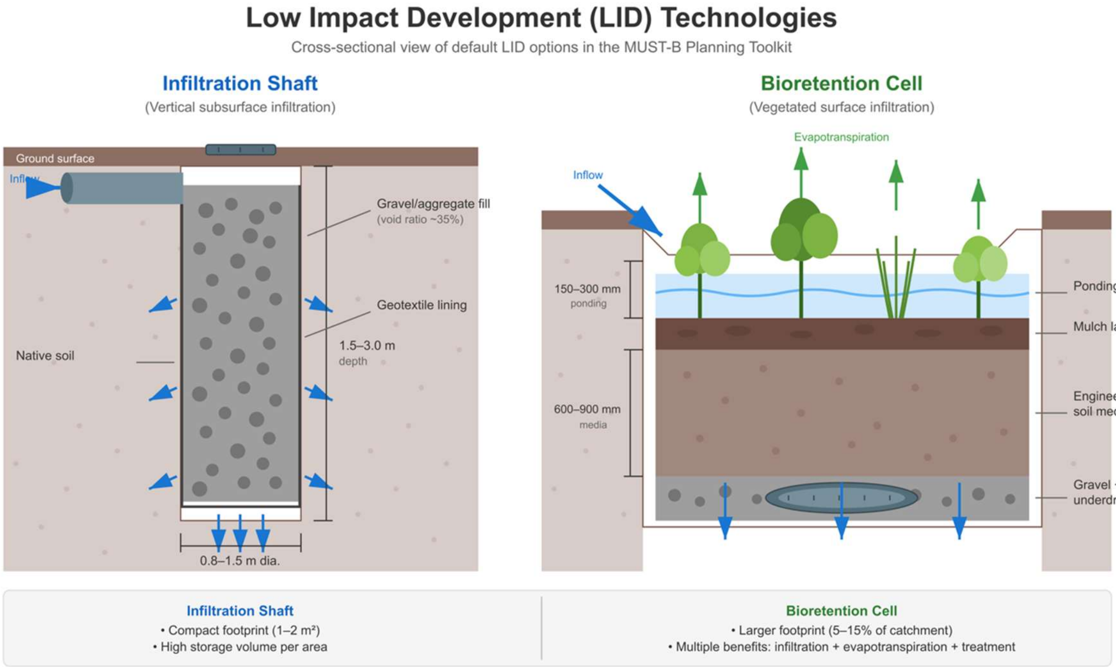

Figure 8: Low Impact Development (LID) Technologies used within the MUST-B Planning Toolkit. The left is a typical cross-sectional view of an infiltration shaft, and the right is that of a bioretention cell.

Application in the Workflow

For each block and design storm, the selected LID technology is sized to control runoff volume. The resulting outputs include:

- required LID area for full retention,
- achievable retention under spatial constraints, and
- block-level retention percentages.

These outputs form the basis for block-scale screening (Subtask 3.4.1) and can be exported for network-based analysis in Subtask 3.4.2.

Note: Pre-existing block polygons may be used directly for LID pre-sizing if they include block identifiers and basic land-cover attributes (total, sealed, and unsealed area).

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3.1.5 Step 4: Export Results and Further Analysis

Results from the block-scale analysis can be exported for further evaluation using network-based tools. LID pre-sizing outputs are translated into formats compatible with pysewer and EPA SWMM, enabling dynamic simulation of flow routing, surcharge, and overflow behaviour where required. This export step links Subtask 3.4.1 to Subtask 3.4.2 and is optional where block-scale screening alone is sufficient.

3.2 Interpreting Results

Results from Subtask 3.4.1 should be interpreted as relative planning indicators, not absolute design values.

Key block-level indicators include:

- Sealing degree (>0.8): High runoff generation and pollution potential
- Percentage retained (>70–90%): Strong suitability for decentralised source control
- Decentralisation potential (D_p): Indicator describing how much runoff generated within a block can be managed locally, given its imperviousness and available area for decentralised interventions (Lippera et al., 2025).

Spatial patterns across multiple blocks are often more informative than individual values. Clusters of blocks with high sealing and high retention potential indicate priority areas for decentralised intervention strategies.

4 SUBTASK 3.4.2 – MODELLING THE REDUCTION OF CSO AND POLLUTION DISCHARGE

Subtask 3.4.2 addresses the network-scale reduction of sewer overflows and pollution discharge by integrating block-based runoff representation with synthetic or existing sewer networks. It builds directly on the outputs of Subtask 3.4.1, in which decentralised interventions are identified and pre-sized at the block scale.

The MUST-B Planning Toolkit supports the generation and analysis of three network types:

- Stormwater networks, conveying rainfall runoff only

- Sanitary sewer networks, conveying dry-weather wastewater
- Combined sewer networks, conveying both wastewater and stormwater

This flexibility allows the toolkit to be applied across a wide range of urban drainage contexts, from separated systems to combined sewers.

At the core of this subtask is the block–network connection framework, in which each urban block is linked to the sewer system via physically plausible drainage inlets along the street network (Despot et al., 2026). Runoff generated at block scale is routed through gravity-driven networks—either synthetic or surveyed—enabling consistent representation of surface processes and subsurface hydraulics.

Dynamic routing simulations are performed using EPA SWMM to evaluate how decentralised source control, storage infrastructure, and network capacity interact under different rainfall scenarios. The primary outcomes include estimates of network overflow volume (pluvial flood), CSO volume and frequency, identification of hydraulically stressed network segments, and comparison of alternative intervention strategies.

4.1 Step-by-Step Workflow

This workflow translates block-scale outputs from Subtask 3.4.1 into a network-based hydraulic model suitable for planning-level CSO analysis. The emphasis is on consistency, robustness, and comparability across scenarios rather than detailed engineering optimisation. Attributes used to link block runoff to the synthetic network are listed in Table B.3.

4.1.1 Step 1: Select Network Type and Outlet

1. Select the appropriate sewer system representation based on local context:
    - Stormwater network: rainfall runoff only, rational formula, and time-of-concentration estimates (Butler et al., 2018).
    - Sanitary network: dry-weather wastewater only—estimated dry weather baseflow based on population and water consumption estimates (Butler et al., 2018; Sanne et al., 2024).

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- Combined sewer network: wastewater and stormwater—applies a combined sewer factor (CSF) to account for weather flows.

2. Define one or more outlet points representing discharge to a receiving water, interceptor, or treatment facility.

4.1.2 Step 2: Generate Synthetic Sewer Network (if required)

When surveyed sewer data are unavailable, generate a synthetic, gravity-driven network using block geometry, street layout, and topography:

- Identify block connection points along block perimeters at the lowest local street elevation
- Route flows toward the outlet using a shortest-path heuristic
- Enforce gravity-driven flow using DEM-based elevation profiles
- Size pipes using a planning-grade method consistent with selected rainfall inputs

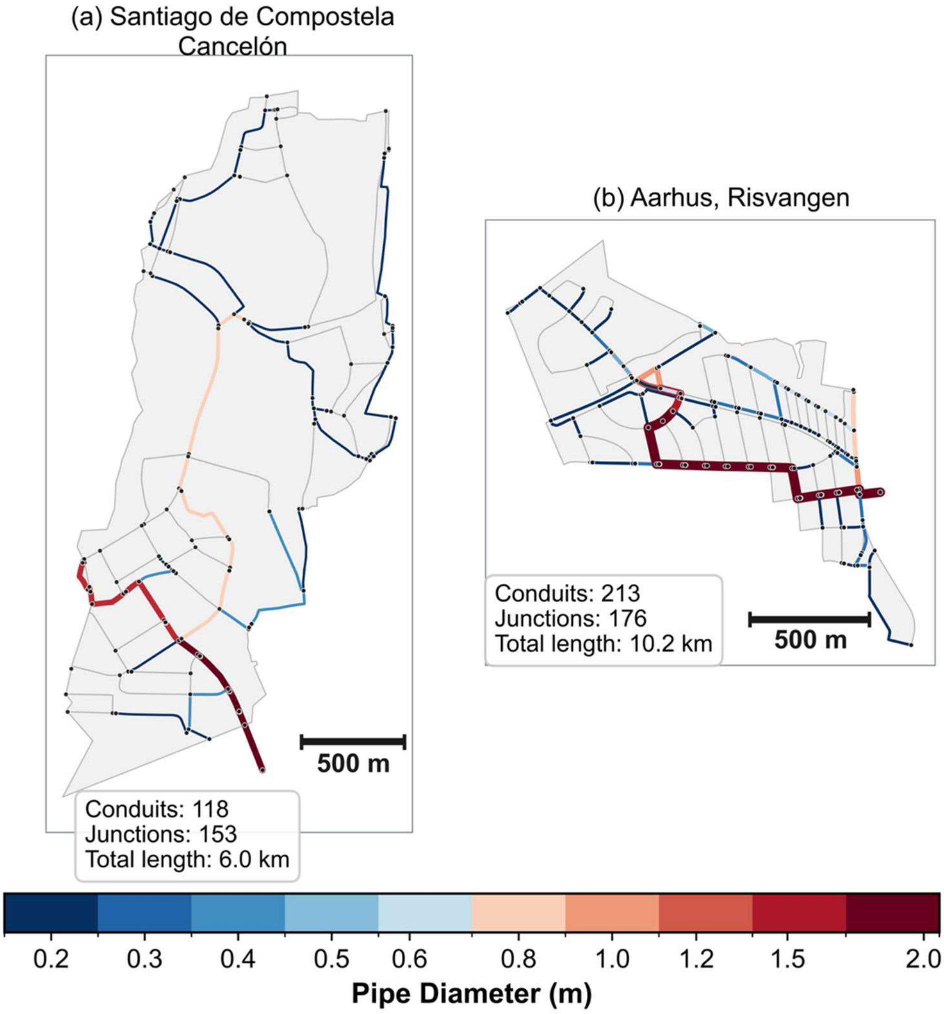

Figure 9: Synthetic sewer networks generated using the MUST-B Planning Toolkit for (a) Santiago de Compostela (Cancelón subcatchment) and (b) Aarhus (Risvangen catchment). In Cancelón, a combined sewer system is represented, with pipe diameters derived using a combined sewer factor (CSF) to account for wastewater and stormwater contributions. In Aarhus, a separate stormwater network is generated, with pipe sizing based on the rational method and event-specific time-of-concentration. Pipe colours indicate diameter, and summary network statistics are shown for each case.

Before hydraulic simulation, perform a network preparation step to ensure connectivity, correct edge orientation, and hydraulic feasibility.

4.1.3 Step 3: Build the SWMM Model

Assemble the SWMM model using:

- Subcatchments: one per block, with sealed area, slope, and width derived from block attributes

- Rainfall: design storms or observed events consistent with Section 3
- Dry-weather flow: population- or area-based estimates where applicable
- Network elements: pipes, junctions, storage units, and outfalls

Block-level LID pre-sizing results are imported as SWMM-compatible LID definitions and linked to the corresponding subcatchments. Both software (UrbanWaterBlocks and pysewer) within the MUST-B planning toolkit interface directly with swmm-api (Pichler, 2025), providing a coherent and structured framework for automated assembly of EPA SWMM models (.inp files).

4.1.4 Step 4: Run Dynamic Simulations

Execute SWMM simulations using the dynamic wave solver to evaluate:

- Flow routing and surcharge propagation
- Activation and frequency of CSO events
- Interaction between decentralised source control and network capacity

Simulations are typically run across multiple rainfall scenarios to assess system sensitivity.

4.1.5 Step 5: Evaluate Network Performance

Planning-relevant performance indicators include:

- Flow routing continuity error (Rossman, 2017)
- Flow instability index (Rossman, 2017)
- Hydraulic Performance Index (HPI): indicates surcharge-related stress in the network (Bennis et al., 2003; Despot et al., 2026)

These indicators help determine the hydraulic credibility of the network implementation, either using real data or a synthetic network. This workflow supports relative assessment of scenarios and prioritisation of decentralised and network-based measures. Detailed parameter tuning and infrastructure design are intentionally outside the scope of this manual.

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4.2 Infrastructure Integration

This step integrates decentralised and centralised infrastructure elements into the network model to evaluate their combined effects on runoff and overflow reduction, as well as on hydraulic performance. The objective is to assess strategic placement and interaction.

Infrastructure elements considered at this stage include:

Decentralised source control (LID/NbS)

Block-level LID measures pre-sized in Subtask 3.4.1 are imported into the network model as distributed source controls. These measures reduce inflow to the sewer system and directly influence CSO occurrence and network stress. Scenario comparisons typically vary in total LID coverage and connectivity assumptions rather than detailed LID configuration.

Storage and conveyance infrastructure

Centralised storage elements (e.g., detention tanks or inline storage) may be represented in a simplified form to capture their buffering effect on peak flows and overflow activation. Where relevant, downstream conveyance constraints (e.g. throttled discharge to treatment) are included to reflect realistic system limits.

Intervention strategy testing

Infrastructure elements are combined into alternative planning scenarios, such as:

- Baseline network without decentralised control
- Distributed LID only
- Storage enhancement only
- Combined decentralised and centralised measures

The emphasis is on relative performance across scenarios, enabling planners to compare the effectiveness of different intervention strategies before committing to detailed design.

This integration step links spatially explicit block-scale measures to network-scale system response and serves as the basis for the performance evaluation described in Section 4.4.

4.3 Planning-Level Cost Estimation (Optional)

In addition to hydrological performance, the MUST-B Planning Toolkit supports a planning-level economic comparison of decentralised stormwater and CSO mitigation strategies. This cost module complements runoff and retention metrics by providing a consistent basis for comparing scenarios with different infrastructure compositions.

The cost module covers:

- Decentralised LID/NbS measures, including bioretention cells and infiltration shafts
- Sewer network infrastructure, derived from synthetic or surveyed networks, exported to SWMM
- Storage elements, when included in scenario design

Costs are calculated using a deterministic lifecycle approach that combines capital expenditure, operating and maintenance costs, and replacement costs over a fixed analysis horizon. Net present value (NPV) enables consistent comparisons across scenarios with different cost structures. Default unit costs and assumptions are provided but can be adapted to local contexts.

The primary purpose of this module is relative comparison, not detailed investment appraisal. Results are intended to support:

- ranking of alternative planning scenarios
- exploration of cost–performance trade-offs
- identification of intervention strategies that deliver substantial benefit at reasonable cost

A full description of the cost model structure, default parameters, and calculation assumptions is provided in Appendix D.

4.4 Interpreting Results

Results from Subtask 3.4.2 should be interpreted as planning-level indicators intended to support screening and prioritisation, not detailed hydraulic verification or regulatory compliance assessment.

The primary objective is to understand how decentralised and network-based interventions influence overflow activation, discharge volumes, and hydraulic stress patterns across the system.

4.4.1 Key Performance Indicators

Key Performance Indicators (KPIs) are applied to evaluate model behaviour under a defined set of planning scenarios and to enable comparison across these scenarios. The specific KPIs used are selected at the planning stage and depend on the type of drainage system and management objective being examined. The KPIs listed in Table 3 are used consistently across the case studies (Aarhus, Amman, Santiago de Compostela) to support comparative, planning-level interpretation of decentralised intervention scenarios.

Table 3: Key Performance Indicators (KPI) Used for Planning Assessment.

KPI	Unit	Purpose	Applied In
Downstream Discharge Volume	m^3	Measures total load to receiving waters	Aarhus, Amman
CSO Spill Volume	m^3	Measures environmental overflow burden	Santiago
Discharge Reduction	%	Relative improvement vs baseline	All
Flooding Volume	m^3	Indicates surface flooding from surcharge	All
Flooded Nodes	count	Identifies spatial extent of flooding	All
Hydraulic Performance Index (HPI)	—	Indicates network stress and surcharge	General
Contributing Area Impact (CAI)	—	Identifies dominant contributing blocks	General
LID Capture Volume	m^3	Quantifies decentralised retention effect	All
Cost per Volume Reduced	€/m^3	Supports cost–performance comparison	Aarhus, Amman

Note: All KPIs are interpreted relative to a baseline scenario and are intended for planning-level screening rather than detailed design

4.4.2 Interpreting Simplified Network Results

Data-reduced and synthetic network representations introduce deviations that are expected at the planning scale:

- Absolute overflow volumes may differ from observed values
- Peak flows may be higher due to simplified in-pipe storage representation
- Flow recession may be faster than in detailed models

These effects are informative at the planning stage and highlight structural sensitivities rather than model deficiencies.

4.4.3 Using Results for Planning Decisions

When using results to inform planning:

- Focus on relative differences between scenarios rather than absolute values
- Prioritise locations with consistently high CAI and elevated hydraulic stress. Further details on the use of CAI and the evaluation of hydraulic stress can be found in Despot et al., 2026
- Use results to identify areas requiring more detailed investigation or design
- Accept that extreme events may exceed the capacity of decentralised measures alone

Detailed interpretation of results, scenario logic, and technology-specific behaviour is provided in the case studies in Section 5.

4.5 Limitations

- Synthetic network simplifications: Generated networks simplify local structures (manholes, controls, cover depth) and may not represent site-specific bottlenecks or operational details.

- Limited operational representation: Real-time control, detailed throttling rules, and equipment constraints are represented only in simplified form unless explicitly provided.
- Input-data uncertainty: Results depend on DEM quality, land-cover classification, and rainfall inputs; errors in these datasets propagate to flows and overflows.

5 CASE STUDIES

This section presents application case studies ordered to reflect the primary focus of the MUST-B Planning Toolkit on combined sewer overflow (CSO) and overflow mitigation. The Santiago de Compostela case is presented first, as it directly targets CSO reduction in a monitored combined sewer system. Subsequent cases illustrate its application in separate systems and data-scarce contexts, highlighting its transferability across contrasting urban and infrastructural settings.

Common Steps Across Case Studies:

1. Block generation from road networks
2. Attribute mapping from raster data
3. Synthetic network generation (where applicable)
   - Scenario analysis for LID deployment—bioretention cells and infiltration shaft as chosen technologies. These technologies were modelled without underdrains to isolate the infiltration-driven performance.
4. Performance evaluation against targets

5.1 Case Study 1: Cancelón, Santiago de Compostela, Spain

5.1.1 System Overview

The Cancelón catchment is a dense inner-city area located in Santiago de Compostela, Spain, characterised by historic urban fabric, narrow streets, and pronounced topographic gradients toward receiving waters. Drainage is provided by a combined sewer system, where

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stormwater runoff and dry-weather wastewater are conveyed together toward a downstream storage and overflow structure.

The catchment exhibits high imperviousness, limited surface space for retrofitting, and short response times during rainfall events. These characteristics make it representative of many historic European city centres where conventional sewer expansion is constrained, and decentralised stormwater control is increasingly considered as a complementary strategy.

Under dry-weather conditions, flow is conveyed directly to the wastewater treatment plant (WWTP). During rainfall events, excess flow is first diverted into a three-tank CSO storage system, and only when this storage capacity is exceeded does overflow occur to the Río Sar. Stored volumes are subsequently conveyed to the WWTP following the event.

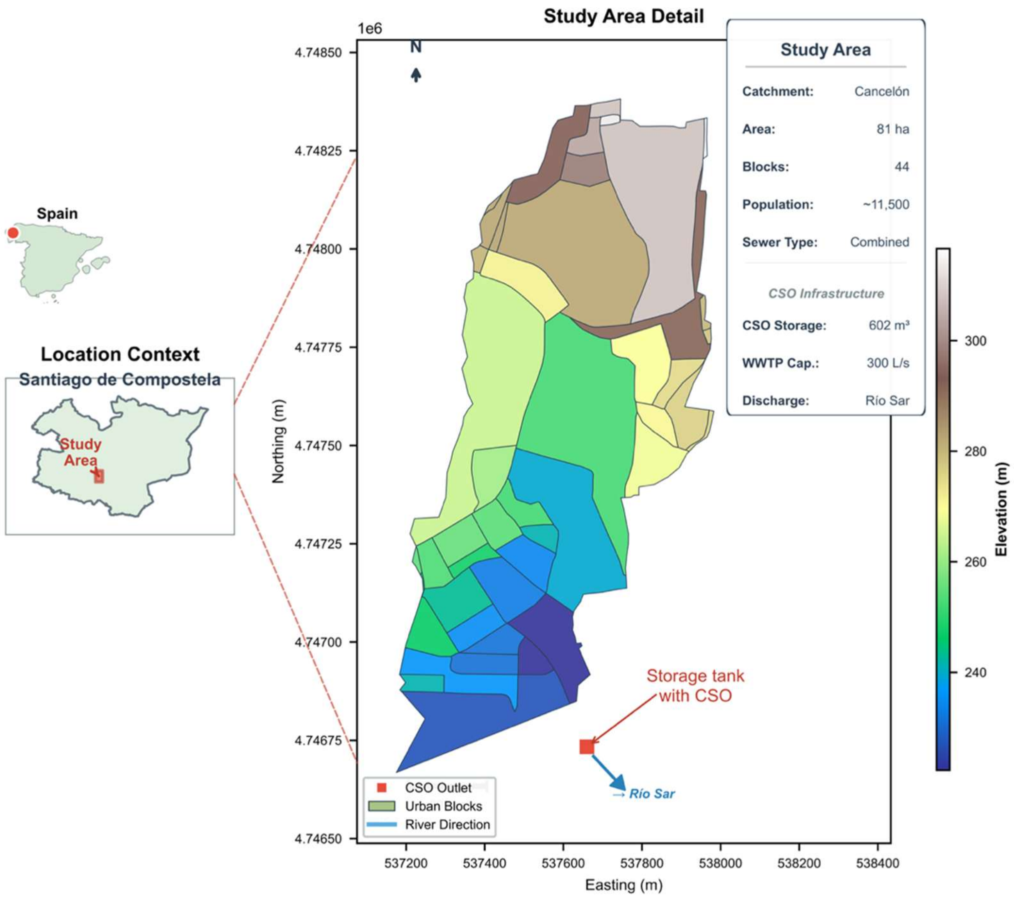

Figure 10: Case study—Santiago de Compostela, Cancelón (Spain).

Figure 10 provides an overview of the study area, including block delineation, drainage direction, and the CSO outlet location.

5.1.2 Data Availability

The Cancelón case benefits from relatively good data availability compared to many urban planning contexts (UFZ-D.3.1 WATERUN, 2023). In addition to open geospatial datasets, information on the existing sewer network and CSO infrastructure is available from previous studies and monitoring campaigns (UDC, 2004).

However, for this application, the available sewer network data were not used directly. Instead, the case was intentionally modelled using the data-reduced workflow of the MUST-B Planning Toolkit, including synthetic sewer network generation based on block geometry, street layout, and topography.

This decision was made deliberately to:

- test how well the block-based and synthetic network approach performs in a real, monitored combined sewer catchment,
- evaluate whether planning-relevant system behaviour can be reproduced without relying on detailed sewer inventories, and
- build on the proof-of-concept results described in Section 2.5 (Block–Network Connection).

Available data used in the analysis included:

- rainfall time series,
- observed CSO occurrences and flow records,
- aggregate CSO storage volume,
- open geospatial datasets for block delineation, terrain, and imperviousness.

Detailed sewer network geometry, internal CSO hydraulics, and operational control rules were intentionally excluded from the modelling scope to maintain consistency with the planning-level, transferable methodology.

5.1.3 Modelling scope and Simplifications

The modelling scope for the Cancelón case was explicitly defined to support planning-level screening rather than detailed engineering verification.

The following simplifications were applied:

- Urban blocks were used as hydrological response units for runoff generation
- Dry-weather flow was estimated from block-level population data
- The CSO facility was represented as a single equivalent storage volume
- Decentralised interventions were modelled as infiltration-based LID without underdrains

The analysis focuses on relative changes in system response—such as reductions in CSO volume, network flooding, and sensitivity to runoff connectivity—across alternative decentralised intervention scenarios.

Prior to scenario exploration, the data-reduced block–network representation was evaluated against observed system behaviour to assess its suitability for planning-level analysis. The simplified model shows strong agreement in inflow to the CSO storage, with a mean Kling–Gupta Efficiency (KGE) of approximately 0.87 across 12 monitored events, indicating that the timing and relative magnitude of wet-weather loading are consistently captured. This confirms that the block-based runoff representation and routing preserve the dominant controls on system inflow response. Further details on the performance of the data-reduced modelling approach are provided in Appendix Note E-1.

For CSO performance, two of the four observed overflow events fall within commonly accepted planning-level ranges for overflow volume and time to peak, while remaining deviations are primarily linked to deliberate structural simplifications. The original three-tank CSO system was represented as a single equivalent, volume-based storage unit, preserving total storage capacity and overflow occurrence behaviour while simplifying internal geometry and operation. In particular, CSO volumes and durations are sensitive to assumptions regarding throttle flow to the WWTP, which were estimated within a plausible operational range. Overall, the evaluation demonstrates that the data-reduced approach provides a robust and transparent basis for comparative scenario analysis, consistent with the intended scope of the MUST-B Planning Toolkit. Additional evaluation is provided in Appendix E.

5.1.4 Planning Questions Addressed

The Cancelón case study was designed to address a focused set of planning-relevant questions related to decentralised stormwater control in a dense, combined sewer catchment. These questions align directly with the objectives of WATERUN Subtasks 3.4.1 and 3.4.2 and reflect the type of decisions faced during early-stage urban drainage planning.

Q1 – Infrastructure Requirement (Subtask 3.4.1)

How much decentralised LID infrastructure is required at block scale to achieve meaningful reductions in runoff contribution under different storm severities?

This question targets the relationship between design storm magnitude, available unsealed space within blocks, and achievable runoff retention, independent of detailed sewer hydraulics.

Q2 – System-Level Effectiveness (Subtask 3.4.2)

To what extent can decentralised block-scale interventions reduce CSO occurrences and overflow volumes at the catchment scale?

Here, block-based runoff reduction is evaluated in terms of its downstream effect on storage utilisation and CSO occurrences, using a simplified but dynamically simulated sewer representation.

Q3 – Sensitivity to Runoff Connectivity

How sensitive is CSO reduction to the fraction of impervious runoff that can realistically be routed to decentralised interventions?

This question reflects practical retrofit constraints in historic urban areas, where only a portion of sealed surfaces can be disconnected and redirected toward LID.

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Together, these questions frame the Cancelón case as a screening exercise aimed at understanding feasibility, sensitivity, and relative benefit, rather than detailed optimisation or regulatory verification. The corresponding scenarios and results are presented in the following sections.

5.1.5 Scenario Design

Scenarios for the Cancelón case were designed to explore how decentralised block-scale interventions influence CSO behaviour under varying storm conditions and implementation constraints. The scenario space was defined by four key dimensions:

- Storm severity: Design storms ranging from frequent to extreme events (T2–T100 years), generated consistently for comparative analysis.
- LID technology: Two infiltration-based decentralised measures were evaluated—bioretention cells and infiltration shafts—both modelled without underdrains.
- Infrastructure sizing: LID systems were pre-sized at block scale for selected design storms and then tested across all storm severities to assess robustness beyond their nominal design target.
- Runoff connectivity (α): Connectivity levels of α = 0.25, 0.50, 0.75, and 1.00 were used to represent increasing degrees of retrofit feasibility in dense urban areas. Here, the connectivity parameter (α) was introduced to represent the fraction of impervious runoff that can be realistically routed to decentralised interventions

All scenarios were evaluated relative to a baseline without decentralised intervention. The resulting scenario set supports screening and sensitivity analysis rather than optimisation and provides the basis for the results summarised in the following section.

Note: **Network flooding**, represents surcharge and surface flooding at nodes
CSO spill, represents controlled overflow from storage to receiving waters. This distinction is important for planning, as decentralised measures may reduce urban flooding more strongly than total CSO discharge.

5.1.6 Key Results (Planning Perspective)

This section summarises the main planning-relevant findings from the Cancelón case study. The results are intended to support screening and comparison of decentralised CSO mitigation strategies, not detailed system design.

Infrastructure requirements and technology choice (Q1)

Figure 11 shows how CSO volume reduction depends on the installed LID area per hectare for different storm return periods and technologies.

Key planning messages are:

- For frequent and moderate storms (T2–T10), substantial CSO reduction can be achieved with moderate LID provision.
- For extreme storms (≥ T50), required LID areas increase sharply, and full mitigation is not achievable through decentralised measures alone.
- Bioretention consistently achieves higher CSO reduction than infiltration shafts for the same installed area.

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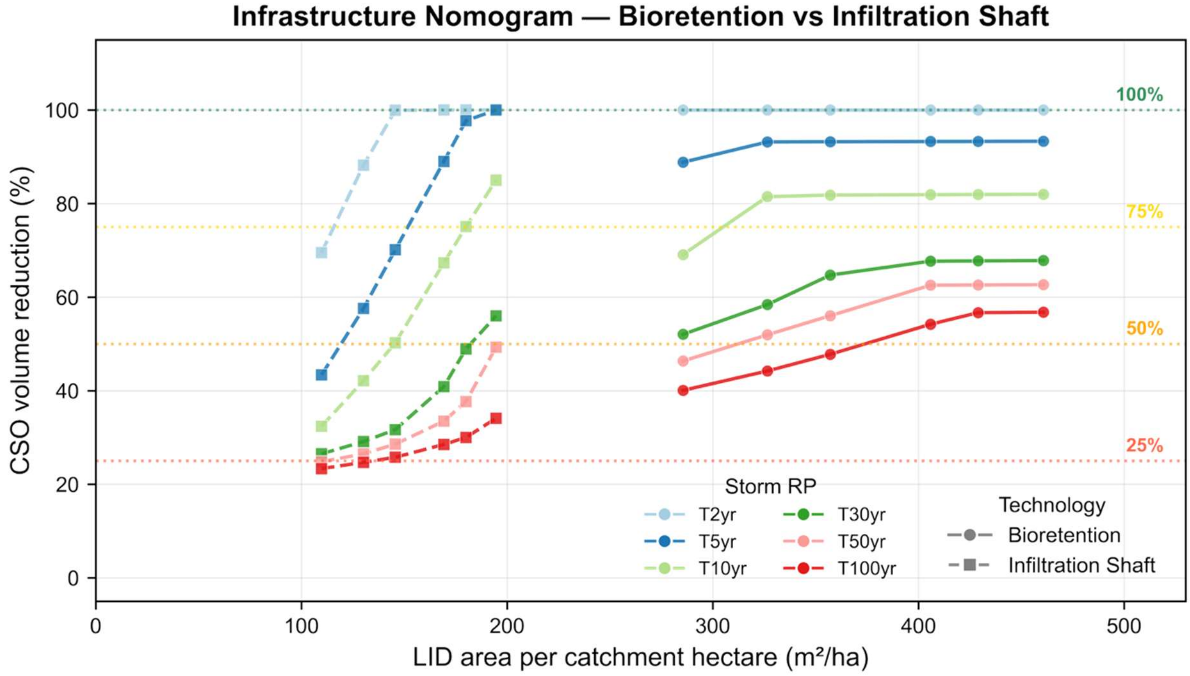

Figure 11: Santiago de Compostela—Infrastructure Nomogram (CSO Reduction vs LID Area). Relationship between installed LID area per catchment hectare and achieved CSO volume reduction for different storm return periods and decentralised technologies. The nomogram supports planning-level estimation of infrastructure requirements needed to reach target CSO reduction levels.

This figure can be used directly to estimate the order of magnitude of infrastructure required to reach target CSO reduction levels (e.g. 50 % or 75 %) under different storm conditions.

Importance of runoff connectivity (Q3)

Figure 12 illustrates the influence of runoff connectivity (α), defined as the fraction of impervious runoff that can be routed to decentralised measures.

The results show that:

- CSO reduction increases almost linearly with connectivity for frequent and moderate storms.
- Even large LID areas provide limited benefit when connectivity is low.
- For extreme storms, connectivity limits remain dominant regardless of technology.

From a planning perspective, this might hint that implementation feasibility and drainage connectivity often constrain performance more strongly than LID size. Connectivity should therefore be treated as a core scenario parameter in retrofit studies.

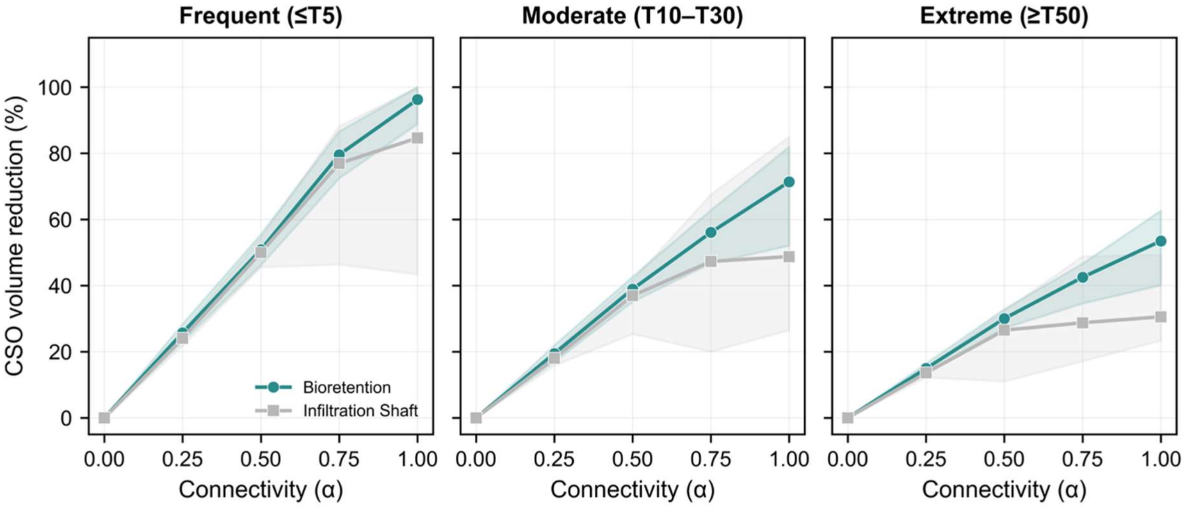

Figure 12: Santiago de Compostela—Sensitivity to Runoff Connectivity (α). CSO volume reduction as a function of runoff connectivity between impervious surfaces and decentralised measures, shown for frequent, moderate, and extreme storms. The figure highlights connectivity as a key limiting factor for retrofit effectiveness.

Combined benefits for flooding and CSO reduction (Q2)

Figure 13 compares CSO reduction with reductions in internal network flooding.

The figure shows that:

- Decentralised measures reduce both CSO discharge and network flooding.
- The magnitude of each benefit depends on storm severity and technology.
- Improvements in CSO performance do not automatically imply proportional flood reduction.

This highlights the value of decentralised interventions for multi-objective planning, where environmental protection and urban flood mitigation are considered together.

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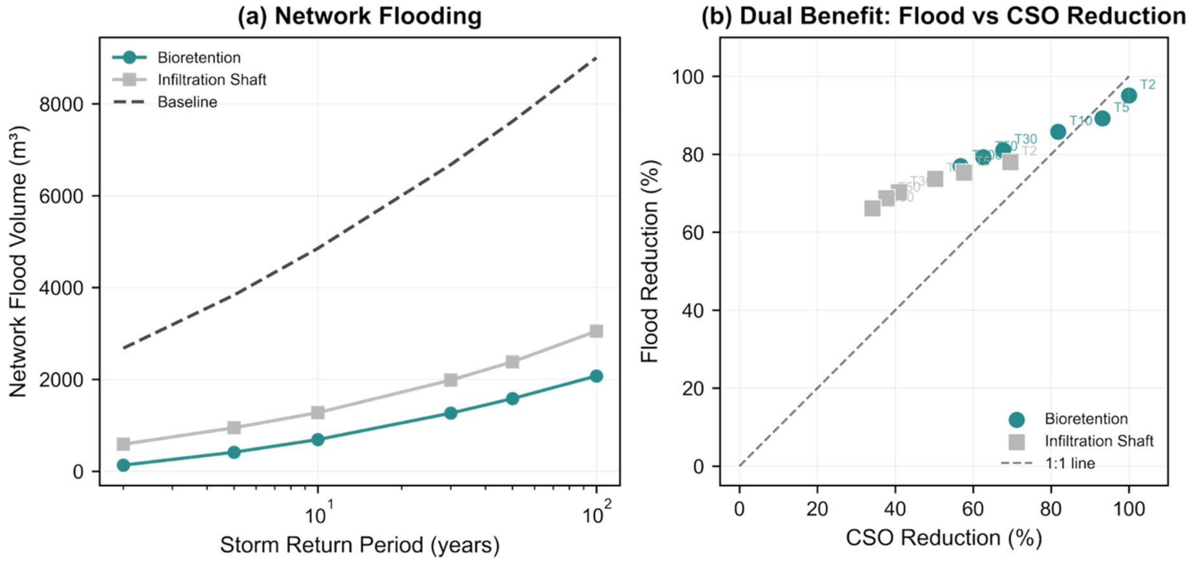

Figure 13: Santiago de Compostela—Dual Benefit: Network Flooding vs CSO Reduction. Comparison of CSO reduction and internal network flooding reduction achieved through decentralised interventions. The figure illustrates the concurrent benefits of block-scale measures for environmental protection and urban flood mitigation

Planning takeaway

For the Cancelón catchment, the block-based, data-reduced workflow:

- Identifies realistic CSO reduction ranges across storm classes
- Makes infrastructure–performance trade-offs explicit
- Highlights connectivity as a key limiting factor
- Supports prioritisation and comparison of decentralised strategies at planning stage

The results are suitable for screening, prioritisation, and scenario exploration, and should be followed by more detailed assessment where implementation is pursued. Lessons for Planning Practice (Santiago de Compostela, Cancelón):

- Block-based screening works. A data-reduced block–network model was sufficient to identify effective CSO reduction strategies.
- Connectivity matters more than size. Increasing the fraction of impervious runoff routed to LID often delivers more benefit than enlarging LID area.
- Available space is not fully exploited. Less than half of the potential planning area was used; expanding connected green space could further improve performance.

- Different LIDs fit different constraints. Bioretention offers higher reduction; infiltration shafts require less surface area.
- Expect diminishing returns for extreme events. Decentralised measures are most effective for frequent and moderate storms.
- Simplified CSO representation is acceptable for planning. Aggregate storage volume captured dominant system behaviour without detailed geometry.

5.2 Case Study 2: Risvangen, Aarhus, Denmark

5.2.1 System Overview

The Risvangen catchment in Aarhus, Denmark, is served by a separate stormwater system designed to safely convey rainfall runoff away from residential areas and discharge it to receiving waters. The primary operational objective of the existing system is flood protection, particularly the prevention of surface flooding and basement inundation during frequent and moderate storm events (Aarhus Vand, 2023; Urban Nature Atlas, n.d.).

From a traditional drainage perspective, controlled discharge of stormwater to the bay is therefore acceptable as long as urban safety targets are met. This planning philosophy underpins the implemented climate adaptation strategy in Risvangen, which relies on distributed surface basins, infiltration areas, and overland flow paths to buffer runoff before controlled release.

From the perspective of WATERUN and this manual, the Aarhus case serves a different but complementary purpose: to evaluate to what extent decentralised Nature-based Solutions (NbS) can reduce total urban runoff volumes and discharges to sensitive receiving waters, even in systems that are already considered hydraulically functional. From that perspective, it should be noted that, to demonstrate the tool’s capability to reduce urban runoff to sensitive water bodies, we assumed that the majority of stormwater flows to the Bay of Aarhus and used this reference point to reduce urban runoff to it. The case, therefore, shifts the focus from avoiding flooding to reducing runoff at source, aligning with broader water quality, ecosystem, and downstream impact objectives.

5.2.2 Data Availability

Compared to the other case studies in this manual, the Risvangen catchment in Aarhus is characterised by relatively good data availability (UFZ-D.3.1 WATERUN, 2023). The drainage concept, implemented Nature-based Solutions, and the overall stormwater management strategy are documented in municipal planning materials and project reporting.

Available information included:

- catchment extent and drainage concept, including an urban drainage model with accompanying data inputs
- descriptions of decentralised stormwater measures and surface storage elements
- rainfall design assumptions used in local planning
- geospatial data, including high-resolution digital elevation model (DEM), stormwater network attributes and location and design attributes of all installed stormwater interventions.

While more detailed system information exists in principle, the MUST-B Planning Toolkit application deliberately did not aim to reproduce a detailed engineering model of the Risvangen system. Instead, this case was used to test how well a data-reduced, block-based workflow can support planning decisions when applied to a well-documented context.

5.2.3 Modelling Scope and Simplifications

The Aarhus case study was designed to test the MUST-B Planning Toolkit under conditions where a stormwater system is already considered functionally adequate for flood protection, but where additional objectives—such as reducing runoff volumes and discharges to sensitive receiving waters—are of interest.

To support this objective, the modelling scope was defined around comparative planning analysis rather than detailed reproduction of the implemented drainage design. Two

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complementary modelling exercises were carried out, referred to as Experiment 1 and Experiment 2 in the project analysis.

Experiment 1 – Existing system retrofit:

The existing drainage concept was retained, and decentralised measures at the block scale were introduced to assess how much stormwater discharge and internal flooding could be reduced under different storm conditions.

Experiment 2 – Integrated LID–network design:

Decentralised measures were treated as an integral planning component, and stormwater network capacity was varied to explore how LID deployment influences required conveyance sizing and overall system performance.

In both experiments, decentralised interventions were limited to bioretention cells and infiltration shafts, applied consistently across scenarios to support direct comparison. Surface basins and buffering elements were represented in simplified form, capturing their aggregate storage and attenuation effect rather than detailed geometry, control rules, or local hydraulic structures.

The modelling therefore focuses on:

- relative performance across scenarios,
- sensitivity to storm severity and connectivity, and
- interaction between decentralised, block-scale measures and network capacity.

Detailed hydraulic optimisation, site-specific design constraints, and operational control strategies are intentionally outside the scope of this case study and are not required to address the planning questions explored here.

Note: Infiltration shafts are modelled for comparison only; high groundwater levels may limit their suitability due to basement flooding and downstream impact risks.

5.2.4 Planning Questions

The Aarhus case study addresses the following planning questions relevant to stormwater management in separated systems:

Q1 – Runoff reduction potential:

To what extent can decentralised Nature-based Solutions reduce total stormwater runoff and discharge to receiving waters in a system that already meets local flood protection objectives?

Q2 – Technology trade-offs:

How do different decentralised measures (bioretention cells versus infiltration shafts) compare in terms of runoff reduction performance under varying storm severities?

Q3 – Role of decentralised measures in system design:

How does integrating decentralised interventions influence required stormwater network capacity when considered early in the planning process?

These questions reflect a shift from flood avoidance toward runoff minimisation and receiving-water protection, aligning the Aarhus case with the broader objectives of WATERUN and the MUST-B Planning Toolkit.

5.2.5 Scenario Design

Scenarios for the Aarhus case were designed to explore how decentralised measures influence stormwater runoff and discharge to receiving waters in a separated system that already meets local flood protection objectives.

The scenario space was defined by four elements:

- Storm severity: Design storms covering frequent to rare events (T2–T100) to assess sensitivity across rainfall conditions.
- Decentralised technology: Two LID/NbS types were evaluated consistently across all scenarios—bioretention cells and infiltration shafts.

- Infrastructure role: Scenarios distinguish between retrofit of the existing system (Experiment 1) and integrated consideration of decentralised measures within network capacity planning (Experiment 2).
- Connectivity assumptions: Partial and full routing of impervious runoff to decentralised measures to reflect practical implementation limits.

All scenarios were evaluated relative to a baseline without decentralised intervention. The objective was comparative screening, not optimisation, to identify performance ranges and trade-offs relevant at the planning stage.

5.2.6 Key Results

The Aarhus case study highlights how decentralised Nature-based Solutions contribute to runoff reduction, flood mitigation, and cost efficiency in a separated stormwater system that already meets flood protection objectives.

Runoff reduction versus infrastructure provision

Figure 14 shows the relationship between installed decentralised infrastructure and achieved reduction in stormwater discharge to Aarhus Bay. Across storm return periods, runoff reduction increases with installed LID/NbS area, but with clear diminishing returns for larger events.

From a planning perspective:

- Frequent and moderate storms achieve high discharge reduction with relatively limited decentralised infrastructure.
- Extreme events require substantially more infrastructure and remain only partially mitigable.
- Bioretention consistently achieves higher discharge reduction than infiltration shafts for comparable land take.

The figure provides a practical basis for estimating how much decentralised infrastructure is required to reach target runoff reduction levels under different design storms.

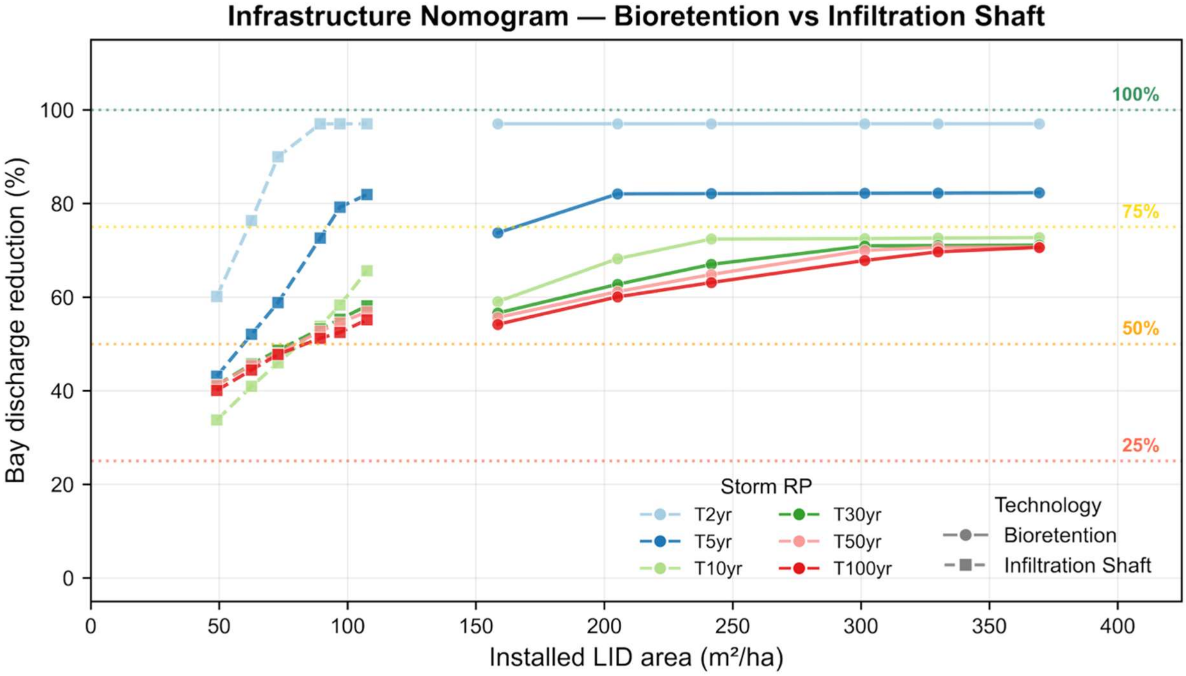

Figure 14: Aarhus—Infrastructure Nomogram: Runoff Reduction to Bay of Aarhus. Relationship between installed decentralised infrastructure and reduction in stormwater discharge to the Bay of Aarhus across storm return periods and technologies. The nomogram supports planning-level estimation of infrastructure requirements for runoff reduction.

Dual benefit: runoff reduction and flood mitigation

Figure 15 illustrates that decentralised measures deliver simultaneous benefits for reducing stormwater discharge to receiving waters and mitigating internal network flooding.

Key observations include:

- Both decentralised technologies reduce network flooding relative to the baseline system.
- Bioretention achieves stronger and more balanced reductions across storm classes.
- Reductions in discharge and flooding do not scale identically, reinforcing the need for scenario-based assessment.

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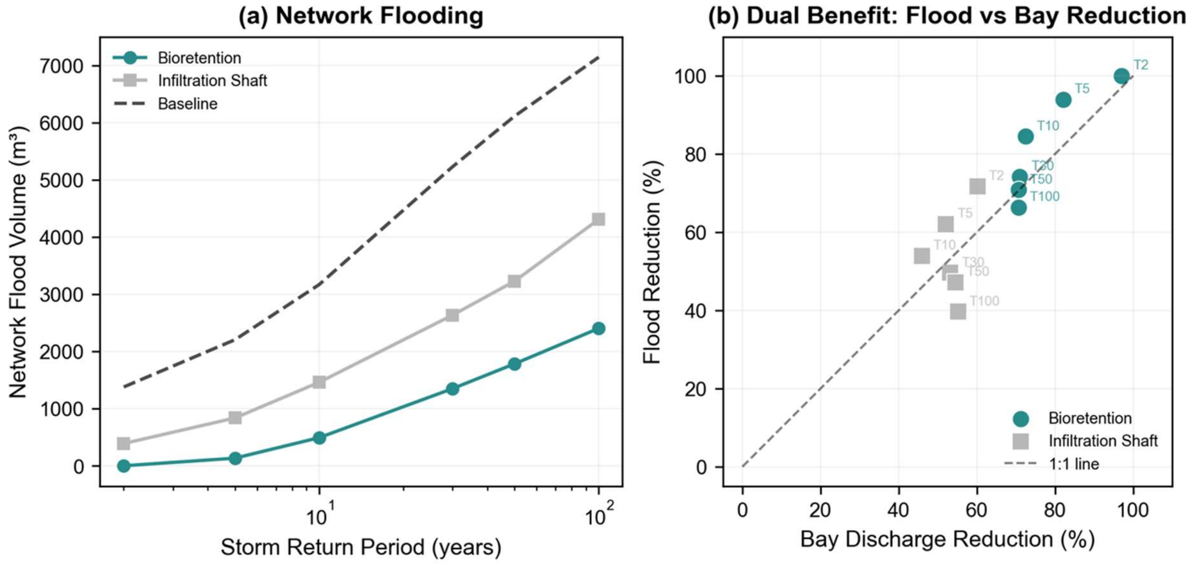

Figure 15: Aarhus—Dual Benefit: Network Flooding vs Bay Discharge Reduction. Comparison of reductions in internal network flooding and stormwater discharge to the receiving water for decentralised interventions. The figure illustrates the combined flood mitigation and runoff reduction benefits of decentralised measures.

This confirms that decentralised measures support multi-objective planning, even in systems where flood protection is already adequate.

Cost–performance trade-offs

Figure 16 relates the total system cost to the normalised discharge to Aarhus Bay for a representative design storm. The figure highlights a clear efficiency frontier, where substantial reductions in discharge can be achieved without proportional increases in cost.

From a planning perspective:

- Moderate reductions in discharge are achievable at relatively low additional cost.
- Beyond a certain point, further reductions require disproportionately higher investment.
- Bioretention options tend to populate the more cost-efficient region of the solution space.

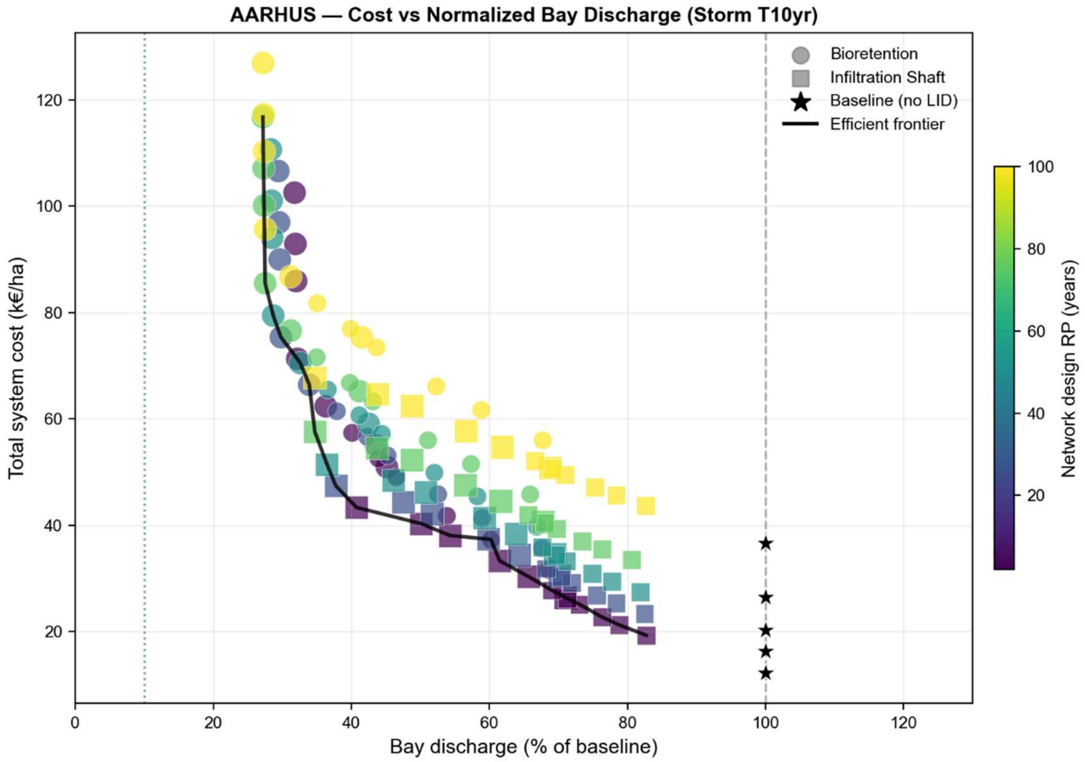

Figure 16: Aarhus—Cost versus Normalised Discharge to the Bay of Aarhus (T10 Storm). Total system cost plotted against normalised stormwater discharge to the receiving water for a representative design storm. The figure highlights cost–performance trade-offs and identifies efficient solution ranges for planning-level screening.

This figure supports cost-aware screening of decentralised strategies and helps identify combinations of infrastructure and performance that warrant further investigation.

5.2.7 Lessons for Planning Practice (Aarhus- Risvangen)

- Runoff reduction adds value even when flooding is controlled. Decentralised measures significantly reduce discharge to receiving waters in systems that already meet flood protection objectives.
- Most benefits come from frequent and moderate storms. High runoff reduction is achievable for common events; extreme storms show diminishing returns.
- Technology choice affects efficiency. Bioretention generally provides greater discharge and flood reduction per unit area than infiltration shafts.
- Cost efficiency matters early. Moderate runoff reductions can be achieved at relatively low additional cost; deeper reductions require disproportionate investment.

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- Decentralised measures support multi-objective planning. Runoff reduction and flood mitigation can be addressed simultaneously without relying on a detailed system redesign.

5.3 Case Study 3: Al Zuhour Triangle, Amman, Jordan

5.3.1 System Overview

The Al-Zuhour Triangle catchment is located in eastern Amman and is characterised by steep topography, rapid urbanisation, and recurrent flash-flood impacts (Figure 17). Stormwater management in this area is primarily driven by the need to convey intense runoff safely through the urban system and reduce downstream flooding in central Amman during short-duration, high-intensity rainfall events (UN-Habitat Jordan, 2023; UN-Habitat and UNDP, 2024).

Drainage in the study area is provided by a stormwater conveyance system, designed for flood routing rather than runoff retention or water quality control. The system relies on downstream conveyance and storage to manage peak flows, with discharge ultimately routed toward major drainage corridors. Decentralised stormwater retention or infiltration measures are not part of the existing system concept.

From a WATERUN perspective, this case study reframes the problem by asking whether block-scale LID/NbS can reduce runoff volumes and peak discharges before they enter the downstream stormwater system. The objective is not to redesign the drainage system, but to evaluate the potential of upstream, decentralised interventions to reduce hydraulic stress under frequent and moderate storm events.

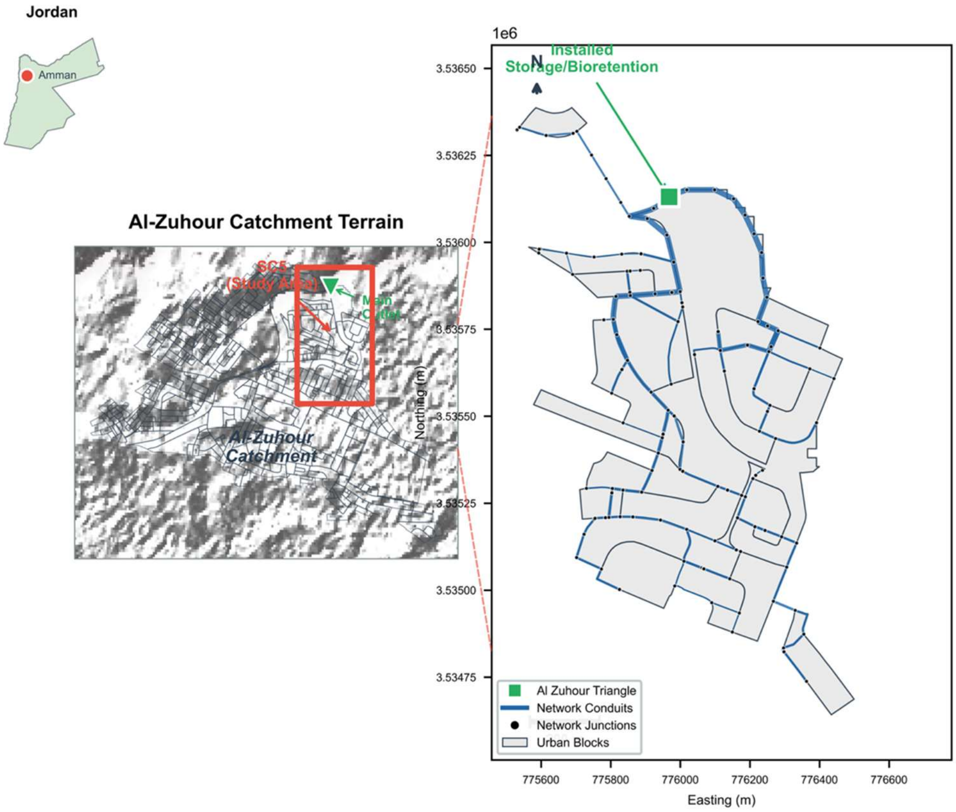

Figure 17: Case study—Amman, Al Zuhour Triangle, Jordan

This case, therefore, serves as a stress test of the MUST-B Planning Toolkit in a data-scarce, high-risk urban environment, where planning decisions must be made with limited infrastructure information and stringent flood-risk constraints.

5.3.2 Data Availability

The Al-Zuhour Triangle case was developed under data-scarce conditions, representative of many rapidly urbanising areas in semi-arid regions. No surveyed sewer or stormwater drainage network data were available for this catchment (UFZ-D.3.1 WATERUN, 2023).

The analysis relied exclusively on open and publicly accessible datasets, including:

- OpenStreetMap road network for block delineation and flow routing
- A publicly available digital elevation model (DEM) for slope and drainage direction
- World Settlement Footprint (WSF) raster for imperviousness estimation

- National and literature-based IDF curves for design rainfall representation (Hoffmann, 2023)

No local monitoring data for runoff, flooding, or discharge were available. As a result, the case focuses on relative comparison of planning scenarios rather than calibration against observed hydraulic performance.

This data context reflects the intended application domain of the MUST-B Planning Toolkit: early-stage stormwater planning in environments where conventional modelling approaches are constrained by limited data availability.

5.3.3 Modelling Scope and Case-Specific Deviations

The Al-Zuhour Triangle case follows the standard MUST-B workflow described earlier in this manual. This section, therefore, focuses only on the case-specific deviations required by the size and terrain of the catchment.

Two adaptations were necessary:

Hierarchical subdivision of the catchment

Due to the large catchment size, the area was subdivided into hydraulically coherent subcatchments before network generation. Subdivision boundaries were guided by terrain-driven flow patterns and by clusters of locations where gravity-driven routing is not feasible (identified as pump-edge clusters). This ensured that each sub-area remained hydrologically valid and preserved gravity-driven drainage.

Treatment of uphill edges and high pump incidence

The steep, highly variable terrain led to frequent conflicts with uphill routing when generating gravity-driven networks. These locations were handled explicitly by identifying uphill edges and treating them as indicators of structural drainage constraints. Areas with a high incidence of such constraints were used to inform subdivision boundaries rather than forcing unrealistic gravity routing. This approach avoids over-interpreting local hydraulic detail while still capturing the dominant influence of terrain on drainage behaviour.

All other aspects of the modelling—runoff generation, block representation, design-storm forcing, and network simulation—follow the shared planning-level assumptions described earlier in the manual.

5.3.4 Planning Questions Addressed

The Amman case study addresses the following planning question:

Q1— What is the effect of the existing Nature based Solution at the Al Zuhour Triangle in Amman during design storms, and to what extent can block-scale interventions further reduce the urban runoff?

This question is explored using a data-reduced representation of the drainage system, appropriate for a context where detailed infrastructure data are unavailable. The analysis focuses on:

The performance of the NbS at Al Zuhour Triangle as Baseline:
The effect of the existing NbS on the runoff at the catchment level during design storm conditions.

Effect of block-scale interventions:
How decentralised measures applied at the block level further reduce downstream flow concentration.

5.3.5 Scenario Design

Scenario design in the Amman case focuses on identifying (quantifying) the effect of the existing NbS and screening the added value of block-scale interventions under representative storm conditions.

Two scenario groups were evaluated:

Baseline scenario:
Existing drainage behaviour is represented using a combination of data-reduced, synthetic stormwater network and the existing NbS at Al Zuhour Triangle.

Block-scale intervention scenarios:
Decentralised measures applied at the block level to reduce runoff contributions before flow enters the downstream drainage network.

Scenarios were evaluated using consistent design-storm inputs and identical network representations, allowing the relative effect of block-scale measures on downstream flow reduction to be assessed across the catchment.

5.3.6 Key Results (Planning Perspective)

Results from the Amman case are presented using the same planning-oriented indicators applied in the other case studies, enabling direct comparison across cities and system types.

The existing NBS at Al Zhour Triangle is designed to attenuate peak flows before controlled release to downtown Amman. The storage fills to capacity for all design storms, successfully detaining runoff, with 66–96% of runoff conveyed to the downtown outfall and zero overflow recorded. This operation promotes peak attenuation and protects the downstream receiving system. Despite this available capacity, 4–34% of catchment runoff is lost to surface flooding in the upstream network before reaching the detention facility. For demonstration, we used a 2-year return period for the network generation to highlight the complementary effect of using decentralised stormwater

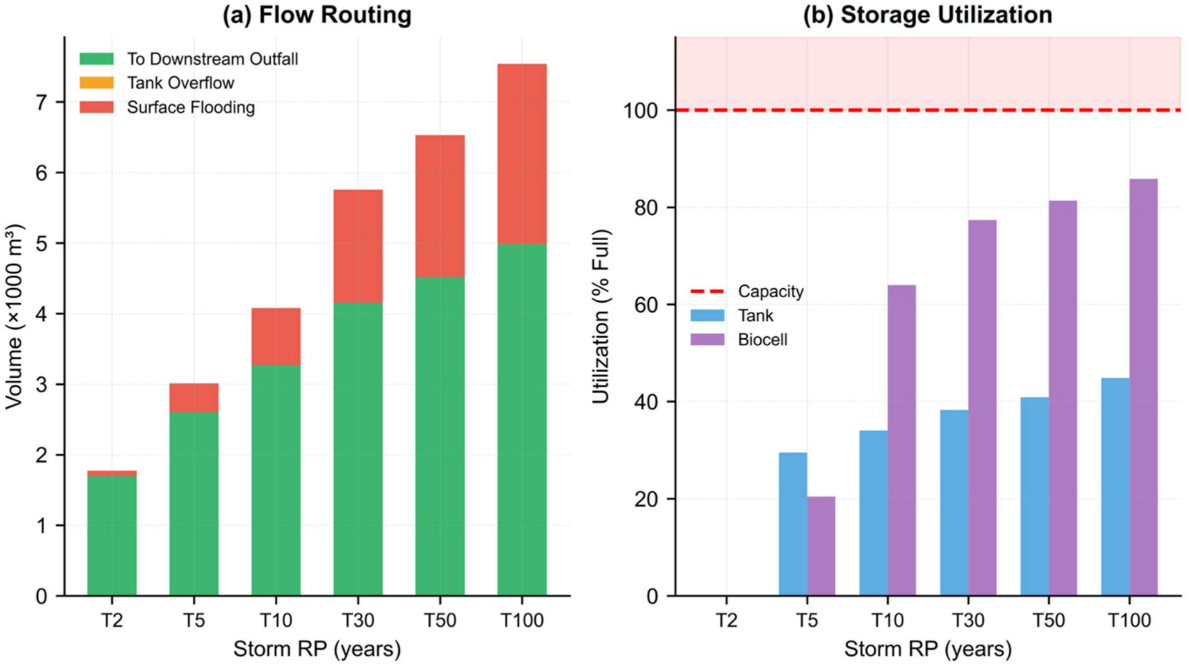

Figure 18: Water balance for existing drainage infrastructure under design storms (T2yr–T100yr). (a) Flow routing showing volumes discharged to the downtown outfall, released as tank overflow, and lost to surface flooding. (b) Storage utilisation showing tank (2,100 m³) and biocell (750 m³) maximum fill levels; dashed line indicates design capacity.

Across all design storms, block-scale interventions consistently reduce downstream flows and network flooding volumes relative to the baseline condition (Figure 19). Even moderate levels of decentralised implementation lead to substantial reductions in conveyed runoff, indicating that a limited subset of contributing blocks dominates downstream flow response.

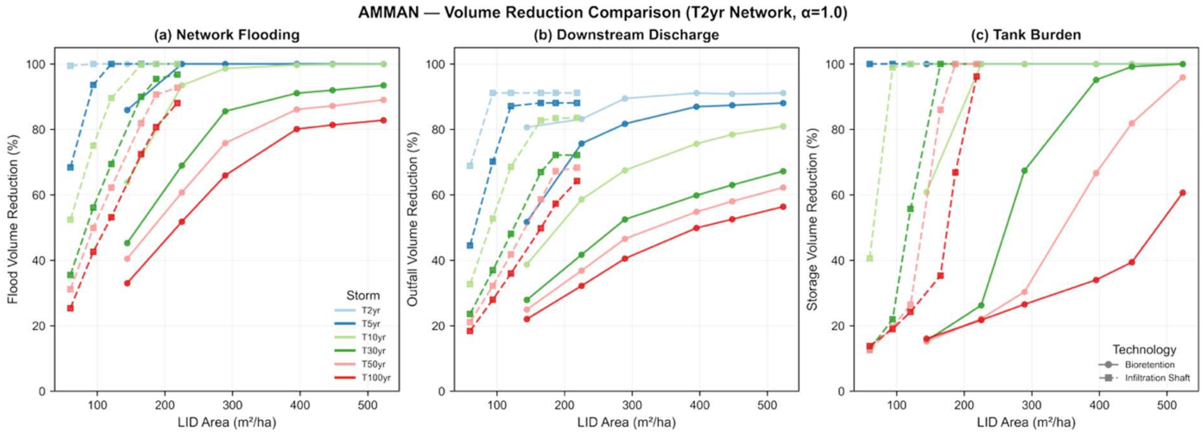

Figure 19: Amman—Volume reduction response to block-scale LIDs under design storms. Relative reduction in (a) network flooding volume, (b) downstream outfall discharge, and (c) storage capacity of existing infrastructure as a function of decentralised intervention area. Results are shown for multiple storm return periods. Baseline conditions correspond to zero intervention area

The results further show that increasing LID area yields diminishing marginal reductions at higher implementation levels, particularly for extreme storm events (Figure 19a–c). While frequent and moderate storms can be effectively mitigated with relatively small block-scale intervention areas, larger storms require substantially greater spatial allocation to achieve comparable relative benefits.

Comparison of flooding and downstream discharge reduction demonstrates a strong dual benefit of block-scale measures under matched design conditions (Figure 20). Reductions in conveyed runoff are closely aligned with reductions in network flooding volume, supporting the role of decentralised interventions as complementary measures to existing stormwater conveyance systems.

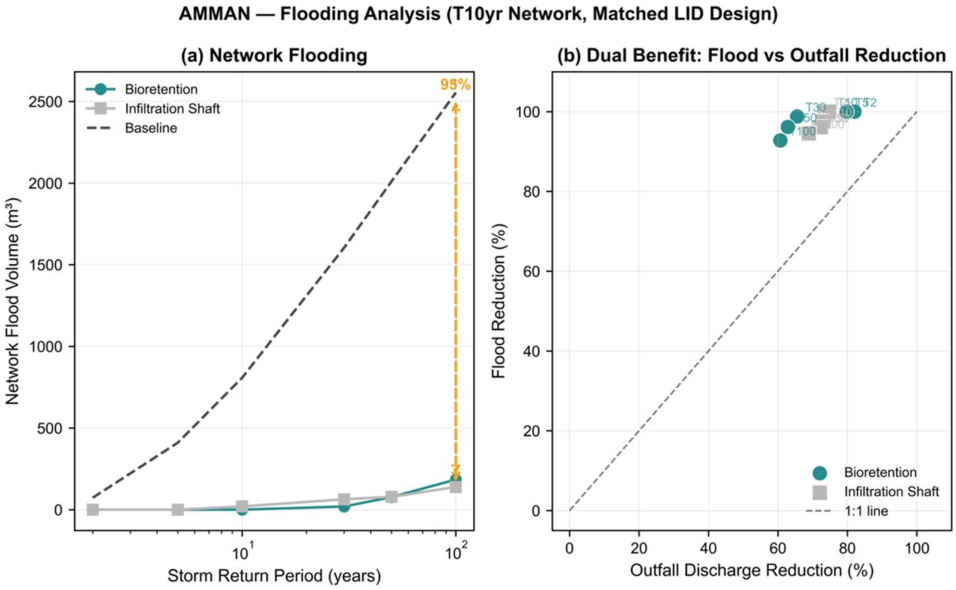

Figure 20: Amman-Flooding reduction versus downstream discharge reduction (T10-year storm). Comparison of network flooding volume and downstream discharge reduction for bioretention and infiltration shaft scenarios under matched LID designs. The dashed line indicates a 1:1 relationship between flooding and discharge reduction.

Cost–performance analysis highlights a clear trade-off between investment and downstream discharge reduction (Figure 21). The resulting Pareto fronts show that multiple intervention configurations can achieve similar reductions at different cost levels, allowing planners to identify efficient solution ranges rather than a single optimal design. Across all scenarios, decentralised interventions provide a supplementary benefit, enhancing the performance of the existing system and underscoring the potential of decentralised measures to alleviate downstream flood risk.

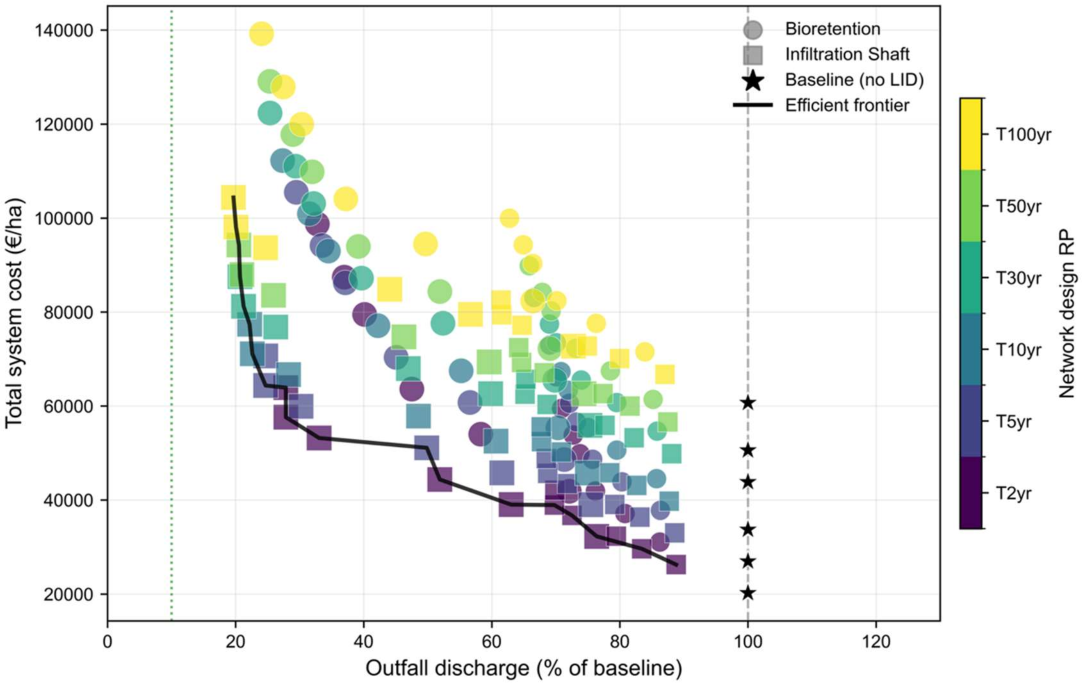

Figure 21: Amman—Cost versus downstream discharge reduction for block-scale LIDs. Pareto analysis showing the trade-off between total system cost and reduction in downstream outfall discharge for T30-year design storms. Star symbols indicate baseline conditions without decentralised interventions.

Baseline conditions correspond to the existing drainage configuration without block-scale interventions and are shown in the figures as zero-intervention states, dashed baseline curves, or star markers at 100% outfall discharge.

5.3.7 Lessons for Planning Practice

- Block-scale measures can meaningfully reduce downstream flows even where detailed drainage data are unavailable.
- Targeted interventions outperform uniform implementation, as a limited number of blocks contribute disproportionately to downstream runoff and can be identified using block-scale screening indicators.
- Decentralised measures complement the existing conveyance infrastructure, particularly for frequent and moderate storms.

- Costs and benefits can be compared early, helping planners identify cost-effective intervention ranges rather than a single fixed solution.

6 CONCLUSION

This manual has presented a structured workflow for applying the MUST-B Planning Toolkit, moving from urban block generation and attribute mapping, through decentralised intervention pre-sizing, to optional network-based analysis and scenario comparison. Together, these steps provide a coherent planning sequence in which block-scale screening informs where interventions are most effective, and network-level analysis clarifies how these interventions interact with downstream conveyance.

Applied across three contrasting case studies, the workflow demonstrates that decentralised, block-scale measures can be evaluated consistently using open data and planning-level assumptions. The results show how targeted interventions can reduce runoff and downstream discharges, support prioritisation, and reveal cost–performance trade-offs before detailed design decisions are made.

After completing the workflow described in this manual, the next steps typically involve refining priority areas, testing a reduced set of promising scenarios, and transitioning to detailed hydraulic modelling and site-specific design using local data and regulatory requirements. The MUST-B Planning Toolkit is therefore best understood as a front-end planning and screening tool that structures decision-making and narrows the solution space ahead of more detailed engineering and permitting processes.

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APPENDIX A: GLOSSARY/TERMINOLOGY

Table A-1: Glossary of Terms Used in the MUST-B Planning Toolkit

Table A- 1: Definitions of key terms and indicators as used in this manual. The glossary is provided for clarity and consistency across the conceptual framework (Section 2) and the workflow descriptions (Sections 3 and 4).

Term	Definition
CAI	Contributing Area Impact — volume-weighted flow accumulation
CSO	Combined Sewer Overflow
CSF	Combined Sewer Factor
DWF	Dry Weather Flow
D_p	Decentralisation potential
GI	Green Infrastructure
HPI	Hydraulic Performance Index — surcharge height / burial depth
IDF	Intensity-Duration-Frequency (rainfall curves)
KGE	Kling-Gupta efficency
LID	Low Impact Development
MUST-B	Management of Urban STormwater at Block-level
NbS	Nature-based Solutions
RSPH	Repeated Shortest Path Heuristic
SWMM	Storm Water Management Model (EPA)
T	Design Return Period (e.g., T2-year)
Tc	Time of Concentration
WSF	World Settlement Footprint
WWTP	Wastewater Treatment Plant

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APPENDIX B: BLOCK ATTRIBUTES

This appendix summarises the block-level attributes derived and used by the MUST-B Planning Toolkit. These attributes form the input basis for block-scale runoff estimation, decentralisation potential assessment, and LID pre-sizing described in Sections 3 and 4.

Table B-1: Block Attribute Definitions and Usage

Table B- 1: Core attributes computed for each urban block and used throughout the block mapping, LID sizing and network generation.

Attribute	Source	Description
Geometry Attributes		
Block identifier	Generated	Unique identifier for each block (e.g., B_001)
Block boundary	OSM/cadastral	Polygon geometry defining the block outline
Total area	Calculated	Total block area in square metres
Land Cover Attributes		
Sealed (impervious) area	WSF raster	Area covered by impervious surfaces (m²)
Unsealed (pervious) area	WSF raster	Area covered by pervious surfaces (m²)
Sealing degree	Calculated	Proportion of block that is impervious (0–1)
Population Attributes		
Population	GHSL/Urban Atlas	Estimated number of residents in the block
Population density	Calculated	Residents per square kilometre
LID Potential Attributes		
Selected LID technology	Sizing analysis	Type of LID recommended (e.g., bioretention, swale)
Required LID area	Sizing analysis	Area needed to achieve target retention (m²)
Runoff generated	Sizing analysis	Total runoff volume from sealed surfaces (m³)
Volume retained	Sizing analysis	Volume captured by the LID system (m³)
Retention percentage	Sizing analysis	Share of runoff retained on-site (%)
Decentralisation index	Sizing analysis	Ratio indicating block’s contribution to catchment-wide decentralisation

Table B-2: Attribute Usage by Workflow Component

Table B- 2: Block attributes used by each major workflow component in the MUST-B Planning Toolkit, showing how block-level information is reused consistently across runoff estimation, LID pre-sizing, prioritisation, and export to SWMM.

Workflow Component	Key Attributes Used
SWMM Subcatchments	Block identifier, block boundary, sealed area, unsealed area
Network Generation	Block boundary (perimeter used for connection points)
LID Sizing	Sealed area, available green space
Priority Ranking	Sealing degree, decentralisation index, retention percentage
SWMM LID Export	Selected LID technology, required LID area

Table B-3: Default assumptions for treating missing or incomplete data

Table B- 3: Conservative default assumptions for block-level hydrological attributes when spatial data is unavailable, representing worst-case runoff scenarios.

Attribute	Default Assumption	When Applied	Rationale
Sealing degree	Completely sealed (100%)	Block has no WSF raster overlap	Assumes worst-case runoff generation
Sealed area	Equals total block area	Block has no WSF raster overlap	Entire block contributes to runoff
Unsealed area	Zero	Block has no WSF raster overlap	No pervious area available for infiltration
Available green space	Zero	Block has no geometry for LID placement	No LID placement possible

These conservative defaults ensure that catchment-wide runoff calculations are not underestimated due to missing data.

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APPENDIX C: DATA SOURCES

Table C-1: Data Sources used in MUST-B Planning Toolkit Development

Table C- 1: Summary of spatial and rainfall datasets required to apply the MUST-B Planning Toolkit, including typical resolution, spatial coverage, and the workflow steps in which each dataset is used (Sections 3 and 4).

Data	Source	URL
City boundaries	OpenStreetMap Nominatim	nominatim.openstreetmap.org
WSF 2019	DLR GeoService	geoservice.dlr.de
GHSL Population	JRC	ghsl.jrc.ec.europa.eu
Urban Atlas	Copernicus	land.copernicus.eu
SRTM DEM	USGS	earthexplorer.usgs.gov

APPENDIX D: PLANNING-LEVEL COST MODEL

This appendix describes the simplified cost model used in the MUST-B Planning Toolkit to support relative comparison of intervention scenarios. The model complements the hydrological and hydraulic performance indicators presented in Sections 3–5 and is intended exclusively for early-stage planning and screening.

The cost model is deterministic and deliberately simplified. It is not suitable for budgeting, tendering, or detailed financial appraisal, but provides a consistent basis for comparing decentralised and network-based strategies under identical assumptions.

Scope and Components

Costs are calculated for:

- Decentralised measures implemented at block scale (bioretention cells and infiltration shafts), including capital costs, routine maintenance, and periodic replacement.
- Sewer network infrastructure where applicable (Subtask 3.4.2), based on pipe length and diameter derived from the planning workflow.

Unit costs are expressed per square metre (bioretention) or per unit (infiltration shafts) and reflect typical planning-level estimates.

Cost Framework and Assumptions

All scenarios are evaluated over a fixed planning horizon using a uniform net present value (NPV) formulation. Default assumptions (e.g. analysis period and discount rate) are applied consistently across scenarios to ensure comparability. No residual value is assumed.

Use and Interpretation

The cost model is applied after LID pre-sizing and before scenario comparison. Outputs include total lifecycle cost per scenario and cost-normalised performance indicators (e.g. cost per unit runoff or discharge reduction).

Cost results represent order-of-magnitude estimates and should be interpreted comparatively rather than absolutely. Local construction conditions, land acquisition, permitting, and institutional factors are not represented.

APPENDIX E: ADDITIONAL NOTES

Note E-1: Validation of the inflow to CSO Storage—best-performing events at the Cancelón catchment

The model captures the overall hydrograph shape and peak timing across a range of event characteristics — from the short, intense storm of 08 Oct 2002 (0.4 h, 28.5 mm/h mean intensity) to the prolonged, low-intensity event of 24 Oct 2002 (11.2 h, 2.7 mm/h). Peak flows are reproduced within +6% to −12% for the three best events, with KGE values consistently above 0.85. Notably, three of the four best-performing events are also CSO events, indicating that the model performs well precisely for the high-flow conditions most relevant to overflow analysis.

Across all 12 events, the median KGE is 0.87, with all events achieving KGE > 0.5. This result confirms that the single-parameter combined sewer factor (CSF) method reliably generates combined sewer networks capable of replicating the drainage behaviour of the Cancelón catchment.

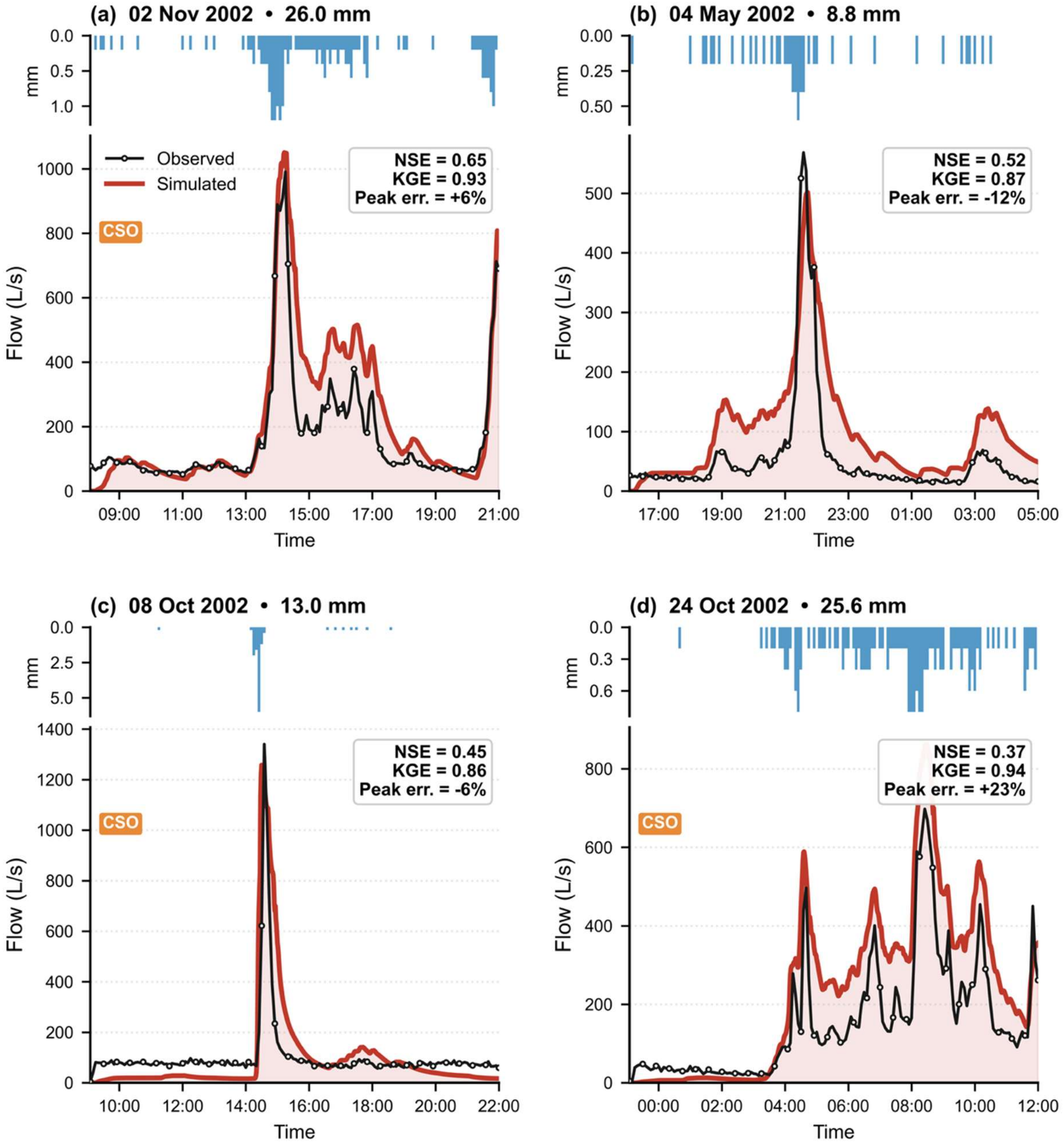

Figure E- 1: Santiago de Compostela- Inflow validation — best-performing events at the Cancelón catchment. Observed (black) and simulated (red) inflow hydrographs at the CSO storage tank for the four best-performing events ranked by NSE, with CSF = 3. Rainfall shown as inverted bars (blue). Events marked with an orange "CSO" produced observed overflow.

Note E-2: CSO Volume and Peak Flow Comparison

The model reproduces CSO peak flows within +7% to +45% for three of the four events. The largest event (02 Nov 2002; 962 L/s observed) is underestimated by 29%.

Overflow volumes show a general tendency toward overestimation (total observed: 3,952 m³; simulated: 5,620 m³; ratio = 1.42), consistent with the conservative volume bias observed in the inflow hydrographs. The strongest event (02 Nov 2002) is the only case in which both the peak (-29%) and the volume (-10%) are underestimated.

For planning-scale application, the uncalibrated data-reduced representation provides acceptable agreement in terms of overflow occurrence, order of magnitude, and relative response. Further calibration and detailed representation of flow control structures would improve event-scale accuracy, but are outside the scope of the screening-oriented framework presented here.

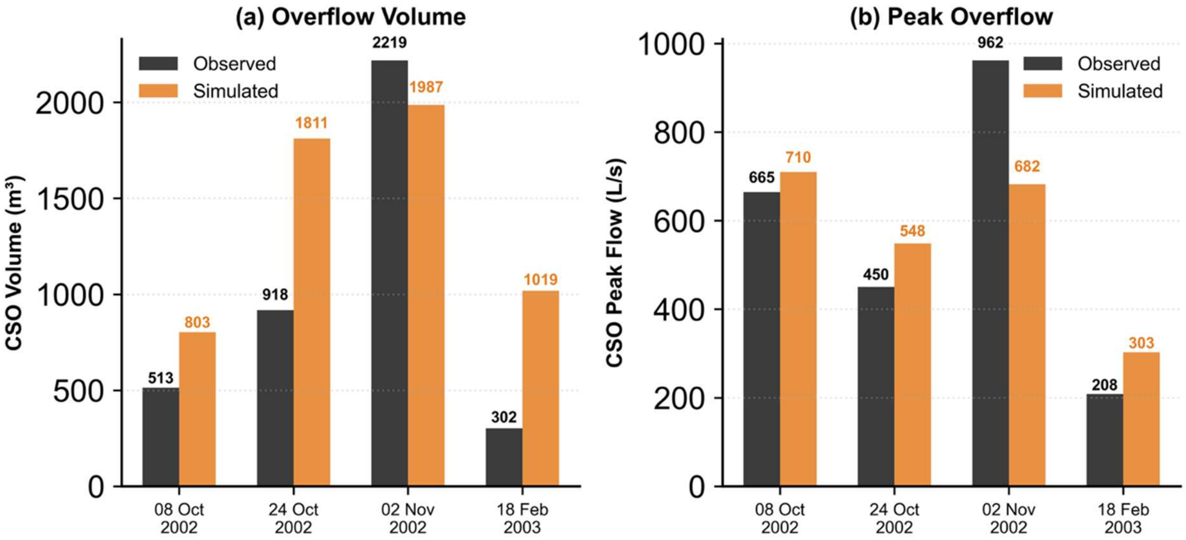

Figure E- 2: Santiago de Compostela—CSO volume and peak flow comparison. Observed and simulated CSO overflow volume (a) and peak discharge (b) for the four CSO events (CSF = 3).