



Spatial-economic scenarios to increase resilience to urban flooding

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ABSTRACT

Due to accelerating climate change and the need for new development to accommodate population growth, adaptation of urban drainage systems has become a pressing issue in cities. Questions arise whether decentralised urban drainage systems are a better alternative to centralised systems, and whether Nature Based Solutions' (NBS) multifunctionality also brings economic benefits. This research aims to develop spatio-economic scenarios to support cities in increasing their resilience to urban flooding with NBS. The novelty of our work lies in the automated routines to assess the potential for decentralised NBS within the existing urban catchment. The identification of locations and dimensioning is based on open, publicly available geospatial data. Moreover, a block-based decentralization potential metric is developed to indicate stormwater mitigation potential in any urban setting. The Ecully catchment, Lyon metropolitan area (France), is presented as a case study to achieve zero combined sewer overflow (CSO) for specific design storm events. This planning workflow enables project cost savings through the most suitable allocation of distributed interventions, with cost functions also incorporating scaling effects. By reducing the number of decentralised NBS sites compared to smaller, wide-distributed interventions up to 34 % of project costs are saved when planning for a 5-year design storm and up to 7 % for a 100-year design storm. When the decentralised NBS scenario is analysed alongside other urban stormwater management practices, the centralised constructed wetland for CSO results to be the most economical solution due to the higher retention capacity and scaling effect, significantly outperforming the grey alternatives.

1. Introduction

The increasing frequency and intensity of extreme precipitation events due to climate change and the expansion of urban areas expose cities to the risk of urban flooding (Kundzewicz et al., 2014). Pluvial flooding is urban flooding caused by high-intensity storms whose runoff exceeds the urban drainage system's capacity, distinguished from fluvial and coastal flooding. With extreme precipitations expected to increase across Europe, only few countries, such as Belgium, Denmark, Sweden and the United Kingdom, have developed guidelines to adjust the design rainfalls (Madsen et al., 2014). The modification of the urban drainage system also in response to evolving urban development is already happening in Europe (Skougaard Kaspersen et al., 2017). This is necessary due to the increasing risk of urban flooding and overloading of the sewer system, leading to combined sewer overflow (CSO) (Gogien et al., 2023). The European Water Framework Directive (2000/60/EC)

had already demanded CSO policies to limit the number of spill events and reduce the pollutant load discharged into water bodies. Although sixteen EU Member States have national standards for regulating stormwater overflows, there is still a need for stricter limits and monitoring data on CSO discharges to upgrade the water infrastructure (Botturi et al., 2021). Cities are nowadays adopting a range of responses and integrating grey and green infrastructure within existing urban sewers (Dolowitz et al., 2018). Grey infrastructure is the built, engineered infrastructure that extends the capacity of the sewer system, while Nature Based Solutions (NBS) are the biological-physical systems for water storage, infiltration, evapotranspiration and reuse according to different levels of treatment. Prominent examples are rain gardens, bio-retention cells, bioswales, green roofs and constructed wetlands. Other terminology for infrastructure that aims at minimising potential impacts on the surrounding environment is BMP (Best Management Practices), LID (Low Impact Development) and WSUD (Water Sensitive

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Urban Design (Fletcher et al., 2015). The question is whether decentralised systems are a better alternative to centralised ones, and whether NBS also bring economic benefits (Dierkes et al., 2015; Fryd et al., 2012). The strategy chosen by cities is mainly driven by environmental and technical constraints, but also by governance, regulatory regime, access to capital investment and social drivers (Dolowitz et al., 2018; Zhang et al., 2017). Previous studies have highlighted the need for integrated decision support tools to assist planning, reflecting stakeholders' preferences in exploring technological opportunities and trade-offs between green and grey stormwater control measures (Bach et al., 2020; Gallo et al., 2020). These tools require main assumptions and imported datasets to identify feasible options for stakeholder discussions, while detailed urban planning can come at the expenses of data that is not publicly available, such as cadastral maps or sewer network data. Given the lack of data availability and monitoring, simple and easy-to-use models are demanded to mitigate CSO impacts (Montoya-Coronado et al., 2024a). There is the need for more accessible, data-reduced methods to enable pre-feasibility analysis even in the absence of detailed sewer network models. This research addresses the following questions:

- Is it possible to assess whether the existing urban environment has the capacity to retain stormwater runoff locally without expanding the sewer system?
- Up to which storm design event can be retained within the urban catchment? And which locations to prioritise when targeting the reduction of CSO spill events?
- In a scenario analysis, are distributed NBS advantageous compared to centralised and grey strategies?

To address this gap, we aim to develop spatial-economic scenarios to support cities in increasing their resilience and mitigating CSO impacts through distributed NBS and benchmarking it with other urban stormwater management practices. For this purpose, we develop automated algorithms fed by open-geospatial data to evaluate whether the urban catchment can retain stormwater within the urban blocks. The block is the minimal urban space delimited by roads and railways (Khurelbaatar et al., 2021b). The Ecully catchment study case, Lyon metropolitan area, shows how this approach can be used for targeted reductions of CSOs under a range of design storms. Urban blocks with the highest potential for decentralised NBS are identified across the urban catchment, and stormwater infrastructure is sized. Finally, a spatial-economic scenario analysis assesses whether the decentralised NBS are advantageous compared to other urban stormwater management practices. The tools we develop provide decisional support to cities, improving their resilience to urban flooding through enhanced nature-based systems. The main advantage is the reliance on open data and their applicability to multiple cities. Given the modular structure, depending on data availability and specific objectives, a higher level of detail can be integrated.

2. Results

Following the ALLOWS (Assessment of Local Lowest-Cost Wastewater Solutions) scenario approach (Khurelbaatar et al., 2021a; van Afferden et al., 2015), four technological scenarios for urban stormwater management are generated to compare the total project costs. Decentralised technologies have the advantage of intercepting and conveying the impervious runoff inside the blocks, ensuring that the road runoff is excluded; thus, apart from sediment trapping, no specific treatment is required. In the scenarios, this is achieved with bio-retention cells (BRC) as nature-based solution and infiltration shafts (IF) as grey infrastructure. In comparison, centralised technologies involve the retention of stormwater and untreated wastewater, requiring at least water pre-treatment directly at the CSO location, i.e., at the catchment outlet. This is achieved with dedicated constructed wetlands for combined sewer overflow (CSO-CW) as nature-based solution and retention

treatment basins (CSO-RTB) as grey infrastructure, also indicated as clarifier-type CSO tanks. Design parameters of the technologies are reported in Appendix A. Fig. 1 summarises the proposed strategies in the scenario analysis to target the same reduction in stormwater volume exceeding the sewer system's capacity. A thorough illustration of results follows, starting from the decentralised NBS solution at the block level.

2.1. Urban block mapping

The urban block mapping technique identifies where NBS technologies could be implemented within the urban catchment based on open-geospatial data, such as roads, population and human settlements (see Section 5.1). Fig. 2 shows the resulting urban blocks map and relative statistics for the Ecully Catchment. Within each block, the partition between sealed and open areas restricts the maximum connected open area and, thus, the available area for a potential NBS with a simple rectangular shape. The maximum connected open area and the potential area for NBS realisation have an extension of 1.04 km² and 0.3 km², respectively, within a total estimated 2.2 km² of the total blocks area, thus relatively a 47 % and 13 % of the whole urban catchment excluding traffic roads. Fig. 2c illustrates the repartition of the open area within each block. While the proportion of the maximum connected open area varies greatly among the blocks, the NBS potential area occupies a small relative portion, with a median of 21 % of potential infrastructure area per block.

2.2. Decentralisation potential

The results from the urban block mapping and site dimensioning are interpreted with the Decentralisation Potential D_p (%) indicator to gain an insight on which blocks have the higher potential to implement decentralised NBS infrastructure (see Section 5.2). It identifies blocks to prioritise for intervention with a specific NBS technology. This easy-to-use indicator aggregates and summarises the information on the block's features, namely the sealed and NBS potential area, the rainfall depth and the equivalent water accumulation height based on the type of planned technology, in this case, bio-retention cells (Eqs. 1 and 2 in Section 5.2). D_p expresses the % of impervious runoff from the entire urban catchment, excluding roads, that the individual block can potentially retain (Fig. 3).

It can be noted in Fig. 3 that the potential for decentralisation varies with the increase in rainfall depth. The blocks that could potentially contribute most to runoff retention do not constantly retain a runoff volume proportional to their impervious area. As rainfall depth increases, the decentralised solution reaches its capacity and begins to

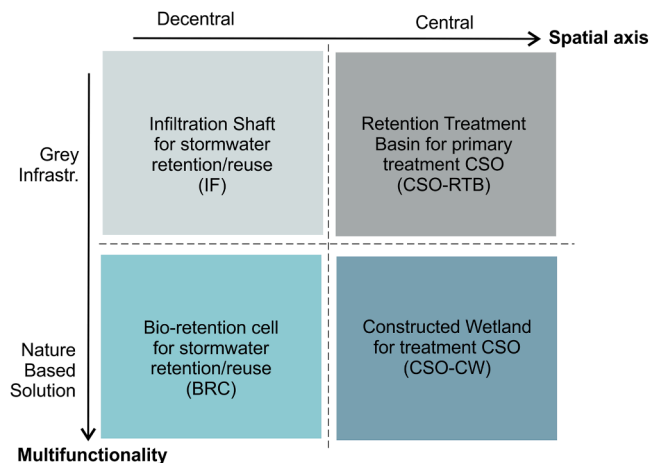


Fig. 1. Spatial and technological strategies for the scenario analysis. The selected solution is indicated within each quadrant.

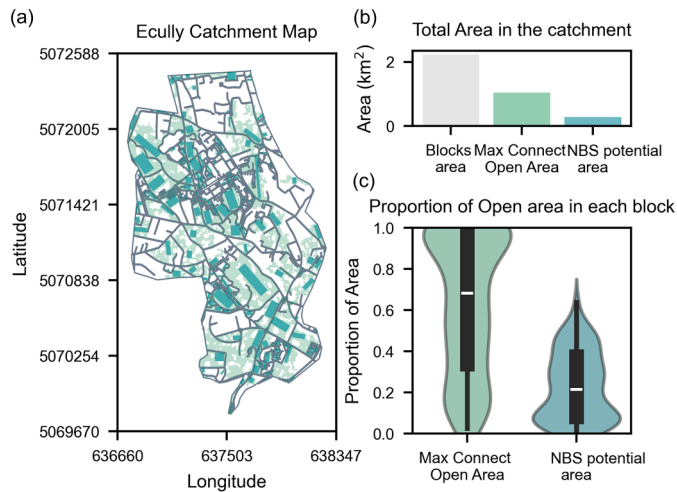


Fig. 2. Urban block mapping at the Ecully catchment. a) Map of the Ecully catchment with the blocks, the max connected open area, and the NBS potential area. b) Bar plot with the extended area (km^2) of each category. c) Violin plots of the share of max connected open area and NBS potential area within each block.

drop (Fig. 3). This behaviour outlines the rainfall depth at which the technology's capacity, constrained by insufficient NBS potential area, cannot store additional runoff volume. It follows that other blocks with more extended NBS potential areas start cumulating higher runoff volumes at increasing rainfall depth and contributing more to the urban catchment's stormwater retention. Thus, the prioritization of locations for NBS intervention depends on the design storm selected for planning. These results are bonded to holding the same type of technology and, therefore, the constant equivalent water accumulation height. Other technologies can be replaced within the individual block to increase its decentralisation potential.

2.3. Spatial setting and capacity of NBS with specified target

This section shows the most suitable configuration of decentralised NBS to achieve zero CSO at the Ecully Catchment. The target runoff volume is the simulated CSO spill from synthetic rainfall events corresponding to design storms of 5, 10, 20, 30, 50 and 100-year return periods (yT) (Table 1 in Section 5.3). In Fig. 4, the bar graph highlights the

required area to contain the targeted volume within the urban catchment. The required area is based on the dimensioning of the bio-retention cell technologies and the algorithm for site allocation described in Section 5.4. The results agree with the decentralisation potential of the blocks illustrated in Fig. 3.

For a design storm of 5-year return period with 35.25 mm of cumulated rainfall in 2-hour, 12,083 m^2 of bio-retention cells should be implemented across the catchment in three widespread locations to retain the 5648.93 m^3 of impervious runoff equivalent to the CSO spill. For the 100-year event with 60.18 mm of cumulated rainfall in 2 hours, a total of 50,380 m^2 of bio-retention cells should be planned in the Ecully Catchment at the selected locations. Given the existing spatial constraints, this would be possible in fourteen locations across the urban catchment, retaining a total impervious runoff of 23,723 m^3 .

2.4. Scenario comparison

The decentralised scenario with NBS technology is compared with the alternative urban stormwater strategies at different spatial scales (Fig. 1). All scenarios target the same volume reduction, equivalent to the CSO spill corresponding to the 5, 10, 20, 30, 50 and 100-year design storms (Table 1). The results are illustrated in Fig. 5. The decentralised infiltration shafts have a depth of 2 m with a gravel bottom, while the centralised retention treatment basin for CSO (CSO-RTB) has an average depth of 2.30 m (Appendix A). Given the highest volume capacity, CSO-RTB is the scenario requiring the least area, ranging from 2101 m^2 (0.19 % of the impervious area of the catchment) to 9993 m^2 (0.89 %). Although the centralised CSO-CW is assumed to have a max ponding depth of 0.8 m, the constructed wetland system has an outflow rate of 0.02 $\text{L}/\text{m}^2\text{s}$, and the bed consists of several gravel layers (Appendix A). This contributes to a required area for the CSO-CW ranging from 4053 m^2 (0.36 %) to 19,881 m^2 (1.78 %), to which 50 % more area should be added for surrounding construction, included in Fig. 5. On the other side, for the decentralised bio-retention cells, the layer of filter soil restricts the infiltration rate to the storage space, and the surface layer has limited ponding depth. Thus, BRC are the technologies that require the most space, ranging from 1.08 % to 4.5 % of the impervious area of the catchment. Fig. 5 summarises the results in terms of area requirement along the technological and decentralisation gradients.

With total costs over the lifetime of the infrastructures expressed in Project Costs Present Values (PCPV), Fig. 6 confirms that NBS are cost-effective solutions compared to their grey alternative. The centralised strategy with the constructed wetland for CSO is the most economical of

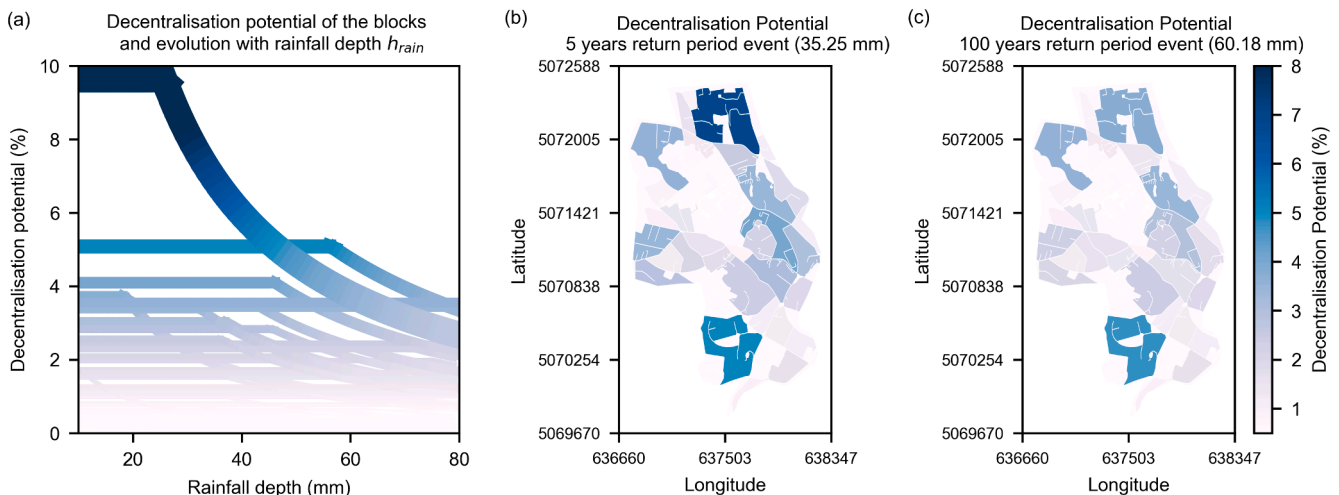


Fig. 3. Decentralisation potential of the blocks a) evolution with rainfall depth: each line represents a block with the width of the line proportional to the sealed area. On the right side are shown the maps corresponding to b) a rainfall depth of 35.25 mm equivalent to a 5 years design storm and c) 60.18 mm equivalent to a 100 years design storm.

all the urban stormwater management scenarios. Especially for high-volume retention, the specific CW-CSO design reduces project costs compared to the distributed BRC across the catchment, namely of 47.82 % for a 5yT-design and 75.49 % for a 100yT-design, and space requirements (50–40 %). Decentralised grey technologies such as infiltration shafts are still economically more advantageous than the centralised grey alternative (CSO-RTB), with a proportional saving of 68 % of total project costs despite a 15 % increase in required area.

3. Discussion

The approach presented in this study provides suitable locations and dimensioning for decentralised stormwater infrastructure. We recommend its application for the initial planning of stormwater measures along different decentralization and technological gradients. Further steps for planners include an informed decision-making process with stakeholders, such as municipalities. Using this pre-feasibility assessment, municipalities can save money by tendering the most feasible scenario for detailed planning. Depending on local data availability, the overall cost estimates can be used to derive subsidy programmes for NBS roll-out. The modular design of our approach enables the use of extensions, such as the integration of cadastral data, or exclusion of protection zones or landmarked sites. In [Montoya-Coronado et al. \(2024b\)](#), it is reported that only in 22 % of the 50 reviewed modelling studies, to mitigate CSO with sustainable drainage systems (SUDS), a selection criteria based on the specific area and available space is mentioned. Of these studies, 73 % percent used a random approach to select the location of the SUDS. The novelty of our work is the use of open, publicly available data in a geospatial module combined with urban catchment hydrology. The dimensioning of decentralised infrastructure based on the block mapping and on a target volume across the urban catchment is not conventional to urban stormwater practices, where the rule of sizing is based on the rainfall intensity of critical value to be multiplied by the extension of the impervious catchment ([DWA, 2013](#)). Also, design return periods can vary depending on the scale of the intervention, e.g. in Germany, green infrastructures for some new development projects are nowadays often dimensioned for a 100-year return period, while at the catchment scale, i.e. for CSO tanks, this is still done for a 5-year return period ([DWA, 2013](#)). Within our work, first flush concepts for sizing at the CSO spill are not addressed, given that – for comparison – the scenarios target the same volume retention and the applicability of the first flush theory is still subject to discussion ([Bach et al., 2010](#); [Bertrand-Krajewski et al., 1998](#); [Niazkar et al., 2024](#)).

Although the proposed urban stormwater management scenarios do not reflect standard practice, they do provide a cost comparison of the two extremes of a decentralised-green strategy and a centralised-grey strategy. In other studies on scenario comparison, [Naik and Stenstrom \(2016\)](#) found that decentralised treatment plants act as source-controlling systems and can have the advantage to be energy-efficient, having modular design and lower initial investments compared to centralised ones. [Quaranta et al. \(2022\)](#) take the view that decentralised strategies aiming at retaining volumes to control overflows are rather expensive compared to treatment measures with constructed wetlands directly at the CSO location. Our economic analysis results confirm these findings. [Casal-Campos et al. \(2015\)](#) included environmental, economic, and social categories in the scenario analysis. They found green decentralised scenarios more robust and adaptable, while grey infrastructures lead to higher regret from downstream performance and costs. Still, NBSs in urban environments provide ecosystem services like carbon sequestration, heat reduction, and air pollution mitigation. They increase the resilience of cities to climate change by integrating natural elements, making these decentralised solutions a cost-effective and sustainable alternative ([Kabisch et al., 2017](#)). However, the assessment of the NBS multifunctionality and integration of the benefits in the scenario comparison is not part of this research.

Our spatial-economic analysis demonstrated that when targeting the same volume reduction, NBS are cost-effective solutions compared to their grey alternative. The IRIDRA cost database is used based on the company's experience in the design of numerous sustainable drainage and CSO-CW projects. Its reference provides a relative cost comparison among scenarios in the absence of a standardised EU cost database for stormwater infrastructure. Within the dataset from IRIDRA, the construction costs of bio-retention cells provided a mean parametric cost of 202 Eur/m² for the reference year 2023, which is in line with the parametric cost of 158 Eur/m² in 2018 from Germany ([Khurelbaatar et al., 2021b](#)). The cost functions for bio-retention cells enabled us to go beyond a parametric cost for this technology, as it is usually done with disregard of the scaling effect. This would have caused the total construction cost being the same for smaller, widespread bio-retention cells within 143 blocks compared to those allocated by our developed algorithm. Our approach allows to save up to the 34 % of project costs for the 5yT scenario and up to the 7 % in the 100yT scenario. Despite these considerations, the specific design of constructed wetlands for high-flow CSO is the scenario that most reduces project costs and space requirements compared to the criteria-based distributed bio-retention cells across the catchment. Of course, these results also depend upon the design parameters of the technologies in compliance with those of the commissioned projects.

4. Conclusion

Our approach can be applied across multiple urban catchments or sewersheds to assess additional retention capacity and increase urban stormwater resilience without extending the existing sewer system. The capacity of the urban environment to retain stormwater at the block level is determined for several design storms, and the most suitable spatial setting for distributed NBS is provided. The scenario analysis enables the comparison of the total project costs with other urban stormwater strategies to achieve zero CSO at the catchment outlet. The spatial-economic analysis shows that NBS are economically more advantageous than their grey alternative. Particularly, the CSO-CW designed to retain high flows in one location proves more effective in terms of costs and spatial requirement than criteria-based distributed bio-retention cells. The key advantages of our work are the automated routines and the identification of locations for decentralised stormwater control measures based on open, publicly-available data. The decentralisation potential offers an initial mapping for CSO spill mitigation interventions based on stormwater and spatial availability. With the scenarios, it provides a clear workflow that enables stakeholders, such as urban planners, municipalities, or water utilities, to assess stormwater measures along different technological and decentralisation gradients. The approach can address the renewal of the EU Urban Wastewater Treatment Directive, which demands cities to have planning and analysis tools for stormwater and wastewater management plans ([European Commission, 2024](#)). First-cost estimates for stormwater measures to reduce CSO spills also can serve as a basis for financing options.

5. Data and methods

This section contains the collection of methods and data analyses implemented throughout the research process. First, it describes the spatial analysis used to identify the locations for decentralised NBS within urban catchments and the indicator for the decentralisation potential. This method can be applied to multiple cities in Europe. The Ecully Catchment study case is here presented in more detail to showcase the objective of retaining a target volume at the catchment. Finally, the approaches used for the infrastructure dimensioning and implementation of the cost module are presented.

Table 1

Catchment outflows and CSO spill volumes derived from the simulations of outflow rates for the design events of rainfalls with 2-hour duration and return periods (T) of 5 to 100 years.

Design Storm	Outflow Volume (m ³)	CSO spill Volume (m ³)
Rain (2h,5T)	10,102	4832
Rain (2h,10T)	14,913	8817
Rain (2h,20T)	19,642	13,039
Rain (2h,30T)	22,370	15,530
Rain (2h,50T)	25,783	18,683
Rain (2h,100T)	30,391	22,985

5.1. Spatial analysis

The spatial analysis is essential to assess whether the existing urban environment can retain stormwater runoff locally without extending the sewer system and identify suitable locations for decentralised NBS. The urban block mapping clusters information at the block level within the urban environment. An urban block is an area surrounded by roads and railways. It can, therefore, range from a single house, a complex of houses with a courtyard, to a park or agricultural field in peri-urban areas within the municipal boundaries. The potential NBS viable area can be assessed using this functional unit, which provides open spaces'

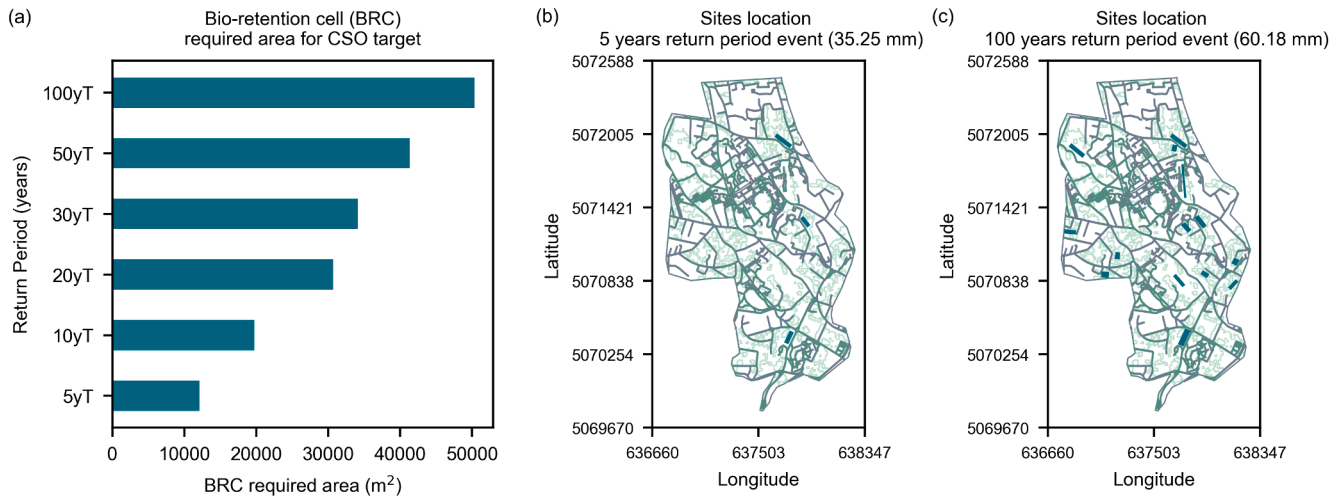


Fig. 4. a) Bar graph with the required area to implement bio-retention cells across the Ecully catchment to target the CSO spill volume. On the left are reported the planned site locations for b) 5 years and c) 100 years design storm.

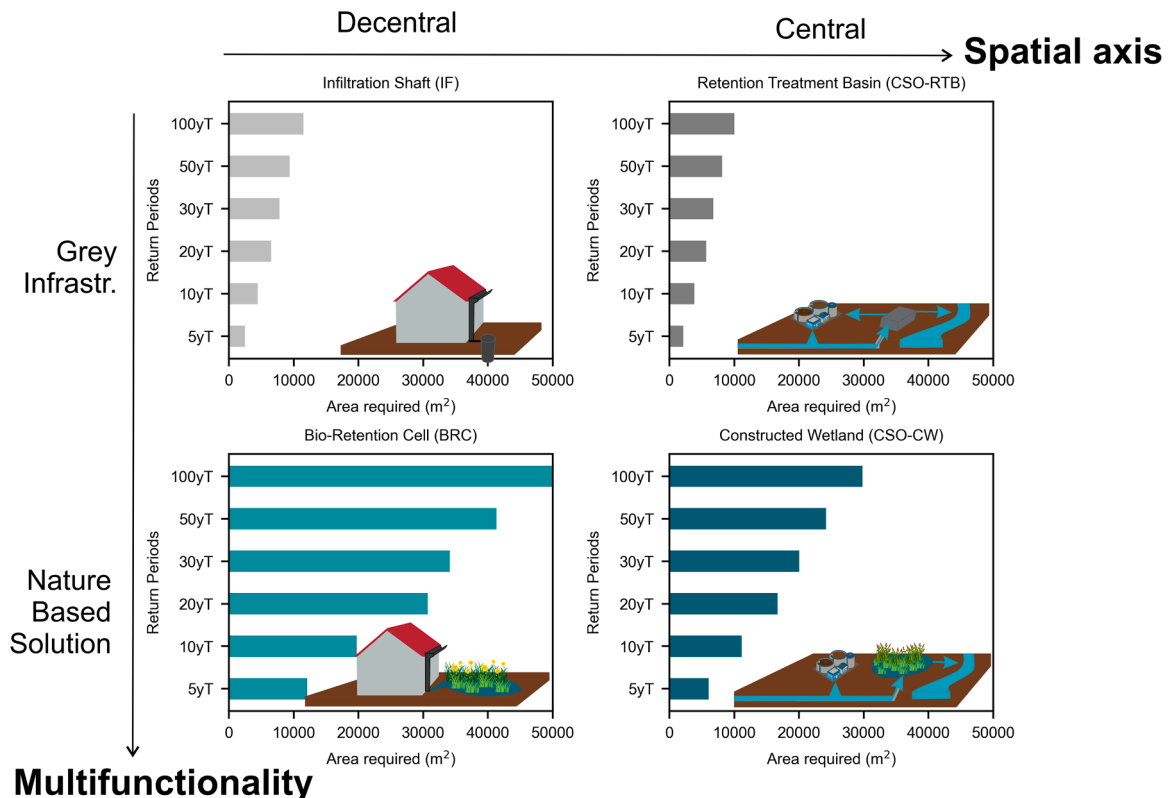


Fig. 5. Area requirements (m²) for implementing NBS-grey infrastructure and central-decentral scenarios for urban stormwater management.

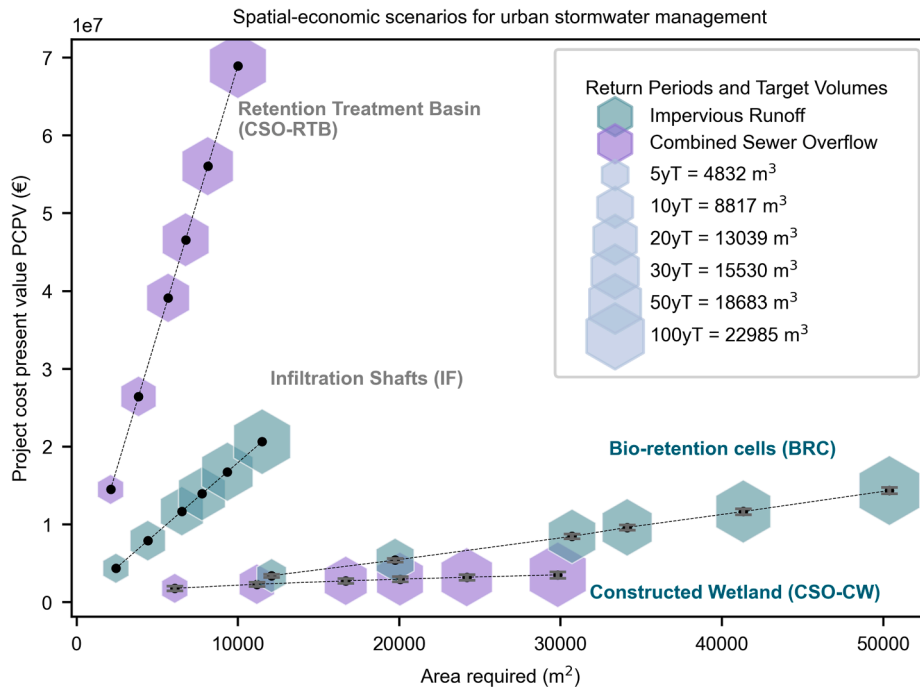


Fig. 6. Comparison of urban stormwater strategies for the target volumes specific to each design storm. For the bio-retention cells and constructed wetlands the uncertainty associated with the cost function is represented by a grey error bar.

availability and distribution in relation to traffic areas and population (Khurelbaatar et al., 2021b). The urban block mapping is implemented and automated in Python with open geospatial data. Geospatial data handling, operations and transformation are performed with Python GIS Packages such as GeoPandas (Jordahl, 2014), Rasterio (Gillies et al., 2013), GDAL (GDAL/OGR contributors, 2020) and Pyproj (Snow, 2024). The developed code creates block geometries from city boundaries and street networks using OSMnx (Boeing, 2017; OpenStreetMap Contributors, 2015). It integrates EU-level population data from the Urban Atlas (Copernicus Land Monitoring Service, 2018) and human settlement data from the World Settlement Footprint (WSF®) 2019 (Marconcini et al., 2021). The block-mapping code returns in output an ESRI shapefile with the multi-polygon geometries of the blocks and relative attributes of the population, as well as sealed and unsealed areas. In its last version, the urban block code delimits the NBS potential area with rectangle-shaped geometries. This is done through an in-house developed rotational search algorithm that inscribes the most extensive rectangle geometry within the boundaries of the maximum connected open area, having irregular shape. The optimal rectangle is found through an

approximated solution by rotating the gridded domain around its centroid for various angles, with the interval defined by the user (e.g. 1°). The smaller the rotation angle, the more accurate the results, at the expense of computation time. An example of the output of the spatial algorithm developed is illustrated in Fig. 7.

5.2. Decentralisation potential

Which block has the higher potential to implement decentralised NBS infrastructure can be identified with the retention potential R_p (%) of each individual block. The indicator expresses the percentage of water from the impervious surface A_{seal} (m²) that can be potentially retained within the A_{nbs} potential area (m²) for reuse or infiltration. A_{seal} (m²) is computed from the extent of settlements within the blocks, based on the WSF 2019 raster dataset (Marconcini et al., 2021), assuming the pixels classified as settlements to be fully impervious. The computation of A_{nbs} (m²) is explained in Section 5.2. This indicator depends not only on the ratio of the two surfaces but also on the design parameters of the planned technology h_{techn} (m) and the rainfall depth h_{rain} (m) of the

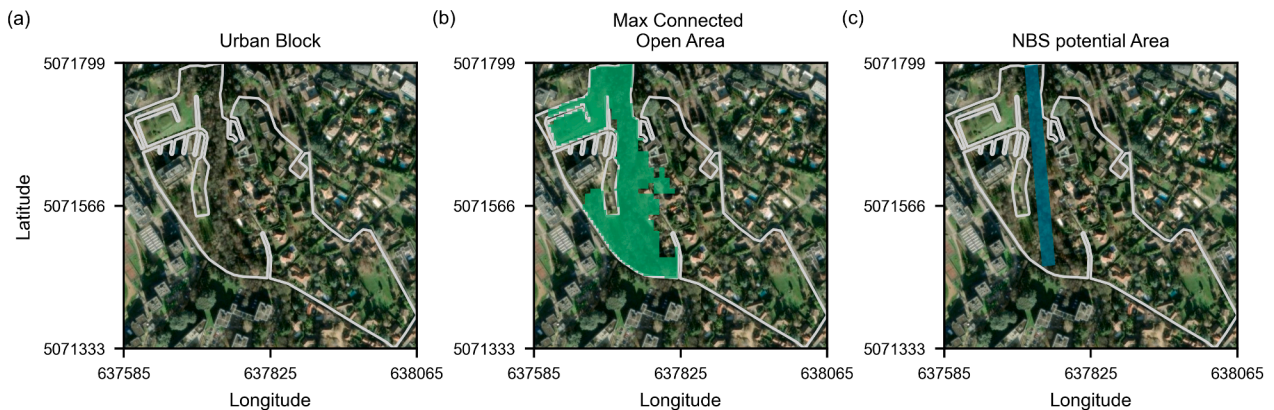


Fig. 7. Example geometry from the geospatial vector data of a) urban block, b) the maximum connected open area and c) the NBS potential mapping. World Imagery Basemap from ESRI.

design storms:

$$R_p(\%) = \frac{A_{nbs} (h_{techn} - h_{rain})}{A_{seal} h_{rain}} 100 \quad (1)$$

$h_{techn} = 0.516 \text{ m}$ is the equivalent water accumulation height the technology can retain during a high-intensity rainfall, resulting from the infrastructure dimensioning (Section 5.4). The $R_p(\%)$ is a summary information on whether the total block's impervious runoff can be retained or just a percentage. For example, suppose the impervious runoff within the block is smaller than the capacity of the technology extended for the NBS potential area. In that case, the total impervious runoff (100 %) and an empty volume in surplus will be stored. While in case the capacity of the technology extended for the NBS area is smaller than the generated impervious runoff within the block, only part would be stored (e.g. 75 %) and the overflow (e.g. the remaining 25 %) would still be directed to the sewer system.

Extending this indicator to the whole catchment, it is possible to deduce which block would contribute most to retaining the impervious runoff of the whole catchment, excluding roads runoff. The *decentralisation potential* $D_p(\%)$ is formulated:

$$D_p(\%) = \frac{\min\left(A_{seal, n}, A_{nbs, n} \frac{(h_{techn} - h_{rain})}{h_{rain}}\right)}{\sum_n A_{seal, n}} 100 \quad (2)$$

with $A_{seal, n}$ the impervious surface of the blocks = 1,.. n, and $A_{nbs, n}$ the potential NBS area of the blocks = 1,.. n. This indicator identifies which block should be prioritised for decentralised intervention with a specific NBS technology in urban catchments.

5.3. Urban catchment hydrology

The Ecully urban catchment is located in the north-west of Lyon in the Rhône department, France (Fig. 8). This residential urban catchment has an extension of 252 ha and a population of 18,361 inhabitants estimated in 2021. A combined sewer system serves the catchment with the longest water path of 1.8 km and an average slope of 2 %. During storm events, the excess flow is discharged to the Trouillat stream through a CSO located at the outlet of the Ecully catchment (Montoya-Coronado et al., 2024a). A data-driven hydrological model was developed for the Ecully catchment and calibrated based on rainfall time series and three years of flow rate observations (2007 and 2009–2010) at the outlet of the catchment (Montoya-Coronado et al., 2024a). To simulate the outflow rates of the urban drainage system under extreme design events, a frequency analysis was conducted with the Extreme Value Type I (EVI) probability distribution function, using sub-hourly resolution 30 years of rainfall time series (1992–2022) from the station 27 Champagne Mont d'Or (Data Grand Lyon). The Sherman equation was selected for the parametrisation of the Intensity-Duration-Frequency curves. Six design storms of 2-hour duration and return periods (T) from 5 to 100 years were selected to compute the hyetographs. The 2-hour duration ensures the generated synthetic rainfalls exhibit high intensity. The data-driven model for the Ecully catchment was fed with the synthetic rainfalls, within longer-running simulations to evaluate the overall response of the catchment. Table 1 shows the catchment outflow and combined sewer overflow simulated for the Ecully Catchment. The volumes of the CSO spill for the design storms are taken as the target volumes for the infrastructure interventions.

5.4. Urban block hydrology and infrastructure dimensioning

For the spatial planning of decentralised NBS targeting at the zero CSO, hydrological computations were carried out within the urban blocks to dimension the bio-retention cells. From the synthetic rainfalls introduced in Section 5.3, the runoff generated from the impervious

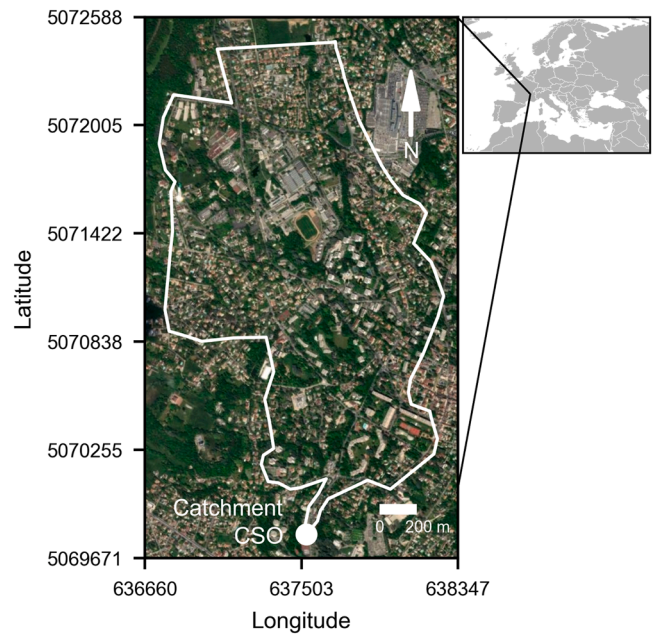


Fig. 8. Ecully urban catchment and its location in Europe. World Imagery Basemap from ESRI.

surfaces within the same block is calculated, assuming it is all directed to the adjacent potential NBS without runoff propagation-transfer effects. The NBS is designed to minimise the required area to temporarily retain and infiltrate the total runoff without overflowing. To achieve this, we dimensioned the bio-retention cell to handle the maximum volume of water that builds up following the peak of the storm event. The water build-up is governed by two rates: the directed impervious runoff plus the rainfall onto the NBS surface, and the infiltration capacity of the soil layer that moves the water to a deeper storage layer. When the difference between these two cumulative rates is at its highest, this is the critical time with maximum water build-up. Within the limits of the maximum ponding depth, this accumulation can be retained on the surface of the bioretention cell without overflowing. By sizing the NBS to handle the maximum volume difference at the critical time, which is the required surface volume (Fig. 9), we ensure that the NBS has sufficient capacity to prevent overflow.

Keeping constant the design parameters of the bio-retention cell (Appendix A), with maximum ponding depth $h_{max} = 0.25 \text{ m}$, the required

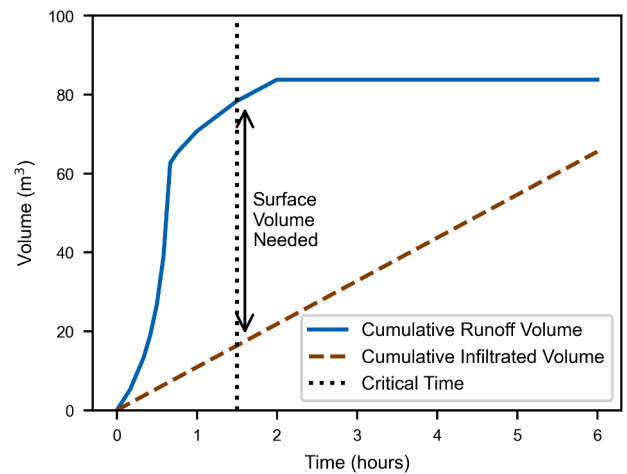


Fig. 9. Comparison of the cumulative curve of runoff and infiltration, derived from the rainfall method, to assess the surface volume of the NBS technology within the block.

area at the critical time is:

$$A_{nbs} = \frac{\frac{R(t_{crit}) A_{seal}}{1000}}{\frac{K_s t_{crit}}{1000} + h_{max} - \frac{R(t_{crit})}{1000}} \quad (3)$$

with $R(t_{crit})$ the cumulated rainfall (mm) up to the critical time t_{crit} (min), K_s the hydraulic conductivity at saturation of the soil layer (mm/h) and A_{seal} the sealed area within the block (m²). Since t_{crit} is dependent on the infiltrated volume, therefore on A_{nbs} , the implicit equation is solved through an iteration method, taking the critical time at the peak of the hydrograph for the first iteration. After pre-dimensioning, the critical time is computed again from the maximum distance of the two curves (Fig. 9):

$$t_{crit} = \operatorname{argmax}_t \left(\frac{R(t) (A_{seal} + A_{nbs})}{1000} - \frac{K_s A_{nbs} t}{1000 \cdot 60} \right) \quad (4)$$

Making again use of Eq. (3) with the updated critical time returns the final dimensioning for A_{nbs} . The design parameters of the bio-retention cell (Appendix A) ensure that runoff volume is contained independently of the native soil type. A set of simple flow continuity equations was additionally developed to check the drainage time and eventual overflow for the sized bio-retention cells in continuous hydrological simulations. The algorithm then selects the bio-retention cells that retain the highest impervious runoff across the urban catchment, until the targeted CSO spill volume is reached. For each design storm, the geometries of the selected sites are rescaled and exported as a shapefile.

In the grey decentralised scenario (Fig. 1), the dimensioning of the households' infiltration shafts is not constrained by the connected open area within the blocks. Based on a minimum of 1 m diameter, several infiltration shafts were allocated with an increase of 500 litres per capacity, in line with the infiltration shafts' models on the market. In the centralised NBS scenario, for each design storm, a CSO-constructed wetland (CSO-CW) was sized according to the CSO spill and design parameters of the French and Italian CSO-CW; the beds are assumed to be filled in parallel for extreme events, up to the maximum ponding depth (Meyer et al., 2012; Rizzo et al., 2020). A retention treatment basin (CSO-RTB) has a total volume dimensioned with parameters from Brombach et al. (2008). The complete list of design parameters used for the sizing of the technologies is reported in Appendix A.

5.5. Cost module

Cost data and estimates were provided by IRIDRA, a small-medium enterprise with expertise in designing sustainable drainage systems and CSO-CW, for individual projects conducted in the Lombardia Region (Italy) over different years. The IF parametric costs for a closed tank in concrete were taken from the Regional Regulation for Hydraulic Invariance (2019), equal to 800 €/m³ and considering 1 % of the investment costs for every year of operation and maintenance (O&M), in agreement with the costs reported in Masseroni et al. (2018). The CSO-RTB parametric cost of 2500 €/m³ was taken from Quaranta et al. (2022) for a CSO tank > 20 m³/ha. The cost dataset provided by IRIDRA for BRC, is based on 8 BRC projects designed from 2018 to 2024, with a parametric construction cost of 184–1188 €/m² and 684–3007 €/m³ and O&M parametric costs between 2 and 4 €/m²/y. The CSO-CW dataset, instead, is based on 7 projects designed from 2015 to 2023, including the system described in Masi et al. (2023), with a parametric construction costs ranging 113–447 €/m² and 158–1885 €/m³, and operational costs of 1.15–13.51 €/m²/y and 1.10–38.96 €/m³/y. All the projects included detailed cost items, the infrastructure area (m²), and other design parameters, e.g., the yearly design volumes (m³/year). The consumer price index (CPI) method (Graf, 2020) was used to normalise the historical cost data from past years to the reference year 2023. The harmonised index of consumer price (HICP) is the official measure of consumer price inflation in the European Union used to compare Member States (Eurostat, 2024). The HICP for Italy was used for the cost conversion (htt

ps://data.ecb.europa.eu/data/datasets/ICP/ICP.M.IT.N.000000.4.INX).

Based on the individual project costs, specific cost functions (Appendix B) were fitted for the total construction and O&M costs. The development of cost functions based on the design volumes is widely used to estimate infrastructure costs for water treatment. In dealing with high flow, the cost functions were based on the total volume capacity the infrastructure could retain during the event (m³/event). Costs were predicted with the standard errors from the regression analysis according to the infrastructure sizing of the scenarios. A life-cycle cost assessment (LCCA) was conducted in compliance with DWA (2011). The Project Cost Present Value (PCPV) is estimated over a 20-year lifetime using a discount rate of 2 % for the construction and annually recurring O&M costs (Khurelbaatar et al., 2021a). Since all of the infrastructure considered in the scenarios has a service life of around 20 years, the PCPV was estimated for 20 years, and no reinvestment costs were considered.

CRediT authorship contribution statement

Maria Chiara Lippera: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Ganbaatar Khurelbaatar:** Writing – review & editing, Resources, Methodology, Formal analysis. **Daneish Despot:** Software, Data curation. **Gislain Lipeme Kouyi:** Resources, Investigation. **Anacleto Rizzo:** Resources, Investigation. **Jan Friesen:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request

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