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Multi-objective Optimization of Nature-based Solutions

Shengnan Yang¹, *  <https://orcid.org/0009-0002-6075-6646>, Matej Radinja  <https://orcid.org/0000-0003-4296-8928> &
Nataša Atanasova¹  <https://orcid.org/0000-0002-8506-1667>

¹University of Ljubljana, Faculty of Civic and Geodetic Engineering, Hajdrihova ulica 28, 1000 Ljubljana, Slovenia

*Corresponding author email: ShengnanYang@fqg.uni-lj.si

Abstract

Urbanization and climate change have exacerbated many urban challenges such as flooding, water pollution and urban heat islands. Nature-based solutions (NBS) have been proposed as nature-inspired and cost-effective solutions that provide environmental, social, and economic benefits while tackling urban challenges. This research aims to identify multiple benefits of NBS and optimize NBS design under the local conditions. The hydrology-hydraulic model was built in Storm Water Management Model (SWMM) to simulate performance before and after NBS scenarios. Adopting a multi-objective optimization algorithm and deriving the Pareto front solution set of NBS scenarios are core methods in this multi-objective optimization procedure, and the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) will be used. Thus, this research will further discuss the method to reduce dimensionality in building functions for multiple objectives optimization. The methodology was applied to a case study in Tivoli Park, Ljubljana, Slovenia, where various land-use types have been involved and frequent flooding problems have occurred. The optimized results demonstrate that NBS scenarios are effective for flood reduction, peak flow control, pollutant reduction, water reuse, infiltration increase, evaporation increase, and green space increase. This research provides an interpretation and explanation of the relationship between trade-offs and NBS scenarios.

Highlights

- Multi-objective optimization of NBS scenarios based on total costs.
- The combination of NSGA-II and the SWMM model for evaluating the NBS scenario.
- Explore the influence of the objective function on the optimal NBS scenario.

Introduction

The increasing urbanization and escalating impacts of climate change have led to a rise in the frequency and intensity of precipitation events, exacerbating the strain on existing urban drainage systems. The existing systems, often operating beyond their designed capacity, struggle to manage heightened surface runoff, resulting in recurrent urban flooding and stormwater pollution. To address these challenges, a fundamental paradigm shift is imperative to enhance the resilience and sustainability of urban water management. The concept of NBS has emerged to foster sustainable development by transversally addressing social, economic, and environmental urban challenges (Castellar et al., 2021). NBS are multifunctional and cost-effective measures that address those urban challenges by protecting, developing ecosystems while promoting biodiversity and human wellbeing, all of which are attributed to their adaptability and versatility (Environmental Protection Agency, 2021).

Water management is one of the most frequently addressed challenges by NBS in urban areas (Langergraber et al., 2021), where the hydrology-hydraulic models play an important role. The models are capable of simulating the response of an urban catchment to various rainfall events. They can also

be used for the design and placement of NBS to retain, detain, infiltrate, and/or evaporate stormwater (Wu et al., 2024). In addition to water-related challenges, NBS can tackle the UHI, improve biodiversity, and create an attractive urban environment.

This paper aims to provide a methodology for a multi-objective optimization of NBS scenarios by integrating an urban drainage model (e.g., SWMM) and a multi-objective optimization algorithm (e.g., NSGA-II), and applying this methodology to a case study. Multi-objective optimisation involves competing objectives, leading to the concept of the Pareto front, where the optimal solution is seen as a non-dominated solution, meaning that there are no alternatives to this collection of solutions (Gao & Xu, 2024). The optimized NBS scenarios show the relationship between total cost and the aimed multiple benefits.

Methodology

The proposed optimization methodology consists of three main parts: hydrology-hydraulic model construction, identification of pre-designed NBS scenarios, and a multi-objective optimization procedure.

1) Hydrology-hydraulic model

The methodology begins with the setup of a hydrology-hydraulic model using the hydrological data (i.e., precipitation, temperature, evaporation), hydraulic data (i.e., drainage system property), and geographic data (i.e., soil property, land-use, digital elevation map). To ensure the model accurately reflects the current situation, it is calibrated and validated using continuous flow rates and pollutant concentrations (TSS-indicated), which are collected using a flow meter and stormwater sampling (i.e., “baseline model”).

2) Pre-designed NBS scenario

According to the calibrated urban drainage model and available area, NBS placement is prioritized. Meanwhile, SWMM provides a module called “LID Controls” that can simulate the performance of the NBS scenario. The simulated evaporation, water flow, water quality, and reused water volume can then be used to calculate benefit indicators. In the pre-designed NBS scenario, the placement location and the selection of NBS unit options are supposed to meet the environmental conditions and legal requirements. A pre-designed NBS scenario was first developed for design rainfall events. An NBS scenario consists of several NBS units (e.g., infiltration basin, retention basin, bio-retention cell, storage tank) in different locations.

3) Multi-objective optimization procedure

The NBS scenario will be optimized by multiple objectives by adopting NSGA-II, which has the advantages of fast execution speed and effective convergence of the solution set (Alves et al., 2020). Initially, while utilizing multi-objective optimization, it is essential to construct three main components: variables, constraints, and objective functions (Alamdari & Sample, 2019). The variables included in the optimisation procedure relate to the size of the NBS units. The constraints imposed on the largest and smallest sizes ensure that the variables change within this range. The objective functions are formulated by the assessment indicators of the NBS scenario.

The whole procedure is triggered by NSGA-II to create the first generation of NBS scenarios. The initial NBS scenarios are simulated in the SWMM model, and the assessment indicator is calculated to obtain the efficiency based on the objective functions. The performance of the current generation of NBS scenarios is passed to multi-objective optimization algorithms. The better NBS scenarios will be retained according to the ranking of the results. Following this, the algorithm will produce a new generation of NBS scenarios. The procedure involves repeating the SWMM simulation and indicator assessment to generate the optimal NBS scenarios, which result in maximum benefits and minimum total cost.

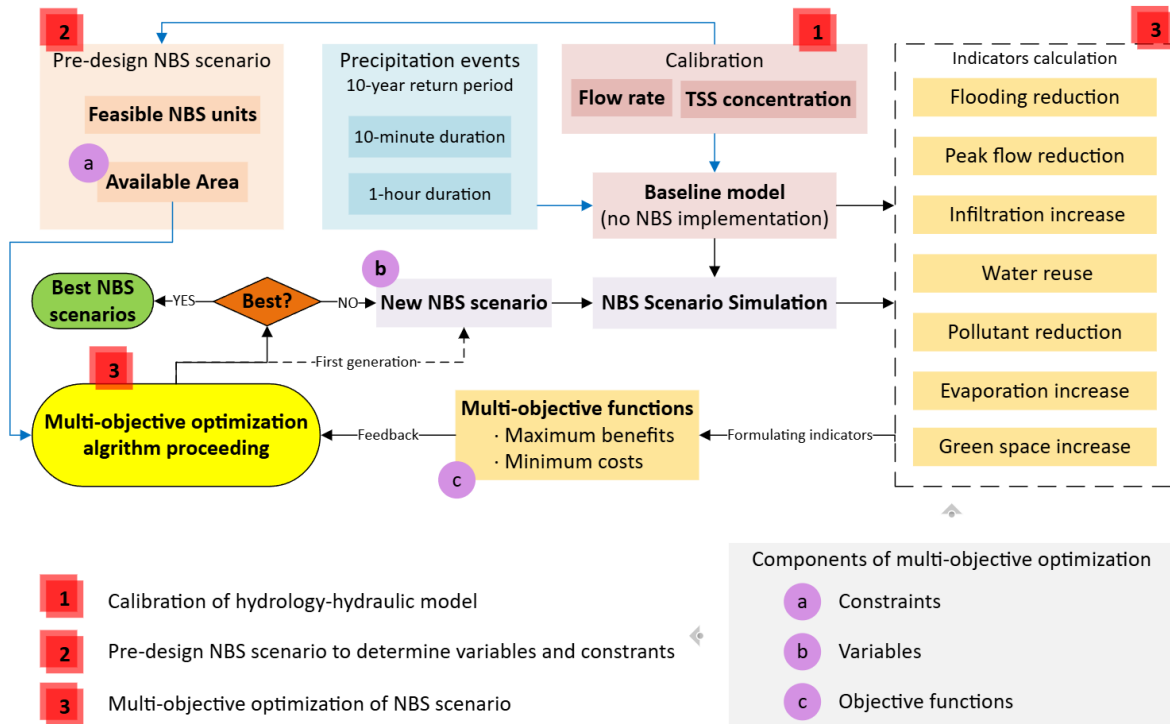


Figure 1. Flowchart of multi-objective optimization methodology.

Indicator calculation and objective functions

The indicators adopted to evaluate the efficiency of the benefits include flooding volume reduction, runoff peak flow reduction, infiltration increase, reused stormwater increase, stormwater pollution reduction (TSS-indicated), evaporation increase, and green space increase.

Table 1: Indicator calculation.

Indicator	Indicator calculation	Equation explanation
Flooding volume reduction	$FV = FV_{baseline} - FV_{nbs}$	$FV_{baseline}$, FV_{nbs} represent the flooding volume before and after the NBS scenario is implemented.
Runoff peak flow reduction	$RP = RP_{baseline} - RP_{nbs}$	$RP_{baseline}$, RP_{nbs} represent runoff peak flow before and after the NBS scenario is implemented.
Infiltration increase	$IN = IN_{nbs} - IN_{baseline}$	$IN_{baseline}$, IN_{nbs} represent stormwater infiltration volume before and after the NBS scenario is implemented.
Reused stormwater increase	$RU = RU_{nbs} - RU_{baseline}$	$RU_{baseline}$, RU_{nbs} represent the reused stormwater volume before and after the NBS scenario is implemented.
Stormwater pollution reduction	$SP = TSS_{baseline} - TSS_{nbs}$	$TSS_{baseline}$, TSS_{nbs} represent TSS mass before and after the NBS scenario is implemented.
Evaporation increase	$EV = EV_{nbs} - EV_{baseline}$	$EV_{baseline}$, EV_{nbs} represent the evaporation loss before and after the NBS scenario is implemented.
Green space increase	$GS = GS_{nbs} - GS_{baseline}$	$GS_{baseline}$, GS_{nbs} represent the green areas before and after the NBS scenario is implemented.

Total cost

The total cost takes into account the construction and maintenance costs throughout the life cycle. The construction costs include base costs and unit costs (per square meter). When calculating maintenance costs, the annual costs are transformed to the present value. According to (*Guide to Cost-Benefit Analysis of Investment Projects: Economic Appraisal Tool for Cohesion Policy 2014-2020*, 2015), the NBS lifecycle is 30 years, and the discount rate is 4%.

Table 2. Price for NBS.

NBS type	Base cost (€)	Unit cost (€/m ²)	Annual maintenance cost (€/m ²)
Infiltration basins (IB)	103	177	55
Biorention cell (BRC)	608	200	85
Retention basins with drainage (RB_D)	103	177	55
Storage tank (ST) (4m depth)	644	400	30

Objective functions

The maximum of the sum of the benefit indicators is the first objective function for optimization. The second objective function is the minimum of the total cost function, which considers construction and maintenance costs over the life cycle. When creating multi-dimensional objective functions, weights should be assigned to each sub-objective depending on local issues and preferences.

The objective function of maximization of total benefits:

$$\text{Max } (FV * W_{fv} + RP * W_{rp} + IN * W_{in} + RU * W_{ru} + SP * W_{sp} + EV * W_{ev} + GS * W_{gs})$$

Where: W_n is the weight of indicator n .

The cost objective function:

$$\text{Min } \left\{ \sum_{x=1}^N \left[C_{bc,x} + (C_{ui,x} + \sum_{y=1}^{LT} \frac{C_{O\&M,x}}{(1 + \frac{i}{100})^y}) * S_x \right] \right\}$$

Where: N is the number of NBS units; $C_{bc,x}$ is the base cost for the measure x ; $C_{ui,x}$ is the unit cost for the measure x ; $C_{O\&M,x}$ is the operation and maintenance cost of the measure x ; LT is the lifetime of the measure x ; i is the local discount rate; S_{xj} is the area of the NBS unit x in the sub-catchment.

Case study

The case study area is part of the Tivoli Park in Ljubljana, Slovenia, and covers approximately 0.58 km² (Figure 2). It involves various land-use types, including roads, parking lots, recreational centres, apartment buildings, and green surfaces. Based on the calibrated model, the placement of pre-designed NBS units was manually identified in critical locations within a feasible range of area. In this case, there are two 10-year return period rainfall events with durations of 10 minutes (21 mm) and 60 minutes (44 mm) that will be used for NBS scenario optimization.

Based on local demands (e.g., available space, runoff quality, need for water reuse), the pre-designed model was built with 12 NBS units. These included 4 infiltration basins (total area 490 m²), 2 retention basins with drainage (total area 360 m²), 3 bio-retention cells (total area 960 m²), and 3 storage tanks (total area 246 m² and depth 4 m). The parameter values were adopted from the NBS Combat of UDM 2025 (Table 3), while the percentage of pollutants removed by each NBS was based on the International Stormwater BMP Database (Clary & Leisenring, 2020).

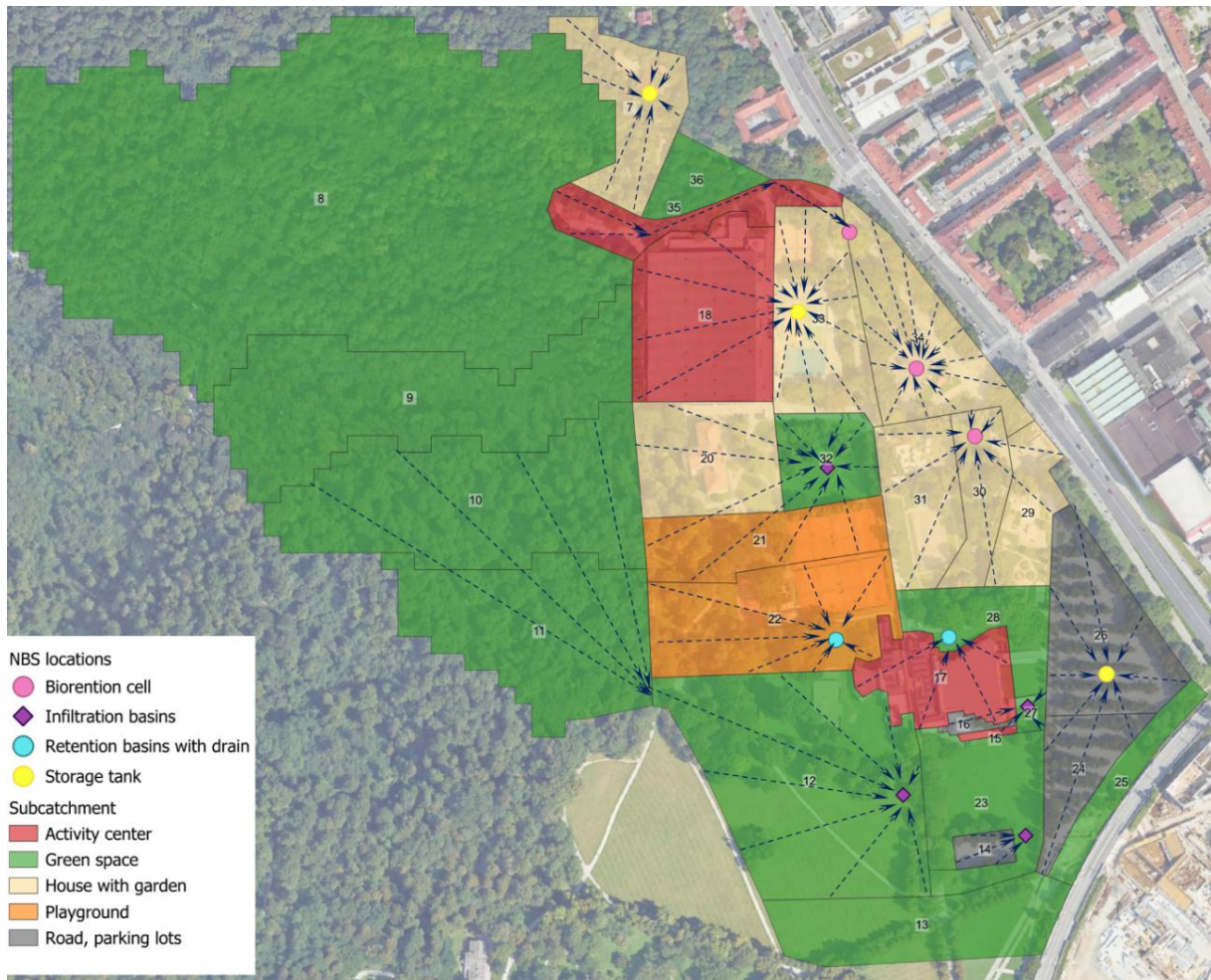


Figure 2. Case study area in Ljubljana, Slovenia, with NBS placement and contributing subcatchments.

Table 3. Parameter values for individual measures.

Layer	Parameter	Biorention cell (BRC)	Infiltration basins (IB)	Retention basins with drainage (RB_D)	Storage tank (ST)
Surface layer	Berm Height (mm)	300	500	500	-
	Vegetation Volume Fraction (-)	0	0	0	-
	Surface Roughness (n)	0.1	0.1	0.1	-
	Surface Slope (%)	0.1	0.1	0.1	-
Soil layer	Thickness (mm)	300	-	-	-
	Porosity (-)	0.437	-	-	-
	Field Capacity (-)	0.105	-	-	-
	Wilting Point (-)	0.047	-	-	-
	Conductivity (mm/h)	30	-	-	-
	Conductivity slope (-)	30	-	-	-
	Suction Head (mm)	61	-	-	-
Storage layer	Thickness (mm)	500	1500	1500	4000
	Void ratio (-)	0.35	0.35	0.35	1
	Seepage Rate (mm/h)	18	18	-	-
	Clogging Factor (-)	0	-	-	-
Drain layer	Flow Coefficient (-)	0	0	1.81	1.81
	Flow Exponent (-)	-	-	0.5	0.5
	Offset (mm)	-	-	100	100
	Drain delay (h)	-	-	-	2
Pollutant removals (%)		87	84	65	10

Results and discussion

Applying the optimization methodology to the case study results in 50 optimal NBS scenarios. Figure 3 presents the relationship between the total benefits and costs for each NBS scenario. As can be seen, the higher the cost, the higher the benefit. For example, scenario 10 achieves 66% of the total benefits at a cost of 0.81 million €, while scenario 35 achieves 84% of the total benefits at a cost of 1.68 million €. Furthermore, each scenario achieves different specific benefits. Table 4 presents the benefits achieved by scenarios 10 and 35 in terms of the benefit indicator values. When comparing their specific benefit indicator values, scenario 35 can generally achieve more benefits, but when focusing on the contribution of reused water, scenario 10 can reuse more water. In addition, other scenarios may also produce different benefit indicator values. The optimization results for the specific indicators are presented on Figures 4 and 5.

Table 4. Example of two optimized NBS scenarios on the specific benefit indicator.

Scenario	Scenario costs (million €)	Flooding reduction (m ³)	Peak flow reduction (LPS)	Infiltration increase (m ³)	Water reuse (m ³)	Pollutant reduction Kg TSS	Evaporation increase (m ³)	Green space increase (m ²)
# 10	0.81	162	779	1085	688	45	4	129
# 35	1.68	175	916	1261	686	51	10	632

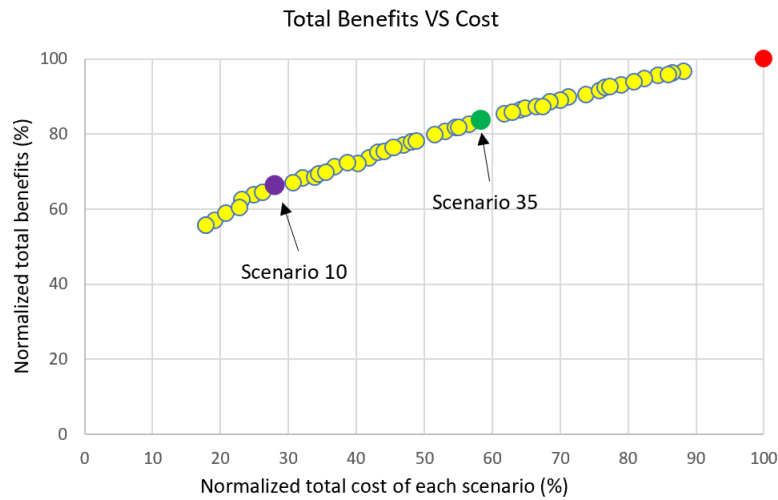


Figure 3. Optimization results of NBS scenario for normalized total benefits and total costs (each dot demonstrates one optimal NBS scenario, the red dot represents the result of the pre-designed NBS scenario).

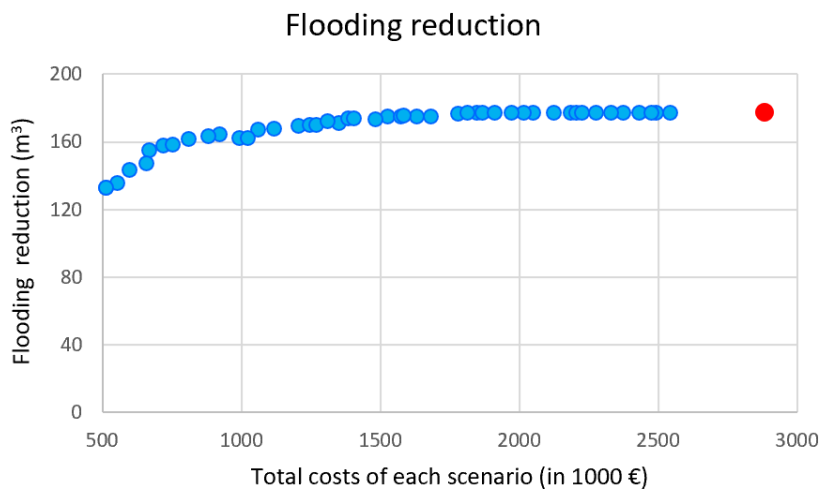


Figure 4. Optimization results of NBS scenario for flooding reduction and total costs (each dot demonstrates one optimal NBS scenario, the red dot represents the result of the pre-designed NBS scenario).

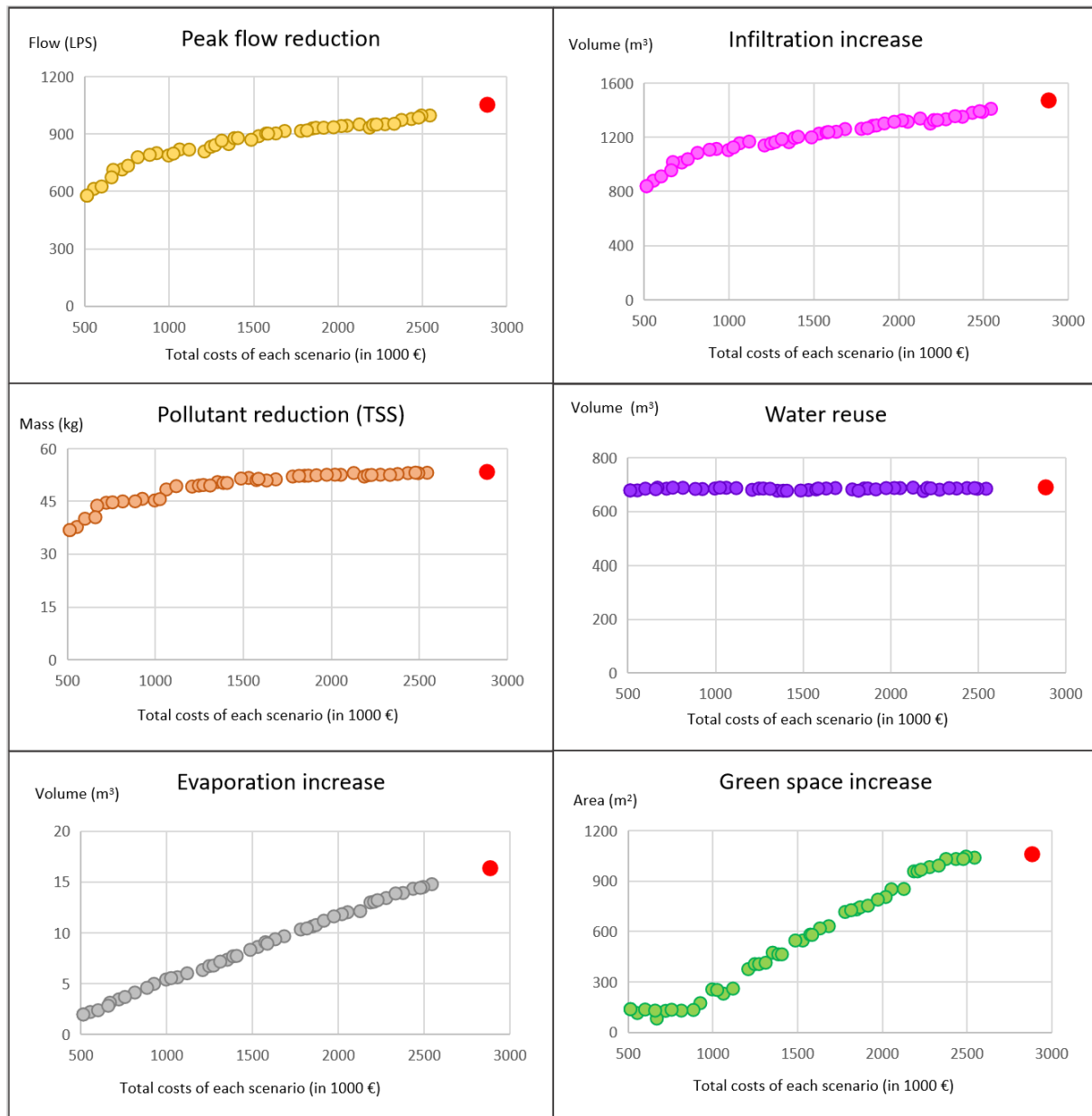


Figure 5. Optimization results of NBS scenario for other benefits and total costs (each dot demonstrates one optimal NBS scenario, the red dot represents the result of the pre-designed NBS scenario).

Conclusions and future work

The proposed multi-objective optimization methodology generates multiple optimal NBS scenarios by modifying each NBS area within the available area range, based on the pre-designed scenario. The optimal scenarios form the Pareto Frontier line, thus each NBS scenario is not replaceable. Although some scenarios may have equivalent effectiveness in addressing flooding based on the specific benefit indicator value, their performance regarding other benefits can vary. Trade-offs between the benefits can be seen from the specific indicator values of each scenario. Thus, this research provides a deeper understanding of the relationship between trade-offs and NBS scenarios. The results can inform evidence-based decision-making regarding preferred benefits.

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