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Planning the multifunctionality of nature-based solutions in urban spaces

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ABSTRACT

Urban infrastructure is under substantial stress due to climate change and urbanisation. More frequent flooding events and heat waves in cities threaten citizens' health and wellbeing. Current infrastructure is mostly based on grey solutions, focusing on only one function. Nature-based solutions (NBS), which are supported by nature and mimic natural processes, are multifunctional and can provide several benefits at the same time. However, this multifunctionality is deficiently considered during planning of urban infrastructure transitions. This work presents a method to help urban NBS planning processes considering multiple climate adaptation objectives. It is a 3-steps GIS-based multi-criteria method, in which the first step is a "priority areas identification", the second step is a "site-specific NBS allocation", and the third step is a "multifunctional performance evaluation". The method was applied to a case study to demonstrate its operation and validate the outcome with stakeholders. This work helps to improve the planning of multifunctional NBS in cities considering local needs, spatial opportunities, and site-specific limitations. Furthermore, it allows to assess the trade-offs among multiple NBS benefits when more than one objective is pursued.

1. Introduction

Climate change and rapid urbanisation have put substantial stress on the current urban infrastructure. More frequent flooding events and heat waves in cities threaten citizens' health and wellbeing and compromise urban infrastructure (IPCC, 2022). Current infrastructure systems are mostly based on grey solutions, focusing on only one function per infrastructure (Dhakal & Chevalier, 2017; Kremer et al., 2016). Nature-based solutions (NBS) are actions inspired or supported by nature, and actions that mimic natural processes (European Union, 2015). NBS are multifunctional, can provide several benefits at the same time and can help solve many of the aforementioned urban challenges simultaneously (Raymond et al., 2017). Even though this multifunctionality is especially important for cities considering the multiple challenges and lack of space in dense urban areas (Ahern, 2011), it is deficiently considered during planning of urban infrastructure transitions (Hansen et al., 2019). This can be a problem in the long term, when NBS selected to address a single problem result in unexpected trade-offs regarding other unforeseeable problems (Salmond et al., 2016).

Nature-based adaptation actions are key to manage climate change related risks, and there are some main aspect to consider. First, planning NBS to achieve multiple benefits requires complex, multi-disciplinary, and multi-stakeholder processes (Hansen et al., 2019; Hansen & Pauleit, 2014). Second, there are still important challenges in understanding co-benefits and their interactions (IPCC, 2014), as well as in assessing their spatial distribution, and site-specific synergies and trade-offs at the city scale (Haase et al., 2014; Kremer et al., 2016). Finally, urban systems have a high spatial heterogeneity that makes spatial analysis challenging and require high resolution spatial data (Cadenasso et al., 2007).

Even though many planning tools and methods concerning NBS implementation have been proposed (Voskamp et al., 2021), there is still a need for models to support collaborative spatial planning processes that deepen the understanding of the multiple benefits provided by NBS and help to integrate them (Ronchi et al., 2020). Recently, several studies have considered the multifunctionality of NBS and spatial analysis in planning processes (Kuller et al., 2019; Meerow & Newell, 2017; Sarabi et al., 2022; van de Ven et al., 2016). However, these studies either lack NBS suitability assessment (e.g. Meerow & Newell, 2017), or do not prioritize among different NBSs considering their impacts (e.g. Kuller et al., 2019), or do not assess NBS impacts on the different benefits (e.g. Sarabi et al., 2022).

More research to estimate the impacts of selected NBS for a specific location, as well as to include more co-benefits and analyse their

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synergies and trade-offs is needed (Choi et al., 2021; Sarabi et al., 2022), as this would help to improve the incorporation of multifunctionality of NBS in urban planning. This research fills the gap by presenting a method to plan urban NBS considering multiple climate adaptation objectives and their interactions, as well as the limitations on implementation induced by urban space characteristics. For this a 3-step method was combined with a GIS-based multi-criteria analysis. The first step focuses on “priority areas identification”, these are the areas of the city with more pressing problems and their identification helps to plan effective investments in the long term. The second step is a “site-specific NBS allocation”, which focuses on a suitability analysis that determines feasible NBS locations in priority areas. The third step is a “multifunctional performance evaluation”, to evaluate the performance of the allocated NBS on the targeted problems. The relevance of considering these steps has been highlighted in previous works, for instance, Albert et al. (2021) present a conceptual framework to plan NBS with several steps including ‘understand challenges’, ‘create visions’, and ‘assess potential impacts’.

Overall, this research outcome helps to improve the planning of multifunctional NBS in cities considering local needs, spatial opportunities, and site-specific limitations. Furthermore, it allows to assess the trade-offs among multiple NBS benefits when more than one objective is pursued. The method was applied to a case study to demonstrate its operation and validate the outcome with stakeholders.

2. Methodology

The developed methodology is a GIS-based multi-criteria analysis (MCA) process that identifies priority areas for applying NBS at the city scale level, and evaluates possible allocations for NBS at the neighbourhood level. The method is applied in 3 steps and allows to consider several objectives. This work focuses on climate adaptation, with stormwater management and heat stress mitigation as objectives.

2.1. Methodological framework

The 3 steps followed in this method are described in Fig. 1: 1) a map of priority areas (neighbourhoods) in need of NBS (Section 2.3); 2) a map which indicates the allocation of the most suitable NBS in the considered priority area (Section 2.4); and 3) map(s) showing the impact of the chosen NBS on different benefits (Section 2.5).

The methodology takes into account the NBS principles stated by Albert et al. (2019), to identify well-established societal challenges to be addressed by NBS actions (by assessing the main challenges in a city), to recognise ecosystem processes used by NBS (by identifying the functions of NBS which allow to mitigate the challenges), and to determine the practical viability of NBS (by assessing the suitability and benefits of each NBS).

2.2. Case study area

The case study area is located in the South of the city of Amsterdam, in Amsterdam-Zuid (Fig. 2) which is one of the eight main subdivisions of the municipality of Amsterdam. The area has about 138,000 inhabitants, with 8500 houses per square kilometre, which makes it one of the most densely populated areas of Amsterdam. It is the subdivision with highest income in Amsterdam (Gemeente Amsterdam, 2013). The city has an oceanic climate with an average annual precipitation of 838 mm (Royal Netherlands Meteorological Institute, 2010).

There are several reasons why the area is convenient for the

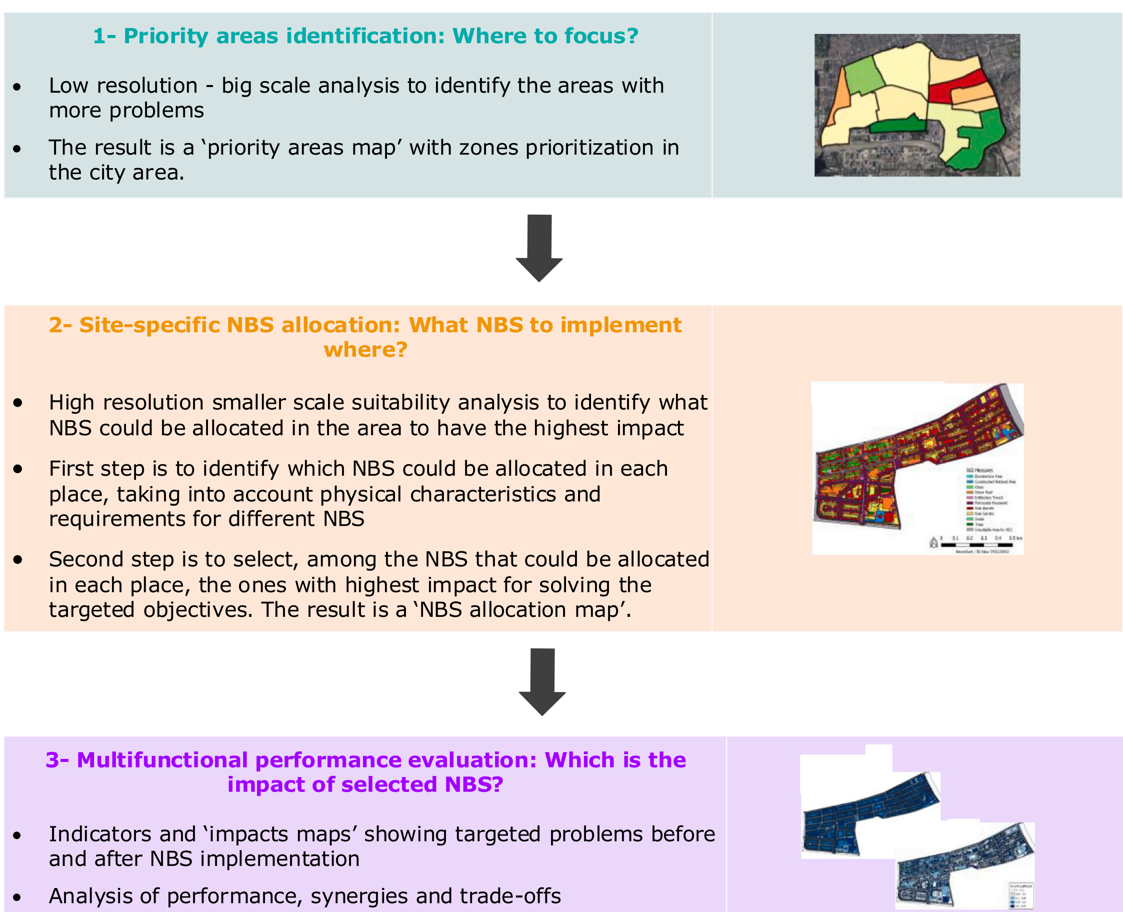

Fig. 1. Methodological framework.

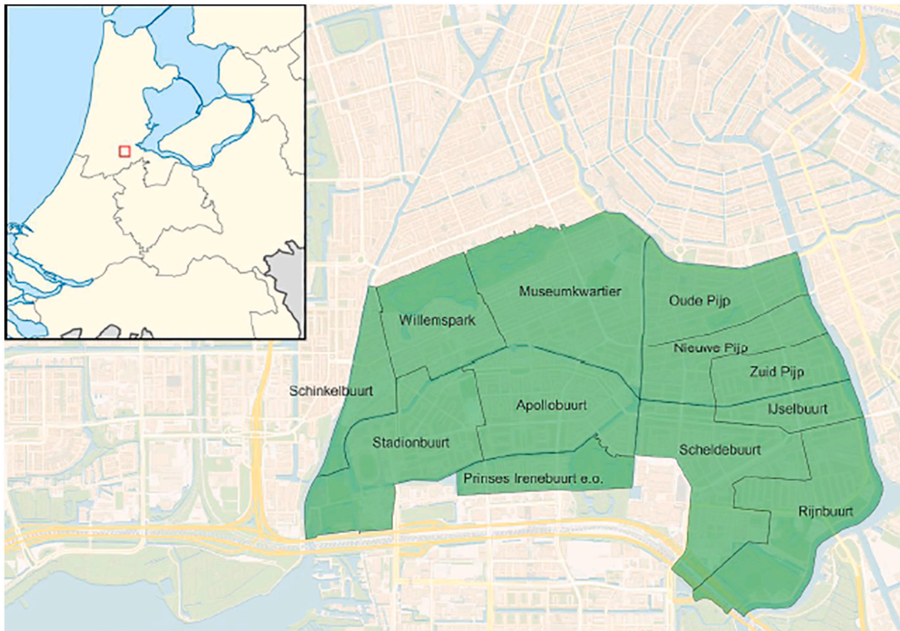

Fig. 2. Case study area in Amsterdam-Zuid.

application of this method. First, Amsterdam has a rich availability of GIS (Geographical Information System) data publicly accessible (Gemeente Amsterdam, n.d.). Second, Amsterdam-Zuid is a dense urbanized area divided in many sub-neighbourhoods, which are used as boundaries to determine the priority area, decreasing the computing time and possibility of errors. Finally, Amsterdam-Zuid has multiple areas which are under risk of pluvial flooding during heavy rainfall which makes it a relevant area for the planning of climate adaptation measures.

2.3. Priority area identification: where to focus?

This is a low resolution – big scale analysis because it is done at the city level (or part of a city) and has a resolution by neighbourhood, this means that values to identify priority areas are calculated per neighbourhood. Two criteria were considered to identify priority areas for climate adaptation, namely stormwater related problems and heat stress. The input data used to identify areas under risk of stormwater related problems were: areas prone to flooding and imperviousness (runoff coefficient) of the urban surface. Using runoff coefficient as indicator, the areas that might have more influence on causing pluvial flooding were identified (see Appendix A for values of runoff coefficient used). Meanwhile, the indicator used to identify areas with high heat stress was Physiologically Equivalent Temperature (PET).

To identify priority areas, three different input data were processed. First, a land use map and a satellite image were combined to create a land cover map. Additionally, several parameters were added to the land cover data, such as land ownership, surface slope, groundwater level and soil type. Details about the data and tools used, and the steps followed in this process are presented in Appendixes B and C.1.

Afterwards, the stormwater priority map was created combining a map with areas prone to flooding and a map with the different runoff coefficients per land cover. The data about areas that experiment flooding was obtained from maps showing water depth in streets after a rainfall of 60 mm/h (see Gemeente Amsterdam, n.d.). The runoff coefficients were assigned based on the land cover data created in the previous step.

The heat stress priority map was created using a map showing PET values in an extremely hot summer afternoon (see Climate Adaptation Services, n.d.; Koopmans et al., 2020). PET values in that map were originally obtained using the calculation method of the Dutch development standard stress test heat from the RIVM (de Nijs et al., 2019). As an advantage of using this indicator, qualitative interpretation of temperatures can be made: moderate, high, and extreme heat stress are associated with perceived temperatures above 29, 35 and 41 °C respectively (Climate Adaptation Services, n.d.).

Once the individual priority maps were developed, they were combined to determine the need for NBS in different areas considering more than one problem simultaneously. To allow this combination, the values obtained for each priority map had to be normalised. This was done using a min-max normalisation method in which the values were set to a range from 0 to 100. For every indicator, the minimum value is converted to 0, the maximum value is converted to 100, and every other value is converted to a number between 0 and 100.

Once the individual priority maps were normalised, the maps were aggregated to define the combined priority areas. The maps were aggregated to a map with the boundaries of the sub-neighbourhoods, which is a distribution frequently used by municipalities for planning. For the aggregation of the final map, weights could been used to determine the importance of the different challenges when planning.

2.4. Site-specific NBS allocation: what NBS to implement where?

After identifying the priority area, the second phase consists of determining the set of NBS that best fit the area's characteristics and its requirements. In this case, the analysis has high resolution and is done at small scale, the scale is now a single neighbourhood and the NBS suitability analysis is done considering small areas of around 100m^2 in average. Appendixes B and C.2 show the data and tools used for the analysis and the steps followed to achieve this result.

The first step was to choose applicable NBS to address the problems targeted, and to build reference tables with constraints for NBS allocation and impact values for the objectives considered (see Appendix D). The data required to build these tables was obtained from literature review of previous works on the topic. The review of these works helped to identify which NBS help to mitigate pluvial flooding and heat stress in urban spaces. In addition, previous works were used to understand physical constraints for applying NBS and to quantify the efficacy of different NBS on providing the benefits considered in this work. Therefore, literature is used to identify applicable NBS, to define where (e.g. in which landcover types) these NBS are applicable, and to estimate their effectiveness to solve the problems targeted (e.g. heat stress).

Constraints analysis determines the opportunities for NBS allocation. The first main physical constrain considered is the type of surface. Each NBS is suitable to be allocated on specific surface types. For instance, a green roof only admits a roof as allocation surface. Merging information on this regard with the landcover map, NBS allocation possibilities for each urban surface were identified. Also, local characteristics such as soil type, groundwater depth and surface slope were considered. For instance, the mentioned green roof could not be allocated on a very steep roof. The analysis of constraints results in an opportunities map. Through this map and its associated attributes table, a list of the (one or more) NBS that could be allocated in each roof, pavement or sidewalk spot, is presented.

The performance values included in the second NBS reference table give an idea of the impact that could be achieved by applying different NBS. These values determine the suitability of the NBS in each location to achieve a specific objective, or objectives. This means, from the list of applicable NBS for a specific location obtained with the opportunities map, this suitability analysis selects the measure that maximises the impact for the objective or objectives targeted.

To perform this analysis when several objectives are targeted, the performance values obtained from the NBS reference table are normalised. The normalised values for different benefits can be summed up, providing a global impact value for each NBS. At this point, weights can be assigned to the value obtained for each benefit, to represent the importance given to the challenges to solve. Finally, different NBS can be compared to choose the preferred one for each location. The result of this step is a map that allocates the most suitable NBS for each specific location.

2.5. Multifunctional performance evaluation: which is the impact of selected NBS?

After the most suitable NBS are defined, it is possible to get an estimation of the general impact that the selected measures would have on the objectives that are being targeted. This analysis was done using the performance value obtained from the NBS reference table. The impact of each implemented measure is estimated by subtracting that performance value to the original runoff coefficient or PET value in each location. The results are a map with new values of runoff coefficients and PET, and an average value indicating the general impact for the whole area. This final step allows decision makers to understand how much each problem could be improved by properly planning and implementing NBS at a district level, and compare how the performance changes when different objectives are targeted.

This method allows the selection of weights to represent preferences among different objectives. In the case presented here, for priority areas analysis, both objectives (stormwater management and heat stress mitigation) were established with the same weight. For suitability analysis three cases were studied. First, stormwater management was given a weight of 1 and heat stress was given a weight of 0. In this case stormwater management benefits were maximised while heat stress related benefits were obtained as co-benefits. Second, stormwater management was given a weight of 0 and heat stress had a weight of 1. Therefore only heat stress benefits were maximised. Finally, both objectives were given the same weight, this means that benefits related to both objectives simultaneously were maximised.

2.6. Validation and usability of the method

The method was evaluated in two steps, one focused on evaluating the method itself, including the concepts and criteria considered, and the second focused on assessing the applicability and usefulness of this method for decision making. For the first step, the method was discussed with experts with in-depth knowledge on the topic. For the second step, the results obtained for the case study area were discussed with local practitioners, who are potential users of the method. First, a workshop with scientific actors was organized to discuss the method and how it could be improved. In this case, the method was presented and specific questions were introduced to a group of experts on green infrastructure and NBS. The objective was to assess the method itself (criteria considered, indicators, etc.) and collect feedback that could be used to improve it. The first question was if what other indicators would be relevant to add to the method to better identify priority areas. The second question was which extra indictors would be useful to add when allocating NBS in the urban space. The next question was for which applications they believed that this method could be useful. The last question was which barriers would impede the application of this method and what is necessary to achieve realistic results.

Second, the validation with practitioners had a focus on method applicability and the validity of particular results for the area studied. A focus meeting with municipal practitioners that work in the case study area was performed, the practitioners work in urban infrastructure planning and design for the area, covering the fields of water, greenery, transport, etc. The objectives were to discuss about the usefulness of the method and to obtain feedback about the results obtained from applying it in the study area. The focus group was designed as an interactive exchange, divided into two parts: a presentation of the method and its application results for the area, and a discussion to evaluate its applicability and outcomes for the study area. The presentation aimed to spark the participants' curiosity and awareness, while the discussion was the main session, guided by questions on various topics. One of the questions was if the method would be helpful for them to plan for multiple objectives, for instance by helping communication and interaction among different disciplines. Another one was if the analysis of trade-offs among benefits when targeting multiple objectives would be helpful when making decisions, and if those trade-offs were acceptable. Finally, practitioners were asked to mention how the method could help them in their work.

3. Results

The method developed is applicable in different contexts and can be tailor made to the particularities of each case. The user can decide to focus on one or multiple objectives, or functions. Besides, the weights of the different objectives considered and the indicators used for the analysis can be changed to develop a specific case analysis.

Next, the specific results for each of the three steps followed in this method are presented.

3.1. Priority area identification and priority areas map

The results obtained from the step 1 of the method were the priority maps concerning stormwater management, heat stress and the combination of both objectives. In the case of stormwater management, the criteria consist of two indicators, areas prone to flood and the runoff coefficient. The flooding potential is a value between 0 and 100 which is unitless and was created using the min-max normalisation method (see Section 2.3). From the priority map obtained, the flood potential is highest in the neighbourhood Nieuwe Pijp (Fig. 3a), an area prone to pluvial flooding and with the highest average runoff coefficient among the neighbourhoods studied.

The heat stress data was aggregated in the different neighbourhoods resulting in a heat stress priority area map that indicates the average PET per area. The final heat stress map shows that the whole area has high heat stress, but the Schinkelbuurt neighbourhood scores highest (Fig. 3b). Paved surfaces increase heat stress, while urban trees provide considerable heat stress reduction. Therefore, big paved surfaces and the lack of trees observed in this area could explain the high average heat stress (Ketterer & Matzarakis, 2014a).

In order to define a single sub-area for further applying the steps 2

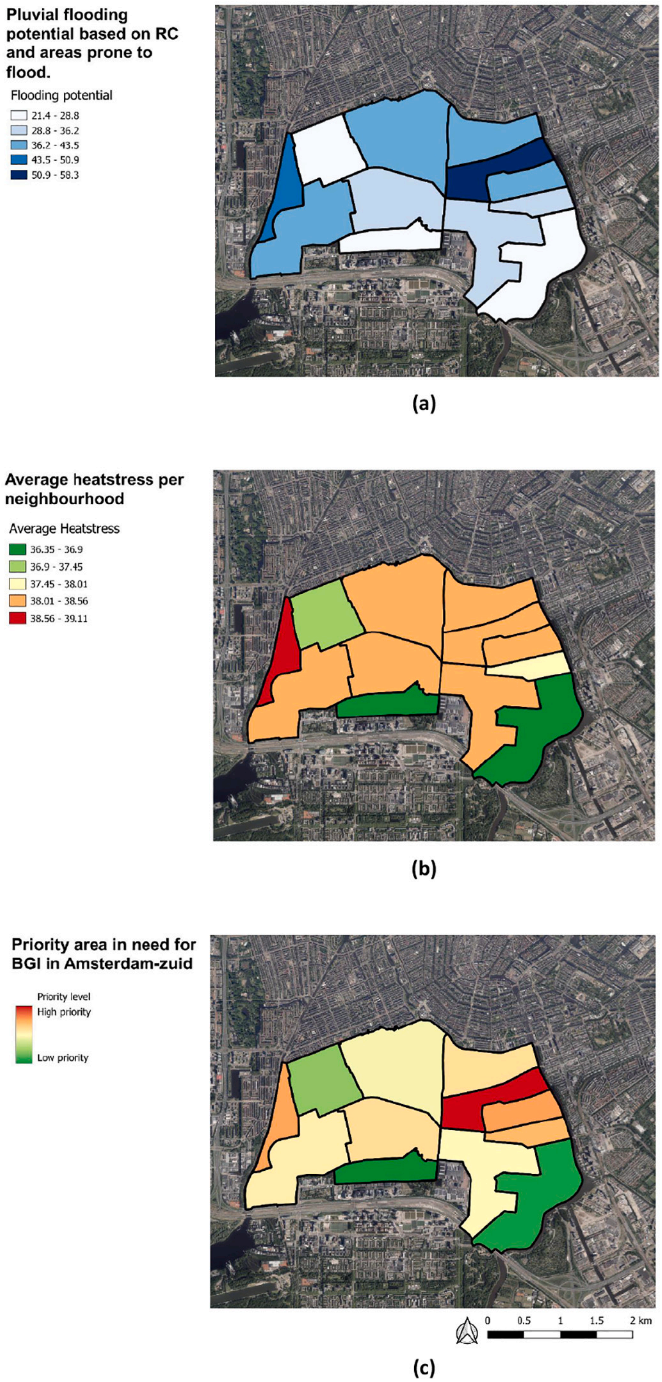

Fig. 3. Priority areas maps for (a) stormwater management (b) heat stress (c) combined stormwater management and heat stress.

and 3 of the method, the priority maps for stormwater management and heat stress are merged. Working with a single sub-area allows to compare results when different objectives are targeted. After normalising and merging the two priority maps, the area with the highest priority when looking at both objectives combined is the neighbourhood Nieuwe Pijp (Fig. 3c).

3.2. Site-specific NBS allocation and NBS allocation map

For the NBS allocation analysis the focus is on the priority area defined in the previous step. The first step is to identify NBS that help to reduce pluvial flooding and heat stress in urban spaces, a set of thirteen NBS that provide benefits related to at least one of the objectives targeted was chosen (see Table 1). The objective was not to compile an exhaustive list of all the potential NBS for addressing these problems, but to identify the most common NBS used in urban spaces for this purpose, with the aim of applying the methodology presented in this work.

The second step is to study the suitability of selected NBS based on the reference tables. All the measures selected in this case provide runoff reduction, whereas only ten also provide heat stress reduction. In Appendix D, the reference tables showing allocation requirements, constraints and expected impacts for each of these measures are presented.

An opportunity map is developed based on the NBS reference tables, this is a map listing all the possible NBS for each single surface unit. The suitability map is obtained by considering the capacity of these NBS to achieve the aimed objectives, and choosing the most effective NBS for each surface unit. Three different maps were obtained, one for each of the three objectives studied: stormwater management, heat stress mitigation, and both objectives combined. Results are presented in Fig. 4 and Table 1.

Fig. 4a shows the allocation of the most suitable NBS based on the single criteria stormwater management. For this objective, nine out of the thirteen measures were chosen. In about 18 % of the area, no NBS could be allocated, which includes waterbodies and roads. The most applied NBS were infiltration trenches, permeable pavements, rain barrels, green roofs, and rain gardens. Urban trees, water squares, bioretention areas and infiltration basins were not chosen in this case. These measures were not selected, either because there was not enough space for centralised measures, or because other measures providing more peak flow reduction could be fitted in the same location. In the gardens of the northwest part of the neighbourhood, grass was favoured over rain gardens, which differs from the rest of the neighbourhood. In this area the groundwater levels are too high, consequently rain gardens cannot be allocated there.

Fig. 4b illustrates the allocation results when the only objective is heat stress. For this case, only five NBS were selected and more than one third of the area was unsuitable for NBS allocation. Permeable pavements, urban trees and green roofs were the most chosen measures. However, in the northwest part of the area, permeable pavements were no longer favoured and grass was fitted instead. This was again based on the constraint regarding high groundwater levels.

In the case that combines the objectives of stormwater management and heat stress reduction (Fig. 4c), ten out of the thirteen NBS were chosen, leaving out water squares, retention ponds and infiltration basins. These three NBS are centralised structures that need high space availability to be implemented, which is not available in this highly urbanized neighbourhood.

Table 1
Results of NBS allocation (in % of area covered) in each of the three cases studied: applying the method for stormwater reduction, heat stress reduction and the reduction of both problems simultaneously.

NBS	% of total area		
	Stormwater	Heat stress	Stormwater + Heat stress
Bioretention area	0.0	0.0	0.1
Constructed wetland	2.0	2.0	3.0
Grass	3.8	3.3	3.3
Green roofs	12.1	12.1	12.1
Infiltration basin	0.0	0.0	0.0
Infiltration trench	13.7	0.0	0.4
Permeable pavement	15.5	28.9	28.9
Rain barrel	18.5	0.0	18.5
Rain garden	15.0	0.0	15.0
Retention pond	0.9	0.0	0.0
Swale	0.2	0.0	0.1
Urban tree	0.0	16.7	0.5
Water square	0.0	0.0	0.0
Not suitable area	18.1	37.0	18.1

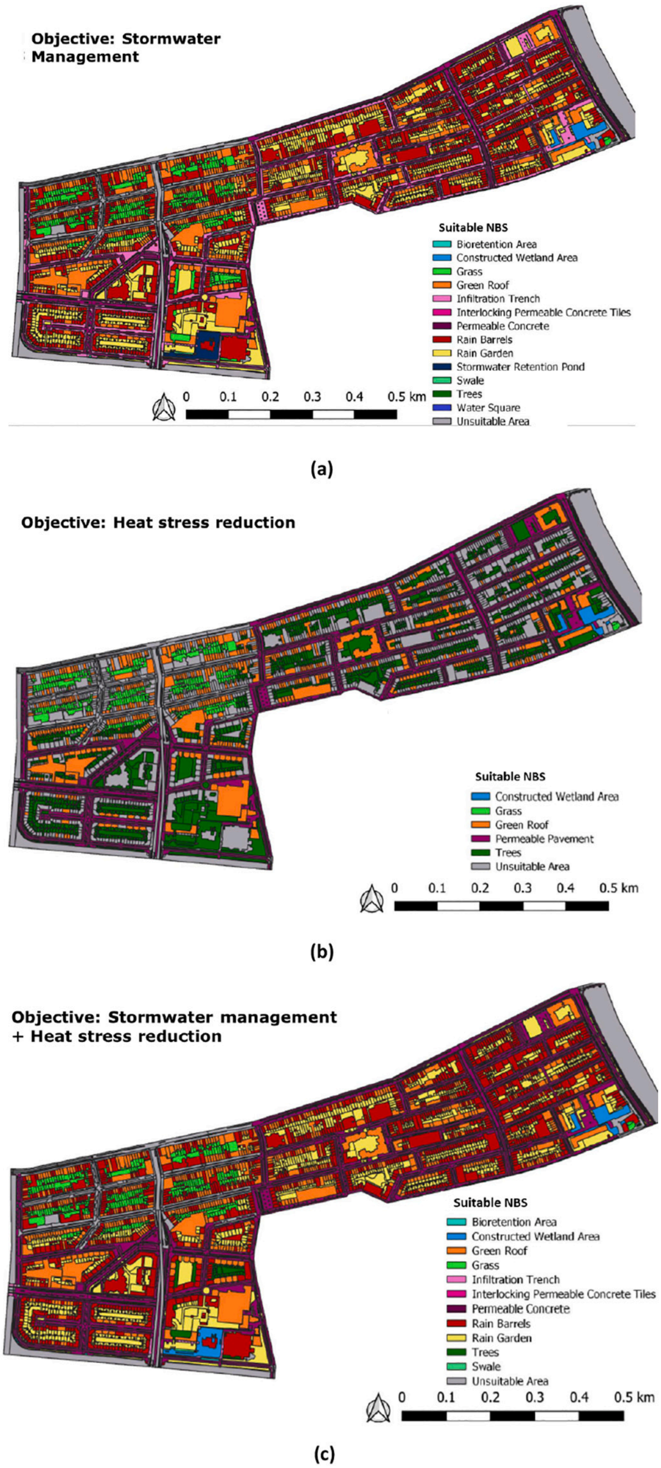

Fig. 4. NBS allocation maps for the following objectives (a) stormwater management (b) heat stress (c) combined stormwater management and heat stress.

Table 1 shows some synergies and trade-offs among the measures and objectives delivered. Constructed wetlands, grass and green roofs were chosen similarly when both objectives were considered respectively. This implies that these measures were the best possible options in several places for both objectives. Therefore, even when only one objective is considered, co-benefits or lateral benefits for the other objective are obtained through these measures. In contrast, trade-offs among infiltration trenches and rain gardens with urban trees are observed. While the first two measures mostly provide benefits for stormwater management, urban trees provide benefits only for heat stress mitigation. These measures compete for space. For instance, both infiltration trenches and urban trees could be applied in sidewalks. Therefore, there is a trade-off among benefits when one measure or the other is chosen, depending on the targeted objectives.

3.3. Multi-functional performance evaluation and impact maps

Obtained from the last step in this method, impact maps describe the state of the different challenges targeted once the measures have been applied, in this case the maps show new values of PET and runoff coefficient after the implementation of the selected NBS. Fig. 5 shows the current situation for runoff (Fig. 5a) and the results of runoff reduction for the three cases analysed, the stormwater management case, the heat stress case and the combination case (Fig. 5b, c and d respectively). Looking at the average values for runoff coefficient in each case, there was a substantial impact when measures targeting only stormwater management were applied (37 % reduction). This impact was considerably reduced when the objective shifted towards heat stress mitigation (18 % reduction). In this case, benefits related to stormwater management were obtained as co-benefits. Finally, when both objectives were targeted, the impact on runoff reduction improved again and was almost as good as when the only objective was stormwater management (36 % reduction). Linking this results with results presented in Table 1, it is observed that preferred measures for stormwater management, such as rain barrels and rain gardens, are not selected when the objective is only to reduce heat stress. However, these solutions are again chosen in the case of the combined objectives, resulting in the high performance on runoff reduction.

Results of impacts on heat stress mitigation are presented in Fig. 6. In this case, when the objective was only to reduce heat stress (Fig. 6c), the impact on PET reduction was considerable (17 %). However, when the objective was only stormwater management and benefits related to heat stress mitigation were obtained as co-benefits, the impact on PET reduction was diminished (12 %). Finally, when both objectives were targeted, the impact on PET reduction was not as good as when only heat stress was targeted, and was close to the result obtained when this benefits was just a co-benefit (13 %). Linking this result with results presented in Table 1, it is observed that trees are not selected in the case targeting combined objectives. The reason is that trees are assumed to have no much impact on stormwater management; however, this is the solution with the highest impact on heat stress reduction, which explains the low performance on heat stress mitigation in the case of combined objectives.

3.4. Trade-offs analysis

Regarding the analysis of impacts when targeting different objectives, it is observed that the impact on stormwater management is medium (18 % runoff reduction) when it is obtained just as a co-benefit from measures oriented to reduce heat stress (Fig. 7). However, when both objectives are targeted, the impact is much higher (36 % runoff reduction) and very close to the maximum (37 % runoff reduction), achieved when stormwater management is the only objective. It is clear that targeting both objectives does not have much negative effect on the achievement of runoff mitigation. These results are different in the case of heat stress mitigation, the impact decreases from about 17 % to 13 % heat reduction if the aim is changed from heat stress as only objective to the prosecution of both objectives. This means that when targeting both objectives, there is a considerable decrease in heat stress reduction. Finally, heat stress mitigation as a co-benefit, when the only objective is stormwater mitigation, is quite low (12 %). Even though this results are case-specific, they show the relevance of addressing possible trade-offs when targeting at several objectives, since this would lead to compromising the effectiveness of some of the aimed benefits.

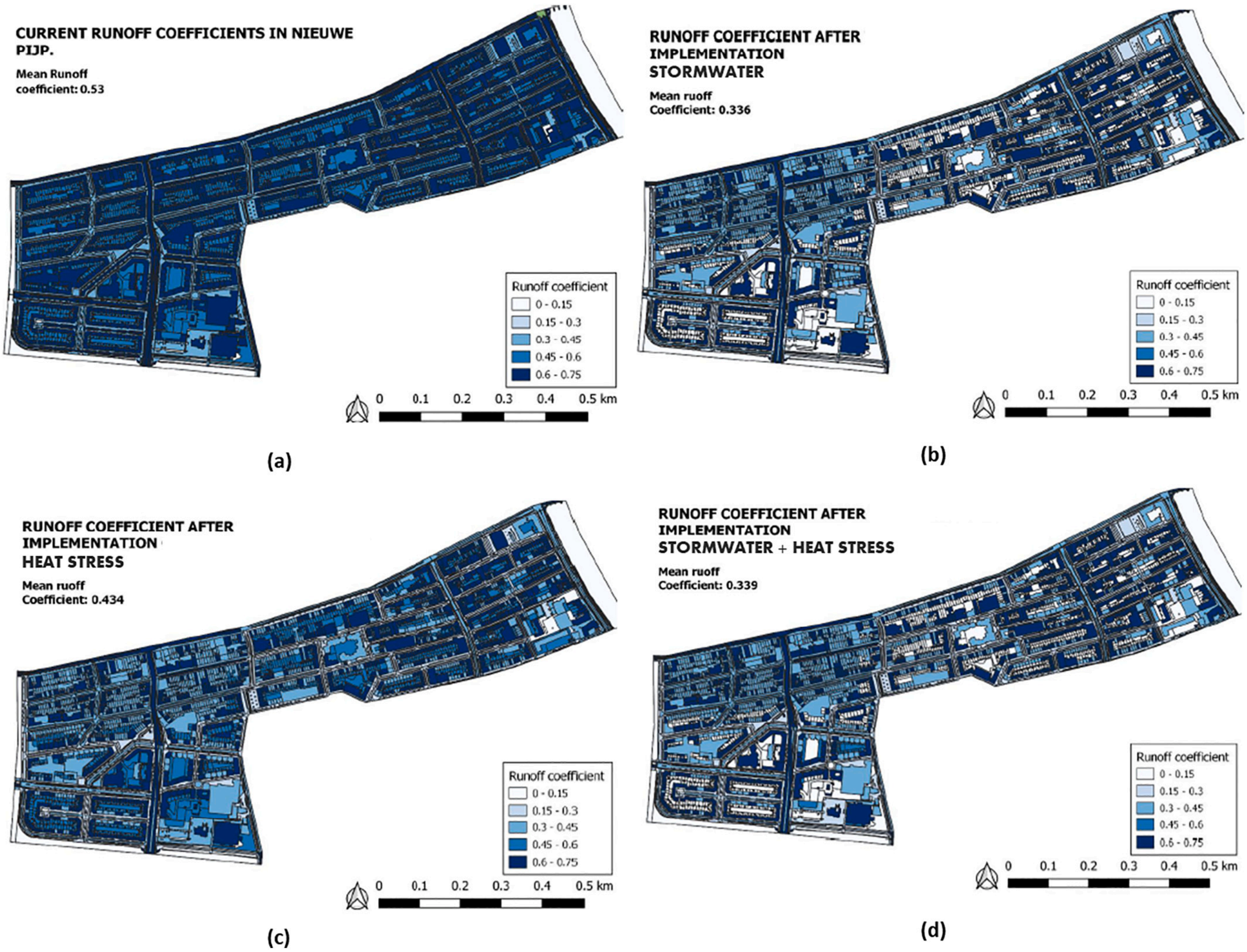

Fig. 5. Impact maps on runoff reduction for the cases (a) current situation, and after implementation with (b) only stormwater management as objective, (c) only heat stress mitigation as objective, (d) both stormwater management and heat stress mitigation as objectives.

3.5. Validation

The first workshop was attended by about 15 people from Europe and mainly from The Netherlands and the focus was on validation of the method itself. All attendants had a scientific background. Regarding what indicators would be useful to add to better identify priority areas, the main answers were oriented to include human vulnerability and population density. The method so far includes only hazards, using indicators to represent the severity of the problems considered. Adding data about population density, age and socio-economic level in the area would help to better understand the risk of a flooding event or heat wave. This would help to improve the identification of priority areas (step 1).

Concerning what indictors to add for allocating NBS (step 2), the main answers were costs and land ownership. Cost is important to add since it is a primary aspect considered by decision makers. However, this should be accompanied by a monetarization of benefits, to provide comprehensive information for comparing among solutions. Regarding land ownership, this data is currently included and used to allocate measures, but is not presented as part of results. A differentiation among measures applied in public and private spaces may help policy makers to visualize the necessity of regulations or incentives to encourage the application of NBS in private spaces (Snel et al., 2020).

When asked which applications this method could be useful for, most of the answers focused on redevelopment or retrofitting designs and at the neighbourhood level. The method was also seen as helpful for participative designs and designs of new development, specially the benefits maps (step 3) could be of help to communicate the impact of NBS implementation. The main identified barrier for applying this method was data availability and its quality. The lack of consideration of extra constraints caused by underground infrastructure was also mentioned. Regarding how to achieve realistic results, several elements were mentioned, such as citizens' feedback, competition for space by different urban land uses, transparency of the decision making and design process and again costs considerations. The questions and results are presented in Fig. 8.

The method's applicability and results were validated with practitioners from Amsterdam's municipality. The validation was conducted with about 10 practitioners in a focus group meeting, which consisted of a general group discussion guided by key questions. Regarding the usefulness of the NBS allocation function for infrastructure planning, it was seen as helpful to identify priority areas where to act and main NBS to be further explored, but for actual design or final decision making on which measures to apply, the neighbourhood scale was seen as too big. An element considered important to integrate into the analysis was the identification of opportunities for implementing measures, for instance assets management plans for different types of urban infrastructure, such as roads and pipes retrofitting. Adding this would allow the

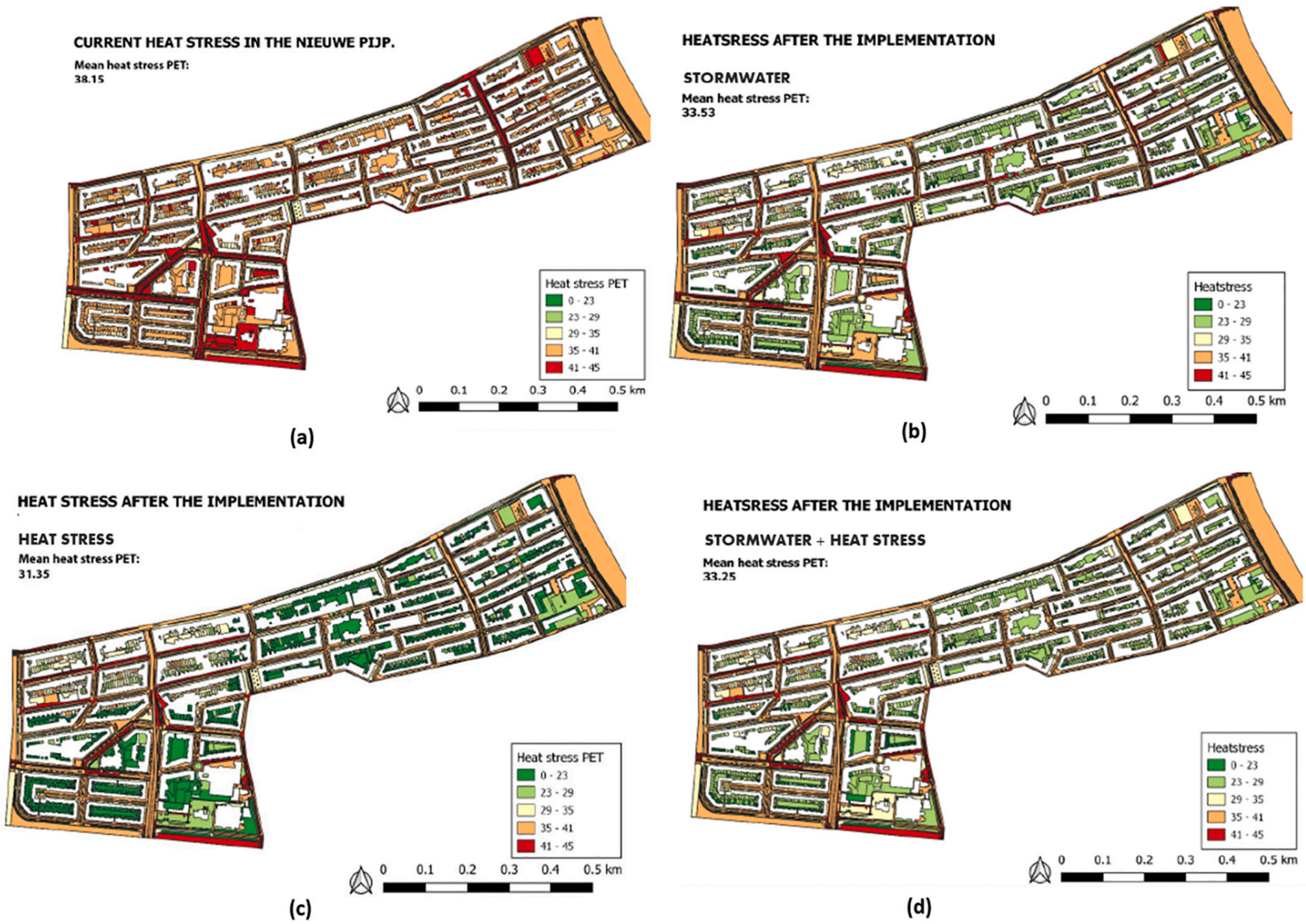

Fig. 6. Impact maps on heat stress mitigation for the cases (a) current situation, and after implementation with (b) only stormwater management as objective, (c) only heat stress mitigation as objective, (d) both stormwater management and heat stress mitigation as objectives.

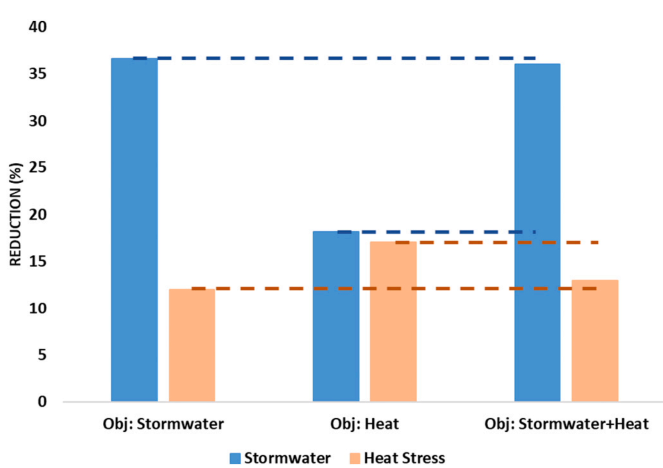

Fig. 7. Analysis of benefits and co-benefits when different objectives are targeted.

alignment of long-term strategies for NBS implementation with short-term activities regarding infrastructure renewal, consequently reducing implementation costs of NBS.

When asked if this method would result useful to plan multifunctional infrastructure, targeting multiple objectives, the reaction was in general positive, seeing a multi-objective approach as interesting and the method as helpful to achieve integral solutions. Nevertheless, the importance of defining and highlighting clear main objectives was emphasized. When trade-offs among benefits were presented and the value of this type of analysis inquired, the idea of multiple objectives was seen as much less attractive, stressing how this approach could be not possible or not convenient in many cases.

Finally, regarding how this method or results of its application could be used in their work, the main application identified was for communication and demonstration of priority areas for action, suitable NBS, etc. It was also seen as helpful for facilitating group decision-making, helping interaction between different actors. In particular, it is considered valuable to support the communication and enhance collaboration between experts in different disciplines or municipal departments. Moreover, it would help the collaboration with the private sector by helping to visualize the relevance of applying measures in private areas. More details about this outputs are presented in Annex E.

During both validation processes and during exchanges with practitioners from other cities in The Netherlands, the importance of adding other urban challenges to the method was expressed. Examples of relevant challenges mentioned are water scarcity, biodiversity loss, health, and energy savings.

4. Discussion

The main strength and applicability of this method is its capacity of providing NBS recommendations for specific urban characteristics. Moreover, it allows to compare the impacts of recommended NBS when choosing single and multiple objectives or benefits. It is an important

Fig. 8. Validation results from scientific perspective, (a) what are other parameters to improve the selection of priority areas?, (b) what are other parameters to improve NBS allocation analysis?, (c) what are possible barriers for applying this method?, (d) for what type of project/planning is this method useful?

advantage since the consideration of multiple benefits and their synergies and trade-offs has been scarcely addressed in previous works (Choi et al., 2021). This permits to develop a long-term plan regarding what solutions to implement but also helps to identify trade-offs among benefits when different objectives are established. As a result, the method improves communication among different disciplines and decision-makers. The results obtained should not be seen as a definitive implementation plan, but rather as approximations to help urban planners to make decisions and to enhance collaboration processes.

The analysis on what NBS are most frequently selected when targeting each objective (i.e. Table 1) shows that there are measures providing benefits for both objectives, even when only one of them is aimed. These are the measures capable of adding extra value to NBS through the delivery of co-benefits, and are crucial to plan multi-functional solutions to make a better use of the urban space. However, there are other measures that compete for space and provide mostly one benefit. For instance, urban trees have the highest impact on heat stress, but minor impact on runoff reduction, and they compete directly for space with measures that have high impact for stormwater reduction. These aspects have to be considered when planning NBS in urban spaces, where an efficient use of space is crucial. Even though it was not used in the example here presented, this spatial MCA method allows the inclusion of weights for different benefits. This enables the inclusion of tailored weighs to perform context-specific analysis that would help to find tailored solutions reflecting the interests of stakeholders (Goodspeed et al., 2022).

From the analysis of priority areas, a positive correlation of priorities for stormwater management and heat stress is observed, this is a similar result than that obtained by Meerow (2019). The author highlights the relevance of this, arguing that even if a main focus for urban NBS continues to be stormwater management, this may also help to mitigate heat stress. Moreover, our results show that the potential reduction of heat stress could be further improved if it is included as a primary objective when planning NBS for stormwater management; a similar conclusion was reached by He et al. (2019).

In the case here studied, it was more difficult to place measures for heat stress mitigation than for stormwater management. The NBS considered with highest impact on heat stress mitigation are mainly centralised measures which can hardly be implemented in a densely urbanized area. Besides, while all the measures considered have impact on stormwater management, several of them have null or low impact on heat stress reduction. Since both the spatial compatibility of NBS implementation (which depends on the NBS strategies and the city characteristics) and its capacity to cope with the targeted problems are relevant in this type of analysis (Simperler et al., 2020), the analysis performed in this work could be improved by having a more balanced list of measures and by applying the analysis in a more heterogeneous area regarding urban density.

The importance of both planning NBS for multiple objectives and recognizing trade-offs among them has been previously stated (Choi et al., 2021). The analysis of trade-offs in this work highlights this. On one hand, good opportunities to tackle runoff reduction would be missed if only heat stress reduction is aimed. On the other hand, there is a compromise on heat stress mitigation effectiveness when runoff reduction is included as an extra objective. Therefore, even though targeting more than one objective when planning NBS may be more convenient in most of the cases, it is important to recognise and manage possible trade-offs among different benefits.

Concerning the method's validation, the interaction with researchers provided useful inputs on how to improve the exposure and vulnerability analysis by including population data. The relevance of including this type of data is also observed in previous works (Kremer et al., 2016). Another valuable suggestion was the inclusion of costs analysis, which usefulness is observed in the work of Sarabi et al. (2022), in which stakeholders were able to compare among possible NBS to implement considering costs besides benefits. Finally, availability and quality of data were seen as possible important limitations to apply this method; this has been previously analysed and discussed by Kuller et al. (2019). To overcome this constraint, a clear communication of uncertainties and limitations related to the data used and the selection of weights is recommended (Walker et al., 2003).

In the case of the interaction with municipal stakeholders, the validation focused on the usefulness of the method and several interesting elements were identified. First, it is concluded that the short term planning approach is mainly opportunistic, confirming the findings from Kuller et al. (2018). This means that the actual implementation of measures in the short term follows an assets management plan, looking for opportunities to build urban NBS during renovation tasks and consequently reducing costs. The methodology presented in this work could help to identify areas where these opportunities could be more effective (priority areas), helping to realise a more effective long-term actions plan at the city level. This is an important contribution since previous works show that often NBS are not implemented in high priority areas (Li et al., 2020; Meerow & Newell, 2017). The combination of long-term strategic plans, which this method helps to develop, with short-term assets management plans may help to enhance the effectiveness of specific actions.

From interactions with municipal stakeholders, an interest on adding more benefits beyond stormwater management and heat stress mitigation was identified. Examples of the extra benefits mentioned are biodiversity enhancement, air and water quality improvement, generation of recreation spaces, droughts mitigation and energy transition. However, the interest for measures targeting co-objectives decreased when the results of trade-offs between benefits were presented. This shows that there may be barriers to the design of multifunctional NBS since specific actors would not accept the detriment of their main aimed benefit to enhance another locally relevant benefit.

Therefore, the validation process with experts and practitioners highlighted some main limitations of this method. The maps obtained from the application of this method could help communication among stakeholders, improving the understanding of problems, possible solutions, and helping collaborative processes. However, the method is based on physical indicators, without considering co-creation and public participation. These collaborative approaches are increasingly encouraged to improve the acceptance of NBS, as often the most appropriate NBS in technical terms are not the most appropriate from a public point of view (Frantzeskaki, 2019). Public consultation and interdisciplinarity should be included along the complete planning process, to better understand local challenges, to help the acceptance of multifunctional NBS and to consider people preferences regarding the type of NBS to be implemented in each context (Derkzen et al., 2017).

5. Conclusions

In this paper, a spatial multi-criteria analysis methodology to improve urban NBS planning processes is presented, considering their impacts as well as synergies and trade-offs among the different benefits they provide. This method consists of three steps: (i) identification of priority areas where problems are more severe and NBS are more demanded, (ii) selection and allocation of NBS considering physical aspects, technical requirements and the benefits targeted and (iii) quantitative evaluation of impacts on the different benefits addressed. In particular, this method allows to target one or more benefits, helping to visualize the impacts of NBS in different cases and to identify synergies and trade-offs when targeting multiple benefits. Therefore, the method allows a more transparent communication on the transition of urban spaces among diverse decision makers.

Even though there is a consensus on the advantages of focusing on more than one benefit when planning NBS, decision makers should understand the impacts that it may have on the improvement of each individual problem. Moreover, these impacts should be considered by stakeholders when defining the benefits targeted and assigning weights in decision-making processes to plan urban NBS. Finally, since the implementation of urban NBS frequently follows an opportunistic approach, this method can help to make long-term plans to improve the effectiveness and reduce the regret when implementing NBS.

CRediT authorship contribution statement

Alida Alves: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Carlo van Opstal:** Data curation, Formal analysis, Investigation, Visualization. **Nout Keijzer:** Investigation, Methodology, Validation. **Nora Sutton:** Conceptualization, Funding acquisition, Resources, Writing – review & editing. **Wei-Shan Chen:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

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Appendix A. Runoff coefficients summary

Table A.1
Runoff coefficient values for different case study surfaces based on data from literature (Dickinson, 2017; Li et al., 2014; Ramachandra et al., 2014).

Type of surface from data	Description from literature	Runoff coefficient
Building	Roofs	0.75
Close pavement	Asphaltic/concrete	0.70
Semi-hardened surface	Gravel surfaces	0.55

(*continued on next page*)

Table A.1 (*continued*)

Type of surface from data	Description from literature	Runoff coefficient
Transition	Sidewalks	0.75
Open paved surface	Bricks and gravel road	0.35
Non-hardened surface	Unpaved soil road	0.25
Sand	Unimproved areas	0.10
Greenery, swamp, reed, shrubbery	Garden or green land	0.10
Parks	Parks	0.10
Other grasslands	Lawn	0.05
Waterway, waterbody	Water	0.00
Private property	Neighbourhood	0.50
Mixed forest, deciduous forest	Deciduous forest	0.10

Appendix B. Tools and data sources used

Table B.1
List of tools and data used.

Material	Category	Purpose	Source
QGIS	Tool	To perform spatial action and obtain new data	QGIS
Excel	Tool	To make calculations, e.g. suitability score for each NBS	Microsoft office
DTM	Data	Used as input to calculate the building slope	PDOK.nl
DSM	Data	Used as input for the spatial constraints	PDOK.nl
Runoff coefficients of land use	Data	Used to calculate the runoff potential	Literature review
BGT (landcover and land use)	Data	Used to create different land use types	PDOK.nl
Heat stress	Data	Used as input for priority areas definition	Klimaateffectatlas.nl
NBS constrains	Data	Used as input for suitability analysis	Literature review
NBS spatial characteristics	Data	Used as input for suitability analysis	Literature review
NBS benefits	Data	Used as input for suitability and impacts analysis	Literature review
Risk of flooding	Data	Used as input for priority areas definition	Amsterdam.maps.nl
High resolution satellite image	Data	Used to validate the land use of the BGT data and correct it using the image classification	PDOK
Neighbourhoods	Data	Used to divide the map in sub-areas	PDOK;CBS
Groundwater level	Data	Used as constraint indicator	Amsterdam.maps.nl and Waternet
Soil	Data	Used as constraint indicator	(de Gans, 2011)

Table B.2
Software specification of QGIS used.

QGIS version	3.20.2-Odense
Qt version	5.15.2
Python version	3.9.5
GDAL/OGR version	3.3.1
PROJ version	8.1.0
EPSG Registry database version	v10.027 (2021-06-17)
GEOS version	3.9.1-CAPI-1.14.2
SQLite version	3.35.2
PDAL version	2.3.0
PostgreSQL client version	13.0
SpatiaLite version	5.0.1
QWT version	6.1.3
QScintilla2 version	2.11.5
OS version	Windows 10 Version 2009
Active Python plugins	DigitizingTools
	inspireNL
	mmqgis
	NNJoin
	pdokservicesplugin
	pdok_locatieserver_locator_filter
	QuickOSM
	db_manager
	MetaSearch
	processing

Appendix C

C.1. Steps followed to identify priority areas and to allocate NBS

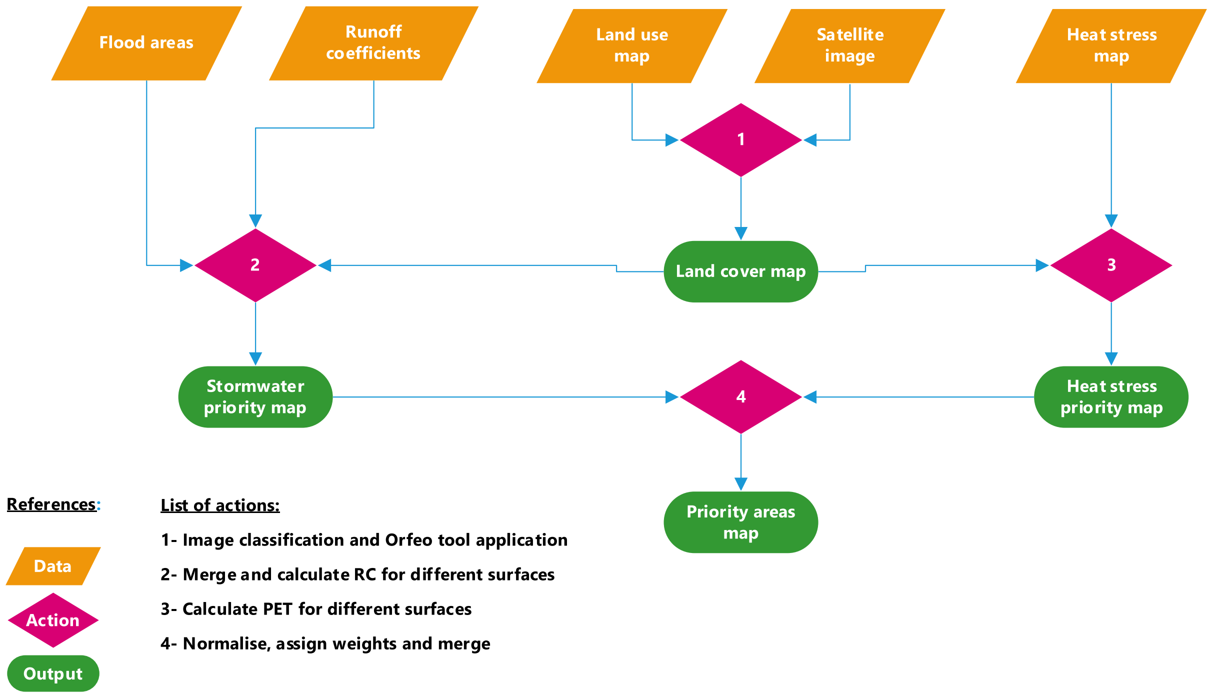

Fig. C.1. Process to find priority areas.

The land use map was updated and rectified using a high resolution satellite image and image classification tools (QGIS, Orfeo toolbox).

C.2. Steps followed to allocate NBS

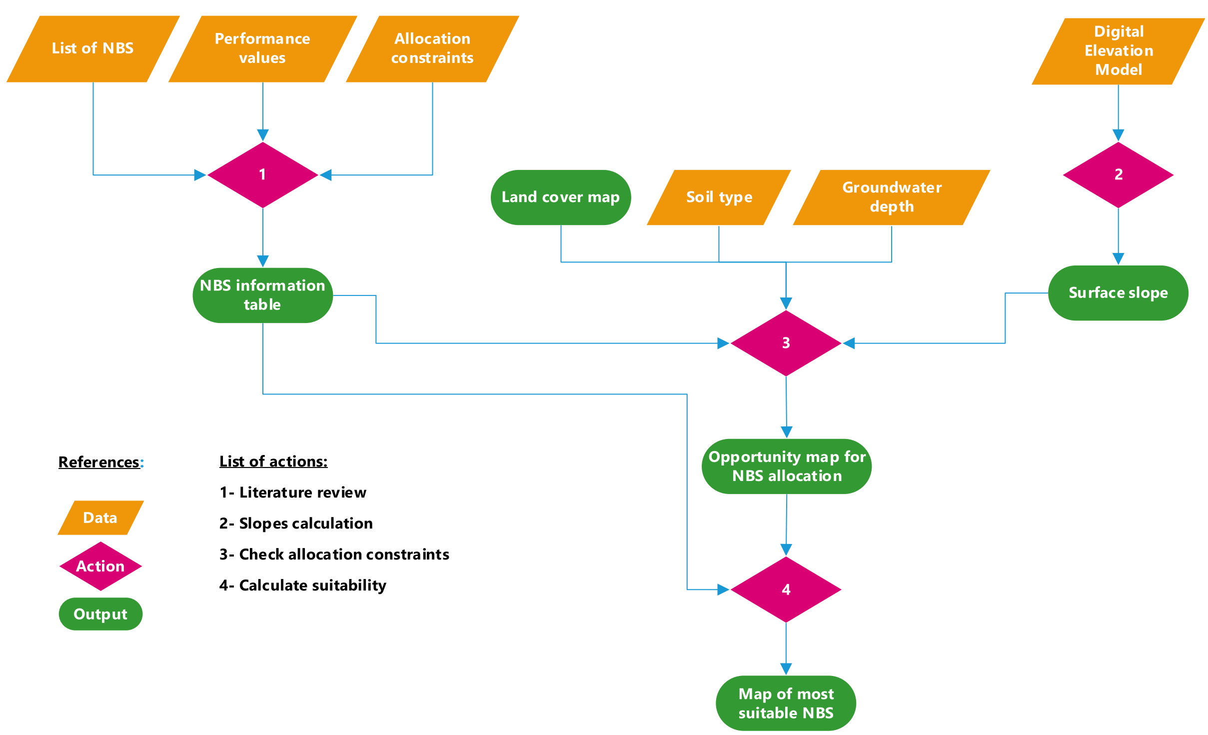

Fig. C.2. Overview of steps to define opportunity and suitability for NBS allocation.

Appendix D. NBS reference tables

Table D.1
Overview of allocation possibilities for the chosen NBS (y: allocation is possible, n: allocation is not possible).

Land use/ landcover	NBS												
	Rain garden[c,f]	Swale[g,h,j]	Infiltration trench[d,g]	Wetland[b,g,j,k]	Infiltration basin[d,f,g]	Green roof[d,j]	Grass[f]	Rain barrel[d,f]	Water square[g,j]	Bioretention area[d,i,j,k]	Retention pond[f,g,j]	Tree[a,k]	Permeable pavement[d,e,g,j]
Roadside	y	y	y	y	y	n	y	n	n	y	y	y	n
Building	n	n	n	n	n	y	n	y	n	n	n	n	n
Private property	y	n	n	n	n	n	y	n	n	n	n	y	n
Bike path	n	n	n	n	n	n	n	n	n	n	n	n	y
Closed pavement	y	y	y	y	y	n	y	n	y	y	y	y	y
Greenery	y	y	n	y	y	n	y	n	n	y	y	y	n
Entrance	n	n	n	n	n	n	n	n	n	n	n	n	y
Unpaved	y	y	n	y	y	n	y	n	y	y	y	y	n
Open pavement	y	y	n	y	y	n	y	n	y	y	y	y	n
Public transport line	n	n	n	n	n	n	n	n	n	n	n	n	y
Parking	n	n	n	n	n	n	n	n	n	n	n	n	y
Local road	n	n	n	n	n	n	n	n	n	n	n	n	y
Regional road	n	n	n	n	n	n	n	n	n	n	n	n	y
Railroad track	n	n	n	n	n	n	n	n	n	n	n	n	n
Road transition area	n	n	n	n	n	n	n	n	n	n	n	n	y
Traffic island	n	n	n	n	n	n	n	n	n	n	n	n	n
Pedestrian area	n	n	y	n	n	n	n	n	n	n	n	n	n
Sidewalk	n	n	y	n	n	n	n	n	n	n	n	n	n
Stairs	n	n	n	n	n	n	n	n	n	n	n	n	n
Waterway	n	n	n	n	n	n	n	n	n	n	n	n	n
Water area	n	n	n	n	n	n	n	n	n	n	n	n	n
Sandy surface	y	y	y	y	y	n	y	n	n	y	y	y	n

[a] Bartens et al. (2009).
[b] CH2M HILL (2014).
[c] Couling et al. (2016).
[d] Alves et al. (2018).
[e] Hou et al. (2019).
[f] Minnesota Pollution Control Agency (2021).
[g] Muthukrishnan et al. (2004).
[h] Rujner et al. (2018).
[i] Un (2016).
[j] Urban Drainage and Flood Control District (2010).
[k] World Bank (2021).

Table D.2
Overview of allocation constraints for the chosen NBS (y: allocation is possible, n: allocation is not possible).

NBS	Site characteristics											
	Ownership		Soil type			Groundwater depth		Surface slope			Available space	
	Private	Public	A	B/C	D	0–1 m	>1 m	0–3 %	3–5 %	>5 %	Low	High
Retention pond[f,g,j]	n	y	y	y	y	n	y	y	y	y	n	y
Bioretention area[d,i,j,k]	n	y	y	y	y	n	y	y	y	n	y	y
Rain garden[c,f]	y	y	y	y	y	n	y	y	y	n	y	y
Swale[g,h,j]	n	y	y	y	y	n	y	y	y	y	y	y
Permeable pavement[d,e,g,j]	y	y	y	y	n	n	y	y	n	n	y	y
Infiltration trenches[d,g]	n	y	y	y	n	n	y	y	y	y	y	y
Wetland area[b,g,j,k]	n	y	y	y	y	y	y	y	y	n	n	y
Infiltration basin/surfaces[d,f,g]	n	y	y	y	n	n	y	y	y	n	n	y
Green roof[d,j]	y	n	y	y	y	y	y	y	y	y	y	y
Grass[f]	n	y	y	y	y	y	y	y	y	y	y	y
Urban tree (box)[a,k]	n	y	y	y	y	n	y	y	y	y	y	n
Rain barrel or cistern[d,f]	y	y	y	y	y	y	y	y	y	y	y	Y
Water square (detention basin)[g,j]	n	y	y	y	y	n	y	y	y	y	n	y

[a] Bartens et al. (2009).
[b] CH2M HILL (2014).
[c] Couling et al. (2016).
[d] Alves et al. (2018).
[e] Hou et al. (2019).
[f] Minnesota Pollution Control Agency (2021).
[g] Muthukrishnan et al. (2004).
[h] Rujner et al. (2018).
[i] Un (2016).
[j] Urban Drainage and Flood Control District (2010).
[k] World Bank (2021).

Table D.3
Overview of performance values for each of the chosen NBS on the objectives considered.

NBS	Peak flow reduction in % (1 year RP, 25 mm)	Heat stress (PET reduction °C/m^2)
Retention pond[k,t]	73.0	1.9
Bioretention area[e,h,n]	54.0	11.0
Rain garden[c,g,n]	74.0	2.7
Swale[d]	62.0	6.0
Permeable pavement[n,r]	42.0	1.9
Infiltration trenches[a]	50.0	0.0
Wetland area[b,u]	54.0	11.0
Infiltration basin/surfaces[o]	37.0	6.0
Green roof[j,n,s]	57.0	5.1
Grass[l,tm]	17.0	6.0
Urban tree (box)[l,p,t]	8.0	17.5
Rain barrel or cistern[i,q]	6.3	0.0
Water square (detention basin)[f]	28.0	0.0

[a] Barber et al. (2003).
[b] Line et al. (2007).
[c] Feldman et al. (2019).
[d] Ghadim and Hin (2017).
[e] Hatt et al. (2009).
[f] Shishegar et al. (2019).
[g] Autixier et al. (2014).
[h] Batalini de Macedo et al. (2019).
[i] Deitch and Feirer (2019).
[j] Fassman-Beck et al. (2013).
[k] Jacobs et al. (2020).
[l] Ketterer and Matzarakis (2014b).
[m] Liang et al. (2021).
[n] Majidi et al. (2019).
[o] Natarajan and Davis (2015).
[p] Van Stan et al. (2020).
[q] Nunes Carvalho et al. (2020).
[r] Santamouris et al. (2012).
[s] Sharma et al. (2018).
[t] Yang et al. (2018).
[u] Bera et al. (2021).

The validity of some of the performance values could be questioned. This is because for some of the values no source could be found and therefore assumptions had to be made. The assumptions made for these parameters are well grounded and make sense, so the reliability of those parameters is not questioned by the researchers. However, some of the assumptions that are made, specifically some of the heat stress PET values, might be less representative for real life cases. This is because in literature the effect for heat stress reduction of certain measures has been researched and other have not been researched at all (e.g. swales, infiltration trenches, infiltration basins). In the case of the measures for which no research has been done, PET reduction values were based on similar measures of which a value could be found in literature. The measures that have been researched show large ranges of PET reduction (e.g. urban trees), but also in these cases the values are arguable because multiple factors influence the impact.

Another problem concerning the validity of the performance values has to do with the sizing of the measures. The peak flow reduction parameter is influenced by several factors, one of which is the size of the measure. The larger the size of a measure, the more likely the reduction parameter is also high. This means that if a measure gets assigned to a small feature in the case study area, the actual reduction of peak flow might be less than the value considered in the results.

Appendix E. Results from focus group with practitioners

Below the key questions and answers/conclusions provided during the discussion at the focus group with practitioners are presented.

Question 1: Would the NBS allocation function be helpful during infrastructure planning processes?

- It is seen as helpful for prioritizing action areas and NBS to be further analysed.
- It could have a positive contribution to identify where to implement or restore green infrastructure.
- The neighbourhood scale of analysis is too big, a street scale would be more useful.

- It would be good to combine this analysis with the actual opportunity to preform interventions (e.g. assets management plans), not every neighbourhood has the same opportunities.
- The method is applicable but does not add much value, the analysis could be done without it.
- It could be very helpful because it allows to visualize which measures could work where.

Question 2: Would the method be helpful to plan for multifunctional infrastructure?

- Yes, when rebuilding/upgrading we are always looking for what could be a better design for the space, the perspective of multiple objectives provides an interesting starting point for what could be done.
- Yes, it could make a good contribution but it is important to define clear objectives, it is important that design of the public space remains unambiguous.
- Many of the solutions presented are in private land, where the municipality itself has very little or no action capacity, but these results could be used to motivate residents.
- The combination of objectives is always good, however a close eye should be kept to the main objectives according to what causes the most inconveniences/stress in the area.
- It is helpful because it clearly shows at the parcel level which measure is possible and preferable according to the function that wants to be maximised; while at the area level it allows to make combinations of measures to achieve integrated solutions.

Question 3: When targeting multiple objectives, is the analysis of trade-offs among benefits helpful to make decision?

- The focus will be on the main problems to be solved, aiming to maximize those specific benefits.
- It is helpful if it is possible to give weights to the objectives, to highlight the main ones.
- It is useful if the aimed values are also known, which may depend on national or regional policies.
- It would be helpful depending on the urgency or scale of the main problem to be solved, sometimes it is better or easier to focus on solving only one problem.

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