Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 13 No 4, 1748 doi: 10.2166/wcc.2022.458

Suitability pre-assessment for decoupling in-sewer captured streams to support urban blue-green climate adaptation measures

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ABSTRACT

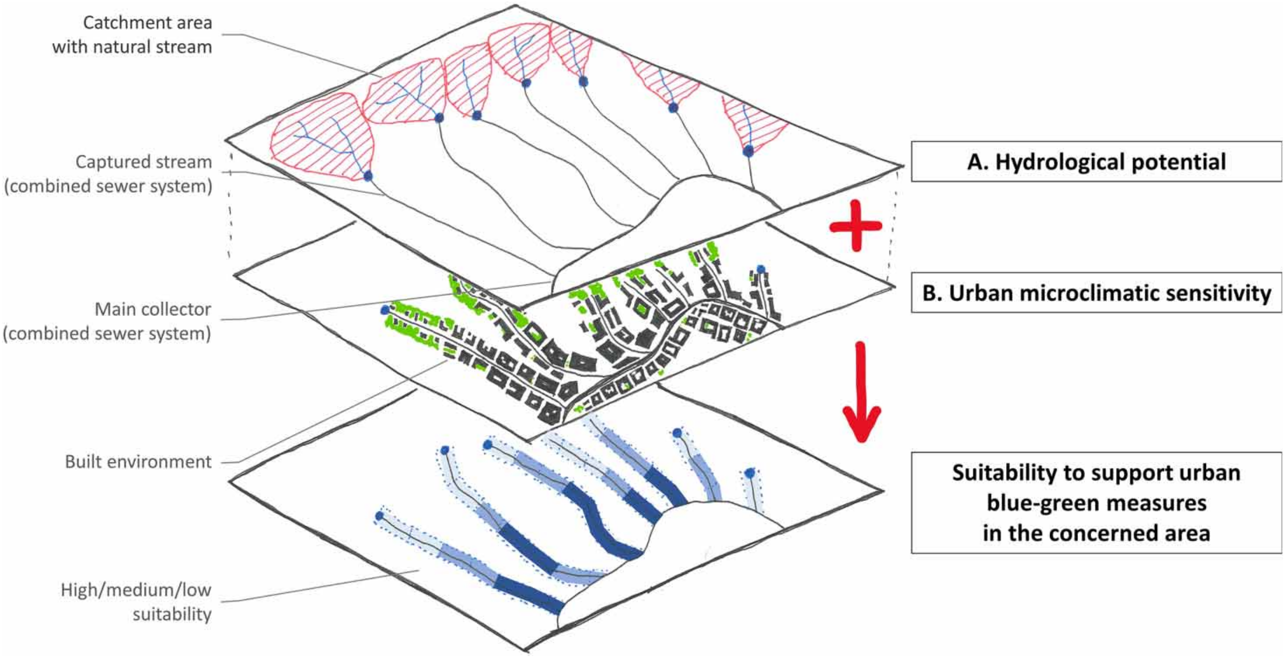
The application of nature-based solutions for climate change adaptation in cities has increased in recent years. To improve microclimatic conditions and to preserve the natural components of related assets, water supply is necessary. As an alternative to drinking water, stream water might serve as a natural source for irrigation. However, due to continuous urbanisation, water courses have often been banned underground in pipes or integrated in the combined sewer network, both making them not directly available for further usage. This article focuses on the perspectives of decoupling captured streams from underground infrastructure to support nature-based urban climate adaptation measures. It introduces a method to identify suitable locations for practical implementation considering the hydrological potential of the stream and the urban microclimatic sensitivity of the concerned area. The approach was applied in a case study in the north-western part of Vienna, including 16 streams with a total length of about 39 km covering an area of approximately 95 km^2 with about half a million inhabitants. This work proved the general practicality of the suggested method. It also revealed that about one-third of the investigated stream lengths appears high or medium suitable to support climate adaption measures, leading to notable cost savings for irrigation (for the substitution of drinking water) and wastewater treatment. Concluding, the decoupling of captured streams could contribute to a more sustainable and nature-based urban water management. The introduced method for suitability pre-assessment is applicable with rather easily available input data, which makes it transferable to other cities.

Key words: combined sewer, decision support, nature-based solutions, stormwater management, strategic planning, urban heat island

HIGHLIGHTS

- In-sewer captured stream water provides a possible water source for nature-based urban climate adaptation measures.
- The proposed method supports the evaluation of hydrological potential and urban microclimatic sensitivity.
- The application on the case study of Vienna reveals promising results.
- Results of the pre-assessment method act as a strategic guidance and decision support for practical implementation.

GRAPHICAL ABSTRACT



1. INTRODUCTION

As stated in the European Green Deal (European Commission 2019), climate change and environmental degradation are an existential threat to Europe and the world. Extreme weather events like heavy precipitation and extended dry periods in combination with high temperatures put cities under severe stress (Emilsson & Ode Sang 2017) and pose a health risk to citizens, even causing fatalities (IPCC 2014; Santamouris 2020). At the same time, increasing urbanisation leads to a progressive reduction and fragmentation of natural landscapes, a conversion of habitats (Kowarik 2011) and reduction of green spaces for human recreational purposes. To tackle the effects of climate change in cities, the use of nature-based solutions (NbS) has continuously increased in recent years. Using natural components such as vegetation and water, NbS provide several ecosystem services for their surroundings (among others temperature regulation, establishment of recreational purposes or biodiversity increase) (European Commission 2015; Castellar *et al.* 2021; Veerkamp *et al.* 2021).

However, in the context of NbS application, two crucial aspects have to be considered: first, from a rather technical point of view, most of these natural components require water supply to provide the mentioned benefits. In this context, drinking water is often considered as the main resource. This is certainly reasonable for applications with high water quality requirements (hygiene). However, if the water is used for irrigation, the use of drinking water should be critically scrutinised as it should primarily serve human purposes due to its high quality level. Especially during dry periods, when irrigation water is most needed, the use of drinking water can even increase pressure on this precious resource. Moving towards a more sustainable water resource for NbS, rainwater application (Fletcher *et al.* 2015; Campisano *et al.* 2017) as well as greywater recovery (Boano *et al.* 2020) are promising alternatives. Still, their application comes with drawbacks regarding a high seasonal variability of rainwater (de Sá Silva *et al.* 2022) and a necessary source separation from black water for the use of greywater (Otterpohl *et al.* 2004; Boano *et al.* 2020). Alternatively, another water resource might be available in cities: stream water could serve as a possible supply source but has often been banned underground over the course of urbanisation. However, if these streams are only piped/culverted, a recovery including a possible water extraction is no big technical challenge. In international literature, this approach is called ‘daylighting’ (or ‘deculverting’). Several practical examples in the USA (Pinkham 2000; Buchholz *et al.* 2016), Italy (Sibilla *et al.* 2017) and Turkey (Delibas & Tezer 2017) have been published. The positive impacts of daylighting have been reviewed by Wild *et al.* (2011), and the available literature on stream daylighting has been summarised by Khirfan *et al.* (2020). But in contrast to only being piped, stream water might have also been integrated into the urban wastewater system. In this case, a simple daylighting is not possible as the (clean) stream water is mixed with urban wastewater and must thus be seen as combined sewage. Here, the decoupling of the stream water from the wastewater network is the only option to make it accessible for further use. In international literature, only a few instances of this approach are documented up to now. Conradin & Buchli (2004) report about the example of Zurich in Switzerland. Hawley & Korth (2014) present a related approach from the USA. A core motivation of these works was wastewater system mitigation, as in-sewer stream water flow was considered as an undesired extraneous water putting pressure on sewerage networks and wastewater treatment plants. Finally, Broadhead *et al.* (2013) investigated types, reasons and consequences of 'captured streams' in combined sewers. Although still receiving little attention from the scientific community, the decoupling of captured streams from urban sewage systems and subsequently using (recovering) this water to support various climate change adaptation measures in urban areas (irrigation of green infrastructure, installation of blue assets, etc.) appears an interesting opportunity. Particularly in the light of increasing emphasis on a more efficient and sustainable water use, this approach is worth being investigated in more detail.

The second crucial aspect in regard to NbS application refers to a more strategic point of view. To maximise the benefits from NbS in reducing thermal loads and improving microclimatic conditions, they must be designed in accordance with urban climatic factors. Integrating climatic assessments in urban planning processes and developing specific adaptation measures at different spatial and temporal scales help to improve and preserve the quality of life of built-up environments and to design cities in accordance with current and future climate conditions. Here, the identification of areas which are prone to overheating is of particular interest. If available, an urban climate analysis can pose a valuable starting point. Based on climate and geodata analysis as well as on numeric climate modelling, these urban climate analyses provide information on local climatic characteristics of a city. It depicts the spatial distribution of climatopes (areas with similar local climate conditions), thermal, dynamic and air quality conditions as well as linkages to the regional climate (VDI 2015; Tschannett *et al.* 2021). These urban climate maps are of high importance for a strategic climate-sensitive development of cities, although they are usually not established by law (VDI 2015). However, today not every city has an urban climate analysis available. Consequently, an alternative and possibly even simplified method to support strategic planning for climate adaption measures serves as a starting point to allow and support initial action.

To contribute to a strategic recovery of captured streams for making them available for urban blue-green climate adaptation measures, this article proposes a pre-assessment approach to identify the most promising locations for practical implementation. This concept includes two core aspects: the hydrological potential (quantification) of the captured streams and the microclimatic sensitivity of the concerned urban area. To test and demonstrate the practicability and the informative character of the suggested approach, it has been applied to selected parts of the city of Vienna, where streams are widely included in the urban combined sewer system at the moment.

2. MATERIALS AND METHODS

2.1. Theory framework

The presented pre-assessment method for decoupling captured streams is based on the theory of relevance trees and preference matrices. The development and the application of the approach deliver the required information to interpret the potentials of decoupling stream water in the context of urban climate adaptation.

Relevance trees are developed following several steps (Fürst & Scholles 2008; Stöglehner 2019). First, pre-assessment categories are selected to fit the scope of the relevance tree and ranked according to their relevance. Second, pre-assessment criteria are selected for each category. Pre-assessment criteria make categories evaluable by introducing threshold values or yes/no questions. Third, the number of (pre-assessment) classes is determined based on the number of categories and criteria. Finally, the categories and criteria are assigned to specific class numbers to receive the final pre-assessment of the relevance tree.

If more than one relevance tree is needed to represent a complex topic, the final pre-assessment can be done by using a preference matrix. In a preference matrix, the class numbers of the relevance trees are combined to receive an integrated judgement (Fürst & Scholles 2008).

As an acknowledged practice in environmental and spatial planning, relevance trees help to classify planning options according to selected categories. By simplifying and evaluating complex systems, this method allows a transparent decision-making (Fürst & Scholles 2008). Based on these strengths, this approach was chosen for the problem presented.

2.2. Development of pre-assessment approach

For the pre-assessment method presented in this paper, two relevance trees were developed: (A) the hydrological potential (of the captured stream) and (B) the urban microclimatic sensitivity (of the concerned urban area). In this section, the methodological approach for the development of the relevance trees and their joint evaluation in a preference matrix are described, according to Figure 1. To create the relevance trees, categories are selected and pre-assessment criteria are assigned to each category. The results of the two relevance trees are combined in a preference matrix, which delivers the pre-assessment result on the suitability of a designated location for the implementation of NbS using decoupled stream water. Finally, a multi-site application of this approach reveals the most promising sites in the concerned area of interest.

2.2.1. Hydrological potential

The relevance tree (A) hydrological potential represents the availability of water along captured streams for NbS in terms of climate change adaptations. In the first step, the pre-assessment categories were selected. Here, the following three categories are defined: (A1) the minimum stream discharge, (A2) the temporal stream characteristics and (A3) the lateral roof runoff area. The categories (A1) and (A2) contain information on the amount of stream water available from the natural catchment. The category (A3) lateral roof runoff area serves as an indicator for an additional water input from rainwater runoff. The roof area along the combined sewer (captured stream) is considered in the hydrological potential as it once was part of the natural stream catchment. Here, due to water quality considerations only runoff from roof areas is considered. Nevertheless, it is recommended to divert the first flush to achieve a better water quality (Abbasi & Abbasi 2011; Zabidi *et al.* 2020). Apart from this aspect, we do not address specific water quality issues here. For detailed planning, related considerations are undoubtedly crucial. In this preliminary pre-assessment, we consider a quantitative evaluation as sufficient.

The subsequent ranking of the categories is orientated towards the quantitative flow characteristics of the streams. Ranked highest is (A1) the minimum discharge of the stream flow from the natural catchment as the discharge determines how much water is available for further use in NbS. Ranked second is (A2) the temporal flow characteristics of the stream, which indicate the water availability throughout the year. Ranked last is (A3) the lateral roof runoff area, as the total (annual) amount and duration (occurrence) of related runoff are assumed to be considerably lower compared to a permanent or even

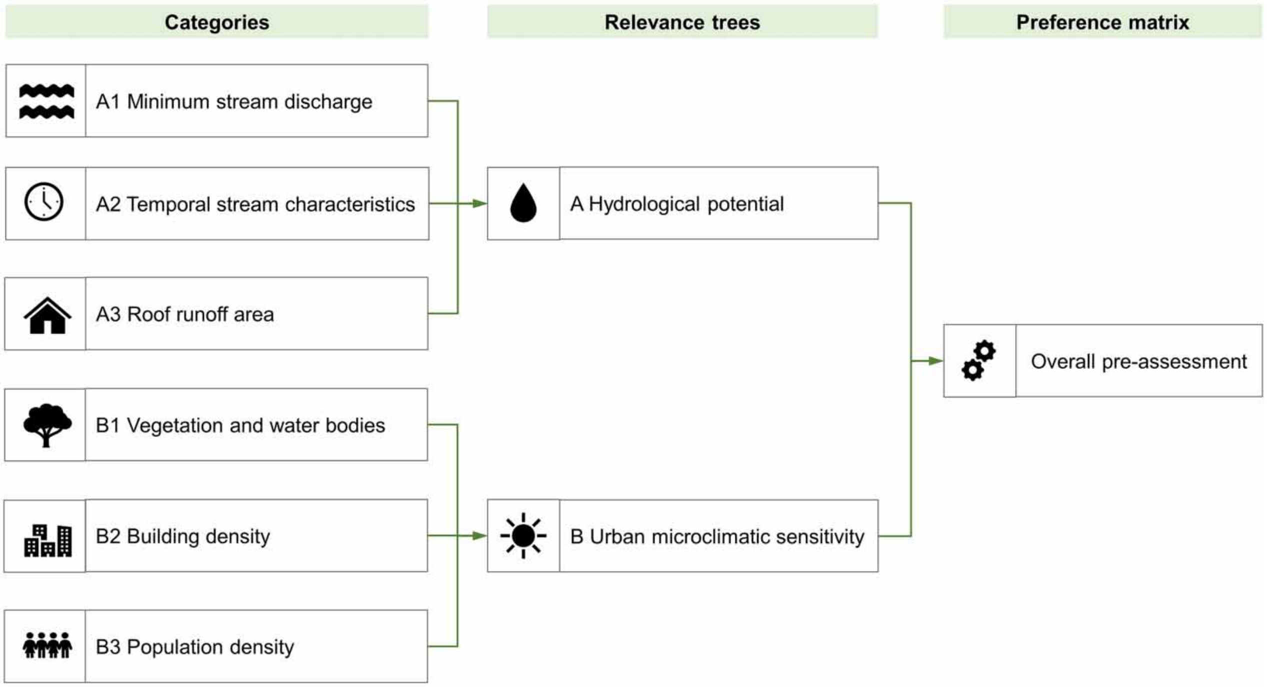


Figure 1 | Overview scheme of the presented pre-assessment method, including categories, relevance trees and preference matrix application (own illustration).

intermittent stream flow. Furthermore, the overall objective of this paper focuses on the decoupling of captured streams and rainwater runoff is only considered for additional (secondary) water input.

In a second step, the pre-assessment criteria are chosen for each category to allow the quantification of the categories. The pre-assessment criteria for the categories (A1) minimum stream discharge and (A2) temporal characteristics are determined at the inflow point of the natural stream to the combined sewer network. In this paper, flow duration curves are used to derive both criteria. Flow duration curves display the relation between discharge data and exceedance probability for a specific location (Ley *et al.* 2011) and can be calculated for gauged streams. The pre-assessment criterion for (A1) minimum stream discharge is set to allow an internal differentiation of the streams based on the characteristics of the flow duration curves. For (A2) temporal characteristics of stream flow, three classes are defined. While a permanent stream flow presents the maximum and best criterion, a grading is needed for intermittent flow in order to generate an internal ranking of potential concerning the available amount of water of the selected streams. The pre-assessment criterion for category (A3) lateral roof runoff area is the available roof area in m^2 for a defined 100 m longitudinal segment along with the captured stream flow (concerned combined sewer). It is calculated based on vector data of the multi-purpose area map, provided by the city of Vienna (Magistrat der Stadt Wien MA 41 2021). The longitudinal distance of 100 m was chosen to represent a potential extension of NbS in a street. The lateral distance of 50 m to the combined sewer is set to include the first row of houses in a street to facilitate the harvesting of roof runoff. Using geographic information systems (GIS) to analyse the roof area along with the combined sewer, the final threshold for (A3) is defined as the upper quantile of these available roof areas. Figure 2 provides a schematic overview to illustrate the applied segment dimensions.

The last two steps for developing the relevance tree are the definition of numbers of pre-assessment classes and the assignment of categories to the class numbers. The number of classes results from the number of criteria defined in the previous step. The assignment of the categories to the class numbers is based on the ranking done in the first step. The higher a category is ranked, the better is the hydrological potential and therefore the assigned class number.

2.2.2. Urban microclimatic sensitivity

The second relevance tree (B) urban microclimatic sensitivity aims at identifying sites within the city where overheating and thus heat stress occur and where an implementation of NbS with decoupled stream water could help to improve local thermal conditions. The factors determining local urban climate conditions and thermal perception are manifold and apply to different temporal and spatial scales (for a well-documented description of factors influencing the urban climate, see Oke *et al.* (2017)). Nonetheless, if not disrupted by dynamical and seasonal effects, each climatope (area with similar microclimatic characteristics) has a characteristic and measurable thermal regime (Stewart & Oke 2012). For a simplified pre-assessment

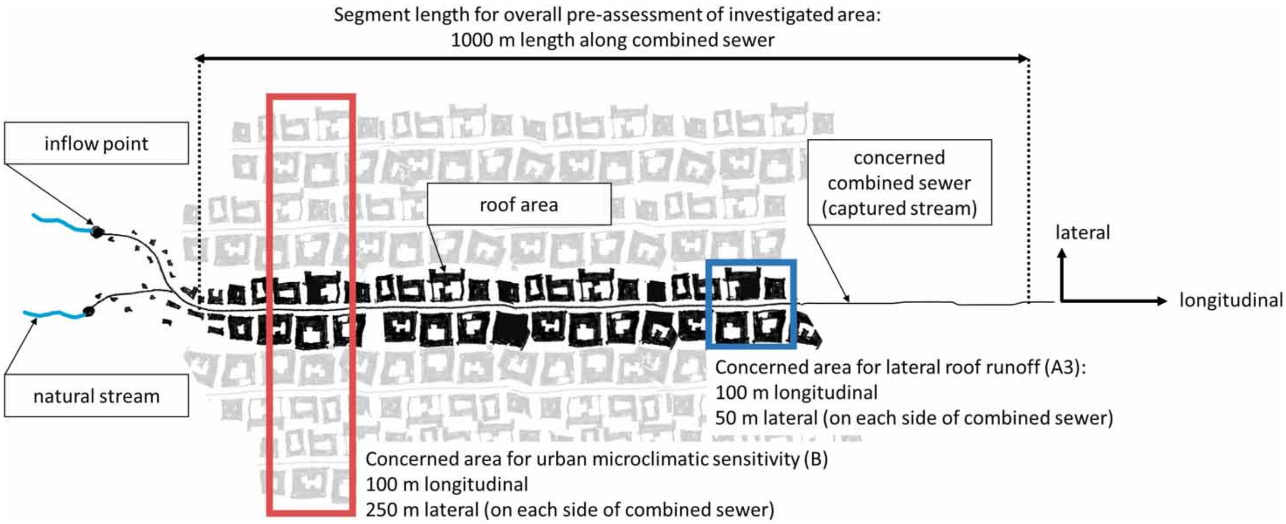


Figure 2 | Schematic overview to illustrate applied segment dimensions for lateral roof runoff area, urban microclimatic sensitivity and overall pre-assessment of the entire investigated area (own illustration).

to depict these thermal differences, the selection of pre-assessment categories includes, in regard to surface cover, (B1) vegetation and water bodies and (B2) building density. Additionally, (B3) population density is chosen to estimate the impact of implemented NbS.

The ranking of categories is, consequently, based on the urban fabric's sensitivity to overheating, which is a driving factor for the implementation of NbS for climate adaptation measures. Ranked highest are the two types of surface cover (B1) and (B2), as studies show that surface temperature distributions are closely linked to the distribution of buildings, vegetation and running water bodies (Jusuf & Hien 2016). Ranked first are (B1) vegetation and water bodies within the assessed area. The presence of vegetation reduces solar heat gains throughout the day and leads to a faster temperature decrease during nighttime. Ranked second is (B2) building density as it influences the accumulation of heat during hot periods and is a driving factor for the urban heat island effect (Oke *et al.* 2017; Kim & Brown 2021). Hereby, we want to reiterate that the suggested approach for a simplified pre-assessment applies this criterion only in the context of surface cover (three-dimensional aspects and/or the specific use of buildings is/are not considered at this evaluation stage). Ranked last is (B3) the population density to acknowledge for areas where a considerable number of people reside, who can benefit from NbS and their positive impact on the surroundings. Furthermore, (cost) intensive measures are more likely to be justified if their improvements reach many people.

The pre-assessment criteria for (B1) vegetation and water bodies and (B2) building density are based on classification schemes for differences in local thermal characteristics. In this paper, the classification of local climate zones (LCZ) as described by Oke *et al.* (2017) and a classification specifically developed for the city of Vienna (Stiles *et al.* 2014) have been adduced as references. The typologies defined in these publications help to identify areas which are prone to overheating. The characteristics of these typologies regarding vegetation, water bodies and building density are used to derive the threshold values for the pre-assessment criteria for (B1) and (B2). Both pre-assessment criteria are expressed as a percentage of the total surface area. For application, the percentage of (B1) and (B2) can be derived based on GIS analysis if data on surface cover for buildings and vegetation and water bodies is available (as it is for the city of Vienna). Alternatively, a visual assessment can be conducted using satellite images. Concerning the pre-assessment category (B3) population density, the pre-assessment criterion is set to a threshold representing the average population density in the concerned districts of the city. It is calculated based on population data and spatial information on sub-district level, both provided by the municipality of Vienna (Magistrat der Stadt Wien MA 21 2021; Magistrat der Stadt Wien MA 23 2021). If several units apply to one pre-assessment segment, the population density is weighted according to the share of each unit in the segment.

All three categories of relevance tree (B) are pre-assessed in a buffer distance of 250 m to the combined sewer (captured stream) through the city (compare Figure 2). This buffer distance has been chosen to attribute the extent of local climatic characteristics in the area of interest and potential climatic influences from surrounding areas.

As shown for relevance tree (A), the last two steps for developing the relevance tree are the definition of the class number and the assignment of categories to the class numbers. Here, we follow the same procedure as already described in Section 2.2.1.

2.2.3. Joint evaluation

As mentioned above, the pre-assessment method is applied within two different proximities to the respective combined sewer (captured stream): for the hydrological potential, a lateral distance of 50 m is chosen to facilitate the collection of roof runoff for an additional water input. For the urban microclimatic sensitivity, the lateral distance is widened to 250 m to include local microclimatic influences from surrounding areas. For the pre-assessment of the entire investigated area, segments with a length of 1,000 m along the combined sewer are defined. This length was chosen to allow a detailed pre-assessment of the categories, without taking extensive evaluation time. For data handling, an index number was assigned for each segment containing the stream and the segment number (e.g., the first segment of the ninth stream Alserbach receives the index R0901). Figure 2 visualises the applied segment dimensions.

To receive the overall suitability of a segment, the achieved class numbers of the two relevance trees are further applied in a preference matrix. The preference matrix is a grid, where rows and columns each represent the number of classes of the relevance trees. Inside the grid, the combination of class numbers from both relevance trees gives the overall suitability of the segment. The higher the evaluation in the relevance trees, the higher is the overall suitability. To allow an easy evaluation, the overall suitability will again be classified into a set number of classes (high, medium and low suitability).

2.3. Case study – Viennese forest streams

The case study area is situated in the city of Vienna, Austria. Vienna is surrounded by the Viennese forest stretching from northwest to southeast of the city. Several streams originating from this area permeated the western districts of the city before reaching the Danube. In the 1830s, these streams were piped to transport waste and wastewater out of the city. Today's combined sewer system still follows these historical courses and carries the remaining stream water (Gierlinger *et al.* 2013).

Figure 3 shows the 16 streams (catchments) selected for this case study. The natural catchment area upstream the inflow points to the (combined) sewage network is 20.75 km^2, ranging from 0.09 to 5.60 km^2. The longitudinal slopes of the streams vary from 6 to 18%, and the time of concentration shows values between 9 and 55 min. After an open flow in the upper reaches, the streams enter the combined sewer system at specific inflow points. These inflow points were identified based on Lehmann (2021) and supportive on-site inspections of all 16 catchments (to verify the location inflow points, to observe their technical design and to get an impression of the actual stream flow regimes). Downstream the inflow points, the stream water flows in the combined sewer. The total length of all captured segments is 38.50 km, running through 10 districts of Vienna. In total, these districts cover an area of approximately 95 km^2 with a population of about 530,000 (Magistrat der Stadt Wien MA18 2021; Statistik Austria and MA23 2021). In Vienna (Hohe Warte), the average annual precipitation is 651 mm (for the available reference period of 1981–2010 according to Zentralanstalt für Meteorologie und Geodynamik no date).

For the concerned Viennese streams, no daily flow data over longer time periods is available. Therefore, flow duration curves were derived by using the drainage area of the ungauged streams in the case study and information on flow characteristics of gauged streams in surrounding areas of the Viennese forest (Gablitzbach, Kleine Tulln, Hagenbach and Weidlingbach). Exceedance flow duration curves of gauged streams were normalised by their drainage area. These normalised curves are used to derive the flow duration curves of the ungauged streams based on their drainage area. This methodical approach was applicable due to a narrow geographical region of observation and given similarity in catchment attributes

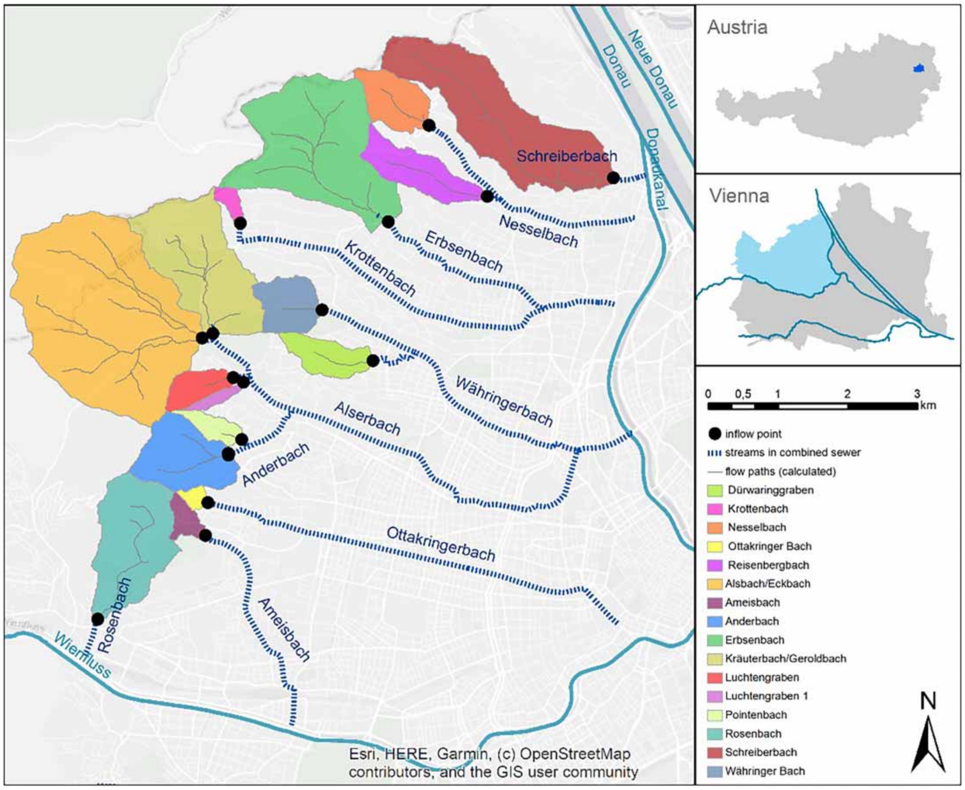


Figure 3 | Case study site Vienna and its Viennese forest streams with remaining natural catchments, flow paths upstream the inflow points and streams in a combined sewer network (own illustration, based on Hohensinner (2021), BEV (2019), Esri (2009) and Umweltbundesamt (2020)). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2022.458.

reflecting the generation of discharge. A check on plausibility was done on basis of the deviation of normalised runoff rates between the gauged river systems. The result showed differences between the streams concerning high-flow situations, with regard to medium- or low-flow conditions the divergence is negligibly low.

3. RESULTS

In this section, the two final relevance trees are presented. This also includes an explanation of the definition of threshold values for the pre-assessment criteria in each category. Based on this input, the approach of a joint evaluation by applying the preference matrix is described.

3.1. Hydrological potential

The pre-assessment criteria for (A1) minimum stream discharge and (A2) temporal flow characteristics are derived from the flow duration curves shown in Figure 4. The figure shows that 38% of the selected streams are intermittent (Ameisbach, Luchtengraben, Luchtengraben 1, Krottenbach, Ottakringerbach and Pointenbach) and more than 80% have discharge values smaller than 5 l/s on more than 50 days of a year. For the exceedance duration of 365 days, the minimum average discharge of all observed streams amounts to 1.40 l/s. To allow an internal differentiation of the river systems concerning the potentially available resources of water, the (A1) minimum discharge was defined with 5l/s. Finally, the thresholds for the (A2) temporal flow characteristics were set to permanent discharge (includes one stream), exceedance of minimum discharge on 270 days (includes three additional streams) and 180 days (includes one additional stream), representing approximately 75 and 50% of the year.

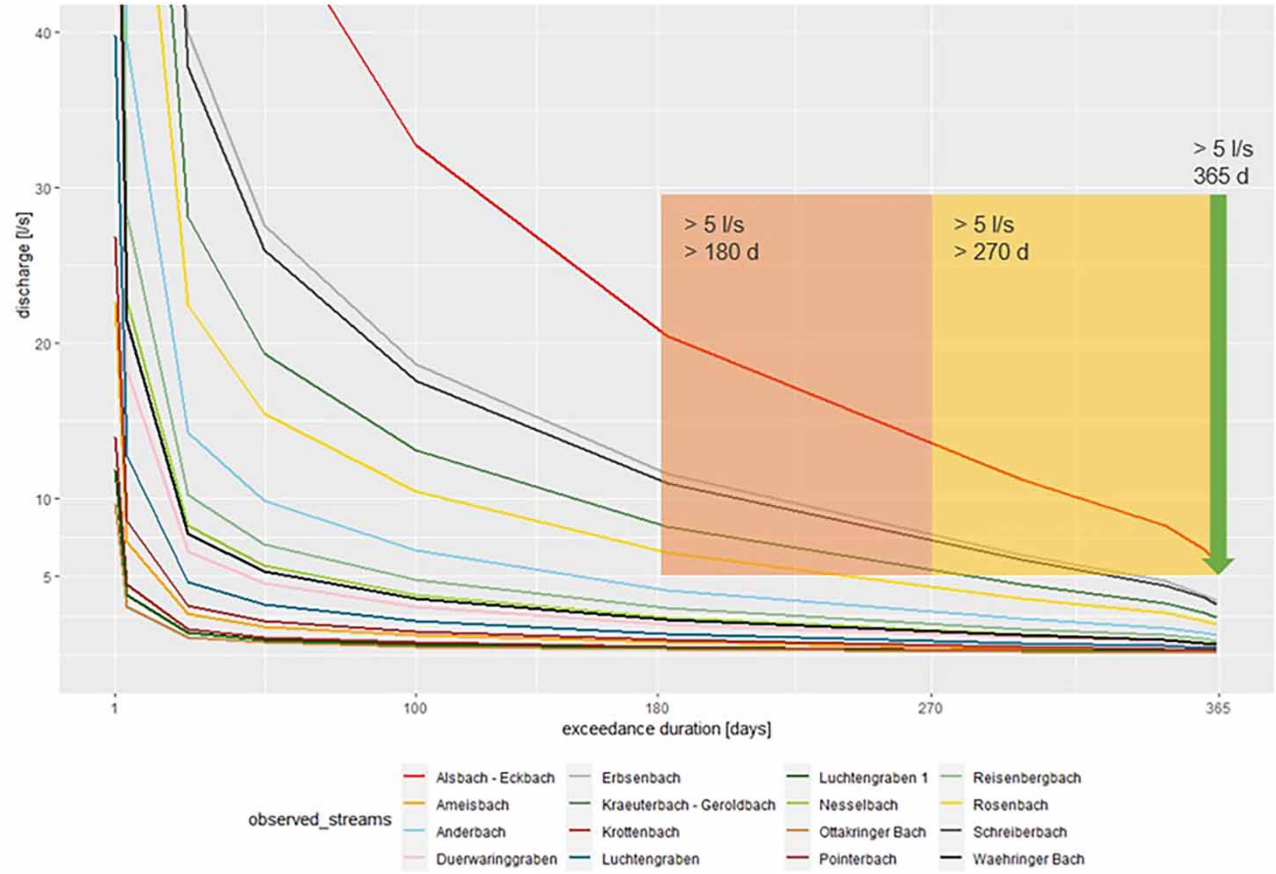


Figure 4 | Derived flow duration curves for the observed streams with the set minimum discharge of 5 l/s and boundaries for temporal characteristics representing 100, 75 and 50% of the year (own illustration). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2022.458.

The pre-assessment criterion for the (A3) lateral roof runoff area is derived from available data on roof area of buildings in Vienna. Based on the GIS analysis, the threshold received is 3,600 m^2 roof area per 100 m combined sewer, representing the upper quantile of roof area along the selected sewer lines of the case study.

The practical application of both categories is visualised in relevance tree (A) shown in Figure 5. The class numbers were chosen to be 1–5 classes according to the number of pre-assessment queries. The highest number (best class) is assigned for a high stream flow of more than 5 l/s throughout the year. The lowest number (worst class) is assigned if the stream flow is below 5 l/s or a discharge of 5 l/s is present on less than 180 days, in combination with a lateral roof runoff area below 3,600 m^2/100 m combined sewer.

3.2. Urban microclimatic sensitivity

The pre-assessment criterion for (B1) vegetation and water bodies is based on literature and the surface fractions of pervious surfaces (e.g., natural components such as vegetation) defined for open arrangements of buildings and densely built areas. The range of pervious surfaces for open arrangements of buildings is 20–60% and for densely built areas it is 10–30% (Stewart & Oke 2012). As the criterion for (B1) aims at differentiating densely built urban environments (with a greater need for adaptation measures) from open built areas, an average value of the two upper boundaries (30 and 60%) is selected as a threshold. The final value is set to the round number of 50% vegetation and water bodies of the total surface area to simplify the application of the method. If the percentage of vegetation and water bodies in an area falls below this threshold, the area is prone to overheating.

For (B2) building density, the threshold value for the pre-assessment criterion is again based on a range of building density defined in literature. Here, areas with a high building density (and which are, therefore, prone to overheating) show that building density ranges from 40 to 70% (Stewart & Oke 2012) and from 20 to 50% (Stiles *et al.* 2014). The threshold for (B2) was

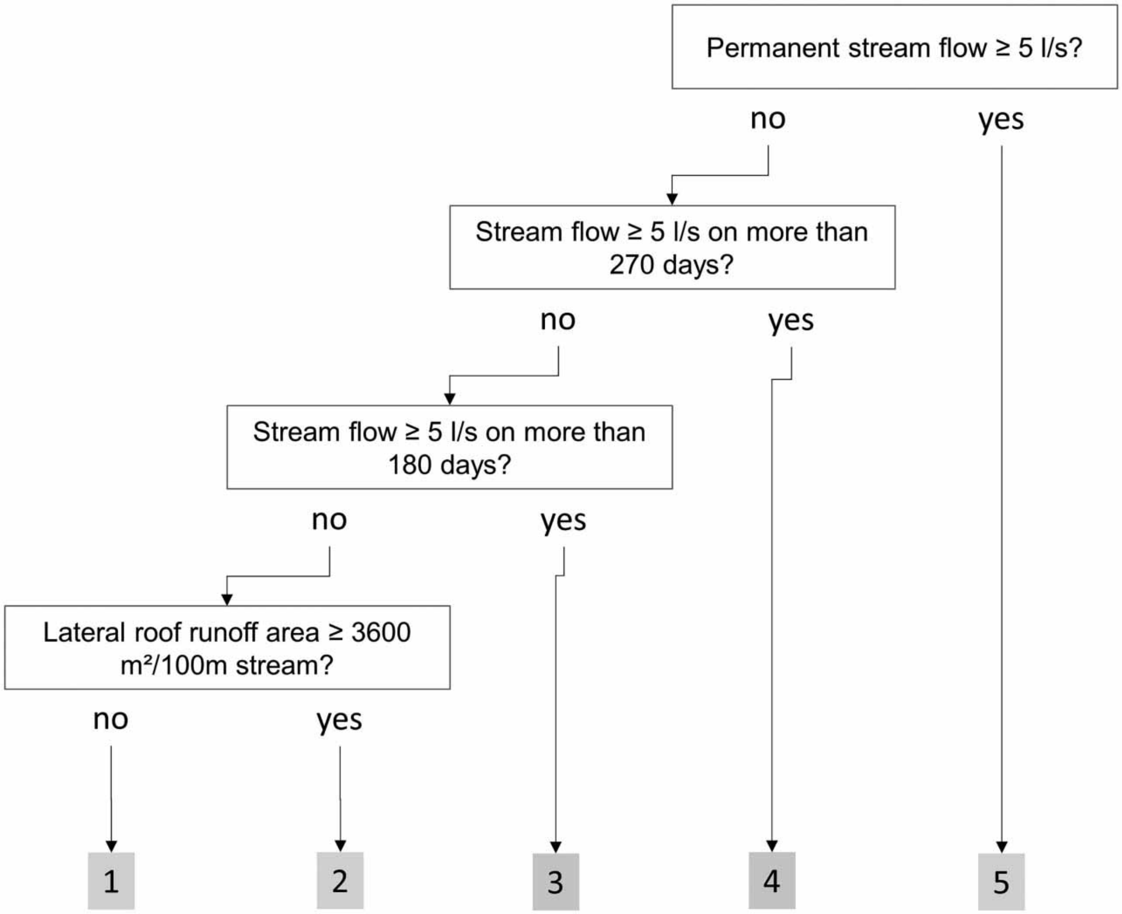


Figure 5 | Relevance tree for the pre-assessment of the (A) hydrological potential of the stream (Prenner *et al.* 2021, adapted).

derived from the two lower boundaries (20 and 40%) and their average, resulting in a threshold value of 30%. If this threshold is exceeded, the area is assumed to be exposed to overheating.

To determine the threshold value for the pre-assessment criterion (B3) population density, data on population density is needed. For Vienna, data is available for registration districts. The average population density of all Viennese districts was evaluated, resulting in a threshold of 10,000 inhabitants per km^2.

The three presented categories that are used to pre-assess the urban microclimatic sensitivity are combined in relevance tree (B) as presented in Figure 6. The class numbers range from 1 to 4, with the lowest number showing the least urban microclimatic sensitivity and the highest number the maximum urban microclimate sensitivity. The highest ranking of urban microclimate sensitivity will be reached, if the surface area fraction of vegetation and water bodies is below 50%, the surface area fraction of buildings is higher than 30% and the population density exceeds 10,000 inhabitants per km^2. If the surface area fraction of green and blue spaces within the investigated area is already beyond 50%, the microclimatic sensitivity can be considered as low and thus the need for additional NbS measures as not prior. Consequently, the first query can also be seen as a 'knock-out' criterion.

3.3. Joint evaluation

The preference matrix (Figure 7) integrates the classification of the two relevance trees. The overall suitability is pre-assessed in three classes: a high, medium or low suitability of the segment. The former comprises sites with high hydrological potential and a high microclimatic sensitivity. The latter accounts for locations with low potential and little sensitivity. Medium suitability represents areas with characteristics in between.

3.4. Case study application

3.4.1. Practicability of the method

To showcase the application of the proposed method and to prove its practicability, it is applied to two pre-assessment segments of the investigated Viennese forest streams. The required data was collected for each of the pre-assessment criteria presented in this method. Figure 8 shows the stream-related input data and its application to trace the relevance trees and to derive the related pre-assessment classes.

For case study site 1 (ID R0905), the hydrological potential is classified with 5 and the urban microclimatic sensitivity with 4. The high hydrological potential and the strong microclimatic sensitivity at the investigated site result in a high suitability of the location for practical implementation of stream water-based climate adaption measures.

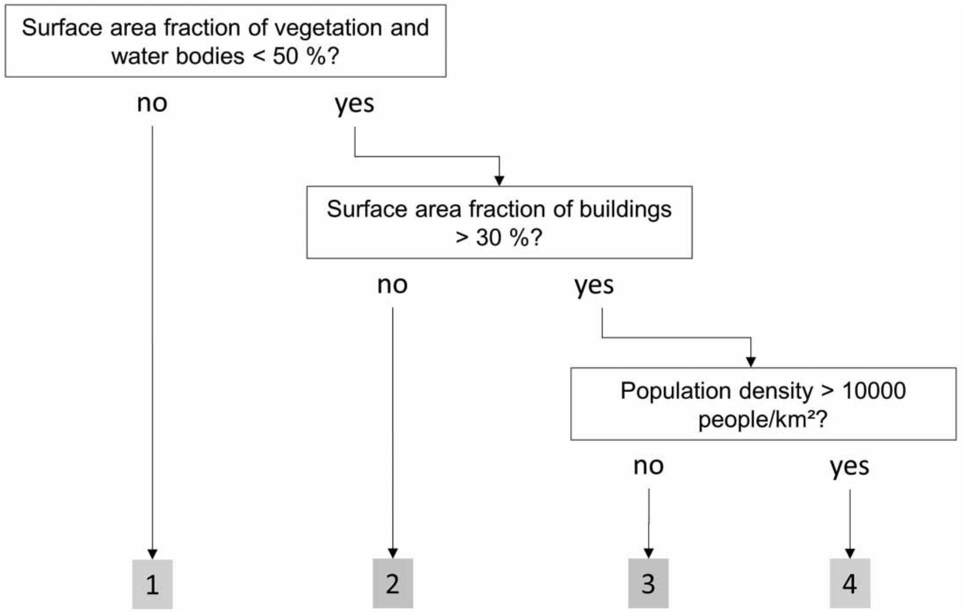


Figure 6 | Relevance tree for the pre-assessment of the (B) urban microclimatic sensitivity (Prenner *et al.* 2021, adapted).

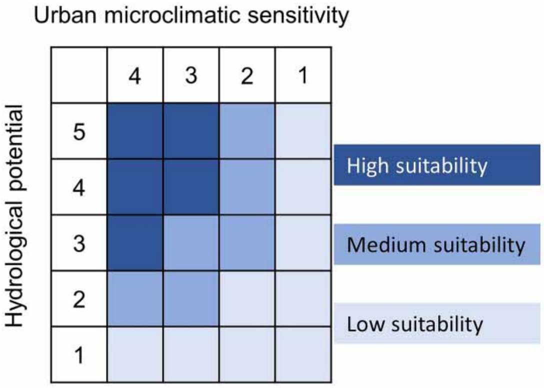


Figure 7 | Preference matrix for the pre-assessment of the overall suitability combining hydrological potential and urban microclimatic sensitivity (Prenner *et al.* 2021, adapted).

	Case study site 1	Case study site 2
Stream name	Alserbach	Währinger Bach
Segment ID	R0905	R0603
A1	> 5 l/s	> 5 l/s
A2	permanent	< 180 days
A3	4591 m²/100 m combined sewer	4356 m²/100 m combined sewer
B1	21 %	39 %
B2	48 %	32 %
B3	22501 people/km²	13486 people/km²

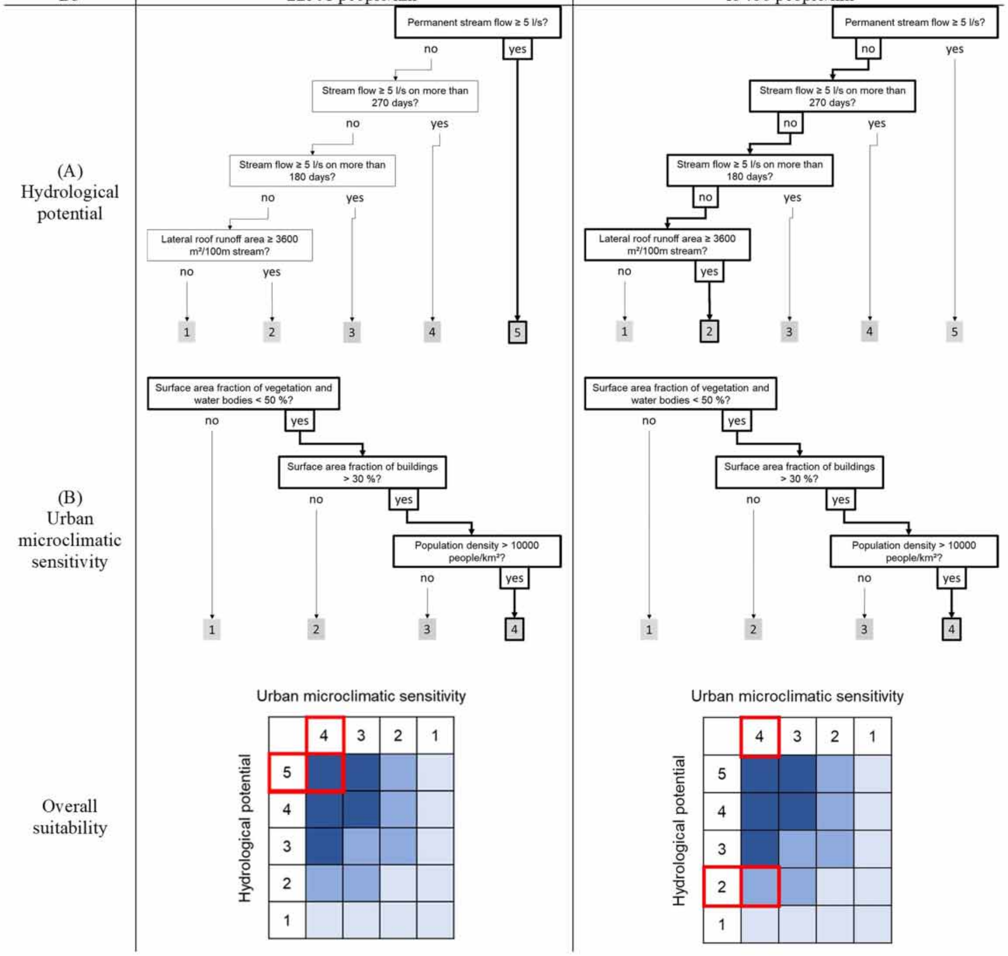


Figure 8 | Examples of two case study segments in Alserbach and Währingerbach streams with tracing of the relevance trees and preference matrices resulting in high and medium suitability (own illustration). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2022.458.

For the case study site 2 (ID R0603), the hydrological potential is graded with 2 and the urban microclimatic sensitivity with 4. The low hydrological potential is balanced out by a high urban microclimatic sensitivity, resulting in a medium overall suitability in regard to a practical implementation.

The location of the selected segments is displayed in the subsequent Figure 9.

3.4.2. Overall pre-assessment of the investigated area

Finally, applying this method to all concerned captured streams delivers results as indicated in Figure 9. Several streams contain segments with different suitability, from high to low. Only two streams show segments with a high suitability (Alserbach and Schreiberbach). Five streams contain segments with medium and low suitability (Erbsenbach, Währingerbach, Ottakringerbach, Ameisbach and Rosenbach). Nine streams solely are evaluated with overall low suitability (Nesselbach, Reisenbergbach, Krottenbach, Dürwaringgraben, Kräuterbach/Geroldbach, Luchtengraben, Luchtengraben 1, Anderbach and Pointenbach). In total, 49 segments with an individual length of 1,000 m (except at the end of the streams, where segments often are significantly shorter) have been evaluated, out of which 5 segments have a high suitability (about 11% or 4.2 km), 11 segments are pre-assessed as a medium suitability (about 24% or 9.1 km) and 33 segments have a low suitability (about 65% or 25.2 km).

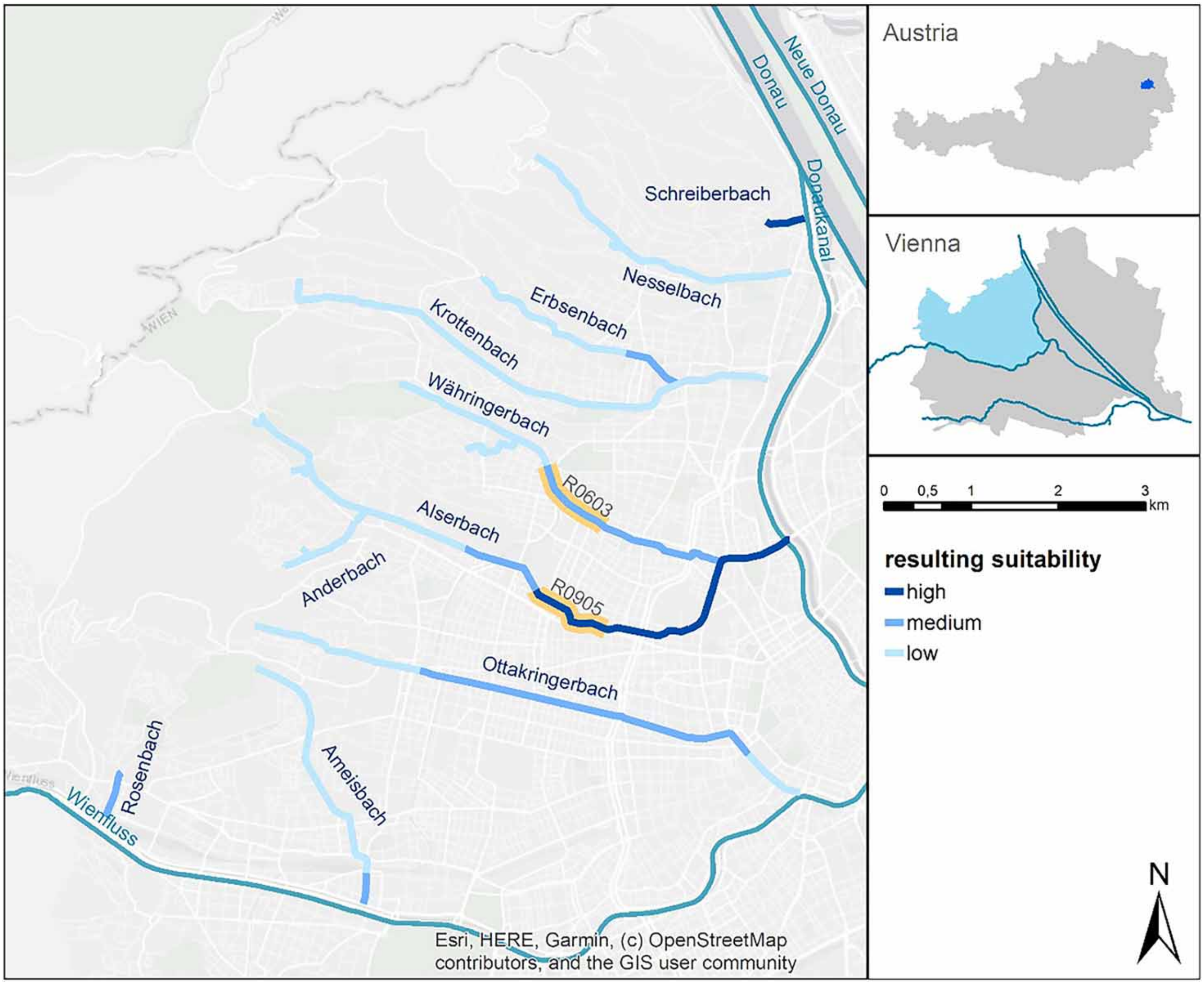


Figure 9 | Suitability pre-assessment of 1 km segments in the entire case study area (own illustration, based on Hohensinner (2021), BEV (2019), Esri (2009) and Umweltbundesamt (2020)). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2022.458.

4. DISCUSSION

4.1. Interpretation of case study results

The results displayed in Figure 9 indicate that not many of the captured streams appear suitable for decoupling for the support of climate adaptation measures. However, this does not imply that a more detailed focus on the few promising sites would be futile. To better illustrate the potential of decoupling stream flow from the combined sewer, the results of the case study in Vienna are contextualised with the application of NbS for climate change adaptation. Here, the example of decoupled stream water for street tree irrigation and the implementation of a newly developed stream bed as a novel approach for NbS are selected.

Taking a closer look at Alserbach and considering again a planning length of 100 m for NbS (see Section 2.2.1), four segments have been rated with a high suitability (dark blue in Figure 9). The Alserbach has a minimum permanent stream flow of 5 l/s. Decoupling this stream from the combined sewer would deliver at least about 158,000 m^3 of additional water for alternative purposes per year. Further, considering a rainwater runoff collection from roofs along 100 m would result, based on the roof area for case study site 1 (R0905) of around 4,600 m^2 and an annual rainfall of 651 mm, in about 3,000 m^3 rainwater annually. Comparing the water quantities from stream and roof runoff confirms the higher ranking of the former in regard to the hydrological potential made in Section 2.2.1. This available water from the decoupled stream and the collected rainwater can be applied for irrigation of urban street trees. For this, a daily water demand of 80 l (about 29 m^3 on annual average) per street tree is assumed (Wimmer 2006). Based on these figures, on an annual basis, about 5,400 trees could be supplied with water from this single stream and another 100 trees with collected rainwater of the specific section. However, it should be kept in mind that the water demand of street trees is subjected to seasonal changes and other influencing factors (Wessolek & Kluge 2021). Also, the available water resources follow seasonality and can change depending on different factors. Still, these estimated values give an idea of the scale at which the two water resources can be used.

Alternatively, a newly constructed stream bed might also be established in the urban fabric to achieve microclimatic cooling in the surroundings. Considering a permanent flow of 5 l/s in a rectangular profile with a width of 50 cm would lead to approximately 1.5 cm of water depth. Although it might seem a little exaggerated to aim at influencing local thermal conditions with water installations of this size, we use this rather rough pre-assessment to narrow down the choice of urban sites which will undergo a more detailed assessment. This subsequent work will reveal whether a stream with this amount of water could contribute to any relevant cooling effects on its surroundings (not to mention aesthetic aspects). Despite the fact that thermal effects of the water body *per se* are most likely negligible, the implementation of urban water bodies in combination with shading by trees and other greening measures could lead to favourable local changes in thermal sensation (Jacobs *et al.* 2020). The installation of water storage and recirculation facilities would further allow us to make better usage of the available water quantities.

Apart from a more sustainable and efficient use of urban waters, the topic also has an economic perspective. As already mentioned above, the decoupling of the captured stream Alserbach and the collection of related roof runoff would result in a total amount of about 160,000 m^3 of additional urban water per year. This water can replace drinking water for irrigation when not being introduced into the combined sewer. Considering current water tariffs in Vienna (1.92 EUR/m^3 for drinking water, 2.11 EUR/m^3 for wastewater (status as of December 2021) (Magistrat der Stadt Wien MA13 no date a, no date b)), the decoupling of stream water and a subsequent usage for irrigation purposes would imply potential annual savings of up to 648,000 EUR. This figure can be brought in relation to possible investment costs. It is obvious that a high complexity arises from the technical aspect of decoupling captured streams in the built environment. Although technically feasible, investment costs rise with the distance to the inflow point of the natural stream to the combined sewer. For a distance of 1,000 m to the inflow point, investment costs for an in-sewer solution, which can be assumed to be the most cost-effective solution, reach around 350,000 EUR (applying an average construction cost of 350 EUR/m (Landesanstalt für Umwelt Messungen und Naturschutz 2007)). At a first glance, this amount certainly appears very high. However, when considering the estimated savings, the investment would pay off within less than 1 year. And this does not even consider financial benefits from a possible increase in physical and mental health for citizens or an additional urban habitat (to name just two examples). These simple calculations confirm our assumption that it appears worth having a more detailed look on the identified promising locations (even if the applied water tariffs might be reduced for municipal irrigation purposes).

4.2. Strengths and weaknesses of the proposed method

The application of the proposed method to the case study sites proved its practicality. The approach supports the identification of suitable locations for the use of decoupled stream water for urban climate change adaptation measures within a city. The method is easily applicable using the presented relevance trees. Once the required data is collected, study sites can be quickly pre-assessed. Only the following (rather basic) data groups are necessary for applying the method: (1) the course of the captured streams (combined sewer) through the city, which can be assessed by using, among others, modern and historical maps of the region (Broadhead Horn & Lerner 2015). (2) Discharge data of the identified streams at the inflow point to the combined sewer might be the most difficult to obtain. Here, contacting the providers of local hydrological stations is advised. (3) The surface cover of buildings and vegetation in the investigated area is needed for the GIS analysis. Ideally, this data is provided by national open data sources and statistical offices. If this data is not available, satellite images of the area can be used alternatively for a visual analysis. Last, (4) population density should be again obtained from statistical authorities. The method has been developed with special attention to transferability. To apply this method to other cities, this paper describes how the threshold values of the different pre-assessment criteria can be derived using local data.

In addition, this method can be used in two strategic approaches: (1) proactively, when searching for promising sites in an area where climate change adaptation measures are mostly needed and where they can unfold their full potential. And (2) reactively, when a specific (assigned) site should be pre-assessed in regard to its suitability for stream supplied implementation of NbS (or just for pre-assessing its microclimatic sensitivity by only applying relevance tree B).

Nevertheless, the hydrological potential and the urban microclimatic sensitivity are both complex systems with numerous influencing factors. To maintain the practicability of the method, a selection of rather simple but expressive pre-assessment categories and criteria was made. This results in a simplification, possibly neglecting other influencing factors. This primarily concerns the pre-assessment of the urban microclimatic sensitivity. For pre-assessing the urban microclimatic sensitivity, factors like the cardinal direction of segments along the combined sewer, street canyons as well as building volumes and dynamic influences like wind direction and speed were neglected. Although including these factors in the method would lead to more significant results, the application of the method would no longer be easy to apply due to more sophisticated data requirements. The simplification in the method further concerns the definition of thresholds for the pre-assessment criteria implying a rather a rigid system using yes/no questions. This does not allow a differentiation of values. However, this issue is accepted as reasonable to maintain the simplicity of the method.

Still, the data quality on stream flow characteristics can vary drastically and, as shown for the case study in Vienna, values may need to be estimated based on reference catchments. Therefore, the values derived from the pre-assessment might be over- or underestimations. Furthermore, the low quality of the data does not allow a differentiation of streams with a very low discharge due to uncertainties arising from accuracy of models, calculations or measurements.

Finally, the chosen segment length of 1,000 m as pre-assessment unit might unify local differences in the urban fabric. This especially affects the lateral roof runoff area and the categories of the urban microclimatic sensitivity as they may vary highly within a certain area. This segment length might, therefore, smooth out local cooling effects through parks or thermal hotspots. However, the segment length can be adjusted if uncertainties arise during the application, or the research goal calls for a more detailed analysis (analysis of a whole city versus single stream only).

Summarising the above, this method allows a pre-assessment of suitable locations to use decoupled stream water for urban climate change adaptation with NbS. However, the results obtained from this method application must not be understood as a final evaluation. With the developed method, locations within a city can be prioritised based on the hydrological potential and the urban microclimatic sensitivity. The results give an overview of the current situation and act as a decision support to find most suitable sites for using decoupled streams as a water resource for NbS such as new stream beds or as irrigation water for streets, trees or parks. In a subsequent step, it is recommended to apply a more detailed analysis to the identified locations to further evaluate implementation options. These investigations will then also include water quality issues as well as possible solutions to convey decoupled stream water to the intended location (separated (clean water) systems in the form of in-sewer pipe installations, ex-sewer networks or even open channels).

5. CONCLUSIONS

NbS can provide a valuable contribution to counteract climate change accelerated urban heat island effects. However, their application implies two critical concerns: (1) covering the water demand of specific solutions and (2) their installation on an urban location of high climate adaptation demand.

In regard to the first aspect, this article investigates the potential of captured streams to serve as an additional source of water. The work was based on a selected area in the city of Vienna, which used to be rich in natural streams. Today, however, most of them are an integrated part of the local wastewater system, which makes direct water access (daylighting) impossible and thus technical solutions for decoupling necessary. Furthermore, the lack of related flow data complicates the quantification of the possibly available resources. Investigations revealed that the majority of the considered streams do not appear promising for decoupling mainly due to their low discharge characteristics. Nevertheless, some of them show an interesting hydrological potential for being recovered. Compared to common rainwater supply for NbS, decoupled stream water can pose a more steady and reliable water resource. In addition, the available quantities of water would incorporate a double financial benefit, on the one hand saving drinking water for irrigation purposes and on the other hand treatment efforts in the local wastewater treatment plant. These aspects could well balance the technical efforts for decoupling resulting in acceptable payback periods. In addition, this solution would contribute to a more sustainable urban water use by closing natural local water circles.

In regard to the second aspect, this article introduces a simple-to-apply pre-assessment procedure to identify urban sites of high microclimatic sensitivity (hot-spots). It proved its practicability and significance in a broad case study application. The approach builds on rather easily available input data. In our suggested context, it is combined with an evaluation of the hydrological perspective of a concerned stream. However, the set-up of the pre-assessment approach also allows a sole and independent evaluation of the climatic perspective. Consequently, the suggested concept can support strategic city planning beyond the rather narrow scope of our work. Furthermore, the low (quantitative) requirements on the input data facilitate a broad applicability in other cities.

Concluding, investigations reveal that captured streams can serve as an additional water source to support a sustainable and nature-based climate adaptation of urban areas. The suggested approach for suitability pre-assessment helps to identify those locations most promising for subsequent and more in-depth feasibility studies. The strategic application of nature-based solutions in combination with an efficient use of water resources are core aspects in regard to urban climate adaptation measures. This article will support related activities by opening up a new perspective.

ADDITIONAL INFORMATION

The presented work builds on the authors' contribution to the 15th International Conference on Urban Drainage (ICUD) quoted as Prenner *et al.* (2021) in the References section. It was carried out in the course of the project 'Local reactivation of Viennese urban streams supported by nature-based stormwater management (ProBACH)' supported by the 'Klima- und Energiefonds' of the Austrian Federal Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology under grant no. 884785. Open access funding was provided by the University of Natural Resources and Life Sciences, Vienna (BOKU).

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 21 December 2021; accepted in revised form 6 March 2022. Available online 18 March 2022