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Suitability indices for assessing functional quality of urban surface water

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ABSTRACT

Urban surface waters are used in many different ways. With increasing demand for human use functions, improved insight is required into the functional quality of these waters. A method to assess this functional quality in a systematic way and for a wide variety of use functions is not available. We propose to use suitability indices (SIs) for assessing the suitability of urban water bodies for a variety of specific human uses. This study provides a new protocol for this, building on the water quality index and ecosystem services approaches in literature, by extending traditional water quality parameters with other characteristics of water bodies that determine suitability for a specific use function. By assessing suitability instead of traditional water quality, the functional quality of a water body for all kinds of uses can be determined in a consistent way. The protocol was demonstrated to be effective in developing SIs for three specific urban water use functions, namely: thermal energy extraction, transportation of goods and primary contact recreation. Application of the suitability indices in a case study in the city of Amsterdam, The Netherlands, resulted in spatially explicit information about suitability of surface waters for the three selected use functions. Sub-scores per parameter showed which characteristics of the urban water bodies should be changed to improve the suitability for these three functions. In this way, the SI approach for assessment of the functional quality of urban surface waters can be used to support function-oriented planning, design and maintenance of urban surface water systems.

1. Introduction

Urban surface water is used for a broad range of human use functions such as water extractions, energy, recreation, water quality and quantity regulation, nutrition provision, floating buildings and transportation [15,29,40]. Research in the cities of Toronto and Amsterdam demonstrated that demand for most use functions is expected to increase towards 2040 [40]. With growing ambitions to use urban surface water, insight is required into the actual and required *functional quality* of urban waters to support planning, design and maintenance of these water bodies. Functional quality is defined as the suitability of a water body for specific human use functions. A large portion of urban surface waters consists of highly modified or manmade water bodies such as canals, ponds and channelized rivers. Koschorreck et al. [20] note that manmade waters are often neglected in water quality research and policy. This low representation of highly modified or manmade waters is likely related to the ecological focus of common water quality evaluation concepts.

A widely applied approach to evaluate water quality is the water quality index (WQI). A WQI describes water quality with a single index value. The basic concept is that a selection of relevant parameters is rated and the scores are integrated into a composite index. Advantages of the use of WQIs are that they are simple [5,23,33], requiring a modest amount of input data, and understandable for a broad audience of non-specialists [3]. A composite index is also considered to provide a more accurate reflection of water quality compared to a review of single water quality parameters [28]. However, existing WQIs cannot be used to assess the functional quality of urban surface water.

Firstly, WQIs typically classify water quality as grade of pollution or purity [23]. This relates to the emphasis of the WQIs, even those designed for urban water (e.g. [1]), on ecological water quality and suitability for drinking or irrigation. For many relevant urban water

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Abbreviations: CEMT, European Conference of Ministers of Transport; HEC, heat extraction capacity; HU, hydro unit (spatial unit); n.a., not applicable; SI, suitability index; TEE, thermal energy extraction; WQI, water quality index.

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uses, like thermal energy extraction, transportation and swimming, assessing traditional water quality parameters like pollution is not sufficient to determine suitability of the water for these use functions. Other characteristics of the water body such as temperature or depth are also relevant.

Secondly, many WQIs target multiple use functions [35]. In the multi-target WQIs, water quality is related to the number of uses for which water quality is sufficient. However, we contend that a specific index per use is required, in line with Lumb et al. [23] finding that the suitability of water depends on its intended use ('fit for purpose'). Some WQIs do define water quality for one specific use function such as drinking water [26] or recreation [3,27]. These provide a good starting point for assessing suitability of urban water for these uses. However, again, WQIs for recreation only consider traditional water quality parameters, neglecting indicators for physical safety. These WQIs cannot be used to assess the suitability of urban surface waters like canals and rivers.

The aim of this study is to provide a methodology for the assessment of the functional quality of urban surface water and to demonstrate its applicability for a selection of use functions for surface waters in the city of Amsterdam. We propose the use of suitability indices (SIs) to assess functional quality of urban surface water. Suitability indices are inspired by the basic model of WQIs with sub-scores for relevant parameters that are integrated into a composite score. However, the SIs include parameters that determine suitability for specific urban use functions beyond traditional water quality parameters. The purpose of the SIs is to enable researchers and practitioners to identify opportunities for water use and to assess the impact of changes in water systems on their functional quality.

2. Methods

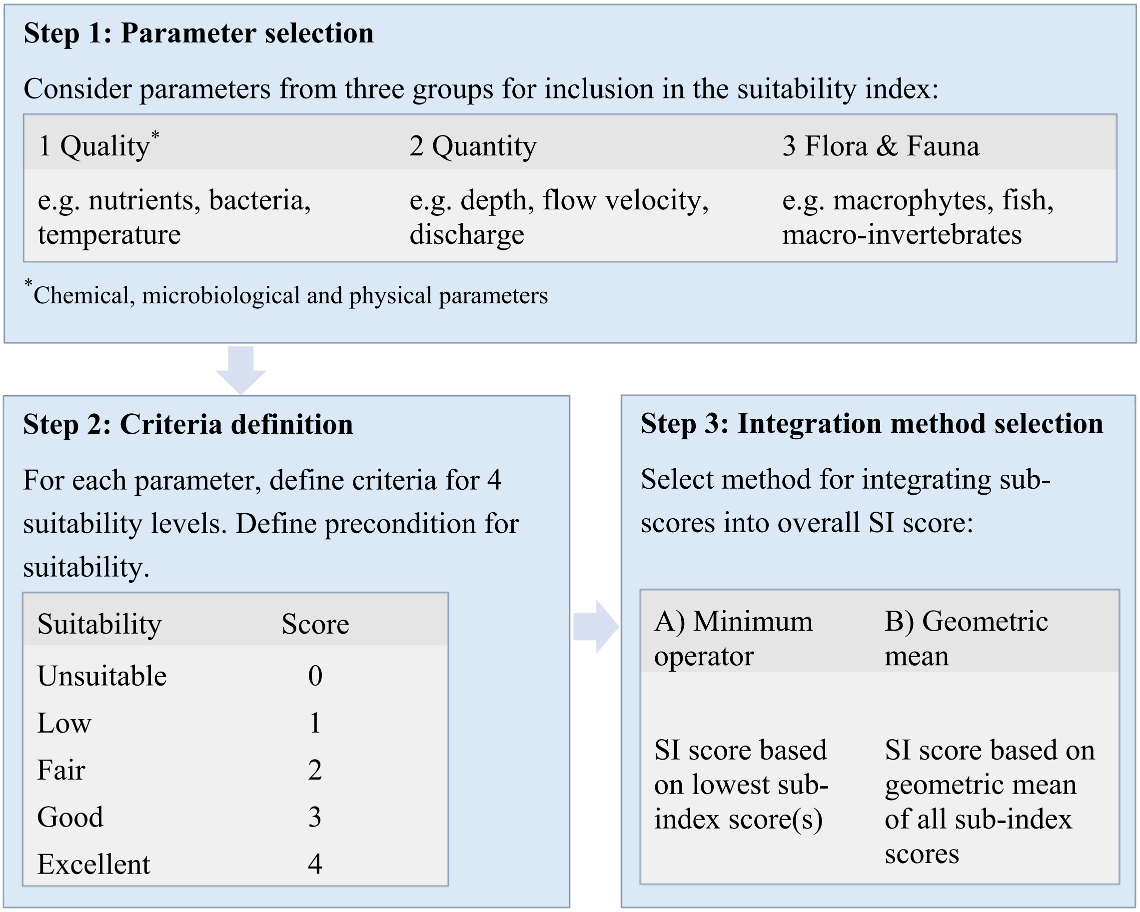
2.1. Generic protocol for SI development

Most use functions of urban surface water can be labelled as ecosystem services. Therefore, we propose a protocol for SI development building on literature on WQIs and ecosystem services. Literature on WQIs provides the generic model for SI development, while aquatic ecosystem services literature provides insight into the type of parameters that should be considered for inclusion into the SIs.

A SI provides insight into the suitability of a water body for a single human use function, based on the water body's characteristics. A SI consists of a set of parameters relevant for the suitability of the water, each rated by a sub-index score. The sub-index scores are integrated into the composite SI score. The development of a SI follows a three-step approach, similar to the main steps in WQI development (Fig. 1). It starts by selecting the parameters. Next, criteria for the sub-scores are defined per parameter. Finally, the method of integration of the sub-scores into the composite SI index is defined.

2.1.1. Step 1: Parameter selection

Parameters are selected based on the characteristics of a surface water body that are significantly limiting suitability for a specific use function from the perspective of the user. The SI should clarify suitability of the water for a single use function, before prioritizing between different use functions. Hence, limitations based on protection of other use functions are not taken into account. Selection of the parameters is based on literature and expert consultation, following the common approach for selection of parameters for WQIs [23,33]. Consulted



Step 1: Parameter selection

Consider parameters from three groups for inclusion in the suitability index:

1 Quality*	2 Quantity	3 Flora & Fauna
e.g. nutrients, bacteria, temperature	e.g. depth, flow velocity, discharge	e.g. macrophytes, fish, macro-invertebrates

*Chemical, microbiological and physical parameters

Step 2: Criteria definition

For each parameter, define criteria for 4 suitability levels. Define precondition for suitability.

Suitability	Score
Unsuitable	0
Low	1
Fair	2
Good	3
Excellent	4

Step 3: Integration method selection

Select method for integrating sub-scores into overall SI score:

A) Minimum operator	B) Geometric mean
SI score based on lowest sub-index score(s)	SI score based on geometric mean of all sub-index scores

Fig. 1. Protocol for the development of an SI for a specific human use function. A SI consists of a set of parameters that are each rated by a sub-index score; sub-index scores are integrated into the overall SI score.

experts must include users of the use function. Parameters of the SI should be specific and measurable, and data collection should be feasible. The selected parameters should therefore be defined as specific indicators. E.g. 'pathogens' is not specific, as opposed to the indicator '*E. coli*'. In order to be measurable, the unit in which a parameter is analysed should be defined. In the selection process, we consider three parameter types: Water quality, Water quantity and Flora and Fauna (Fig. 1).

According to Brauman et al. [6] and Hallouin et al. [16], users of hydrological ecosystem services have requirements related to the hydrological characteristics ('attributes') *quantity, quality, location* and *timing*. We include water *quality* characteristics in the SI framework as chemical, microbiological or physical water quality parameters such as nutrients, bacteria and temperature. Water *quantity* characteristics refer to parameters like water depth and discharge. *Location* and *timing* relate to the spatial and temporal connection between demand and potential supply. These aspects are not characteristics of the water system and are therefore not considered as parameters for a SI. Timing and location of intended use of the use functions should however be taken into account when defining criteria for sub-scores and preparing the dataset for application of a SI. Hallouin et al. [16] describe that some aquatic ecosystem services also depend on ecological characteristics related to flora and fauna. We include microorganisms in the parameter group 'Water quality' because they are commonly considered variables of water quality. Larger organisms are included in the 'Flora and Fauna' group.

2.1.2. Step 2: Criteria definition for SI scores and sub-scores

We define four classes for the sub-index scores per parameter and the overall SI score, ranging from low suitability (score = 1) to excellent suitability (score = 4). This approach is in line with the rationale behind almost all WQIs, where scores are positively related to water quality and the number of water quality classes usually varies between four and six [5,23]. Suitability scores relate to the level of potential supply, or application, of the use function:

- 'Low suitability' (score = 1): potential supply of the use function is very limited and/or high risk to the user is associated with use of the use function.
- 'Fair suitability' (score = 2): common small-scale application is possible, and/or some risk related to use.
- 'Good suitability' (score = 3): common large-scale supply possible and/or low risk
- 'Excellent suitability' (score = 4): more than common large-scale application is possible and/or risk for the user is absent or very low.

If there are conditions in which it is physically impossible to use the water for the specific use function, a precondition is defined for the parameter(s) that impede the use. If the precondition is not met, the water is considered unsuitable and the assigned SI score is 0. This approach resembles the 'special procedure' that is applied in the NSFWQI to key parameters; if their values exceed a certain threshold, the WQI is automatically rated 0 [8].

Parameters are scored, with a sub-score, based on quantified criteria. Criteria are based on literature, guidelines and/or expert consultation. The context of application of the SI is taken into account when defining criteria. For example, in countries with higher pollutant levels, users may accept a higher risk than in countries with higher water quality [3]. The criteria are also time and location specific. For example: in temperate regions, primary contact recreation is almost entirely taking place during daytime in the summer season, and swimming in large water bodies takes place close to the shore. Therefore, the sub-scores should rate daytime and summer conditions close to the shore.

2.1.3. Step 3: Integration method selection

If the precondition, if applicable, is met, sub-scores are integrated into the composite SI. Two integration methods are proposed: the minimum operator and the geometric mean. In the minimum operator approach, the lowest sub-score is also the SI score: $\mathrm{SI}=Min\left(S_{i=1}^{n}\right)$, where S_i is the sub-index score of the i-th parameter. This method is applied when each parameter alone strongly limits suitability and unfavourable conditions of one parameter cannot be counteracted by others. This minimum operator approach was proposed by Smith [36] and is used in WQIs for primary contact recreation by Azevedo Lopes et al. [3] and Nagels et al. [27]. The advantage of this method is that risks associated with one parameter will not be masked by a good sub-score for another parameter. The geometric mean of the sub-indices is calculated as: $SI = \left(\prod_{i=1}^{n} Si\right)^{1/n}$. This integration method is applied if a low score for one parameter can be counteracted to some extent by a high score for another. Sub-scores are not weighted since all parameters are significantly limiting suitability and differentiation between their importance is therefore hard. The geometric mean was proposed as integration method by Brown et al. [7] to solve the lack of sensitivity in arithmetic averaging in the NSFWQI, and is also applied by e.g. Bhargave [4] for a drinking water WQI.

2.2. Developing SIs for three use functions

The SIs in this paper are developed for the context of urban water in the Netherlands. They are potentially also applicable to other delta cities in north-western Europe with highly modified and manmade urban surface water systems. Following the protocol as described in Section 2.1, we develop SIs for three urban surface water use functions: thermal energy extraction (TEE), transportation of goods and primary contact recreation. These are the use functions for which the most prominent increase in demand in expected, as shown in a study in Amsterdam, The Netherlands and Toronto, Canada [40]. For TEE, we focus on heating because in The Netherlands there is a net heat demand for heating and hot tap water, and the national potential of TEE from surface water can meet a large share of the heat demand of The Netherlands [21]. For recreation, we focus on swimming because swimming in urban surface water is rapidly gaining popularity in Dutch cities, also outside designated bathing waters. Transportation of goods is defined as cargo transportation, since the expected increasing demand for urban water transportation is mainly related to transport of goods [40].

3. Application of three SIs for the city of Amsterdam

The three SIs are applied for the city of Amsterdam, The Netherlands, to demonstrate their applicability and added value of the SIs compared to existing information about functional quality of urban water.

3.1. Study area

Amsterdam is a water-rich city where increasing pressure on public spaces and resources results in the need to better plan surface water use [14]. The city lies in a low-lying delta area with highly modified, managed and manmade waters. Water enters the city from the North, East and South through canalized rivers and large canals. Water is discharged through a large canal into the North Sea, 25 km west of Amsterdam but during high tide, the flow direction reverses (Fig. 2). A fine network of connected smaller canals covers all parts of the city. The surface water system also contains ponds in parks and deep lakes, relics of sand excavation. Water levels are managed, and in most of the water bodies that are included in the analysis, water levels are fixed. The surface water system is currently being used for a broad range of human uses: fishing for consumption, water extractions for several non-drinking purposes, extraction of biomass, thermal energy extraction, water quality and quantity regulation, many forms of recreation including swimming and sport fishing, transportation of goods and persons, accommodating floating buildings like houseboats, and the canal system is

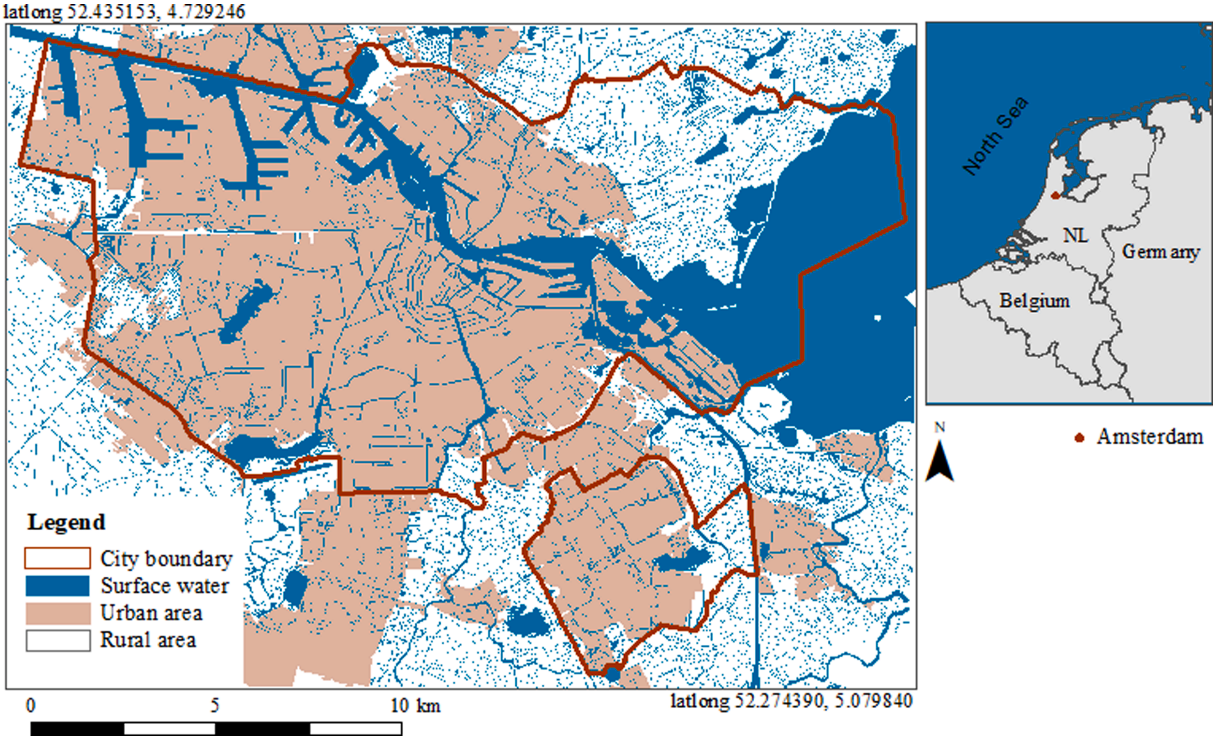


Fig. 2. The surface water system of Amsterdam, The Netherlands (NL). City boundary indicates the municipal administrative boundary.

part of local and world cultural heritage [40].

3.2. Data

The local water authority provided a map in which the entire surface water system is divided into Hydro Units (HUs), spatial units with a length of approximately 50–300 m and varying width. A HU represents a section in a waterway with unique properties that the waterway must meet such as bottom width, water level and slope. Most of the 8,318 HUs in urban areas within the municipal boundaries of Amsterdam cover ditches, ponds and the largest lakes and national waterways that cross the city. We analyse suitability for human uses per HU. If data is available for larger spatial units than the HUs, HUs are merged. Suitability is determined using data for a period of 4 years to take into account variability between years. Data for the period 2016 to 2019 are used as this is the most recent period for which full-year data were available at time of the analysis. For parameters with temporal variability, we use the 95th or 5th percentile of the values at a location to ensure that the suitability score represents the minimum suitability that is valid in 95% of the time.

Data are obtained from the local water management authority 'Waterschap Amstel, Gooi en Vecht' (AGV), that is responsible for most of the local surface water, and from the municipality of Amsterdam (Table 1). Their datasets exclude the rural area in the north-eastern part of the municipalities' territories and the large national waterways that cross the city; these waters are managed by other water authorities. The datasets lack sufficient data for ponds in parks and for many small ditches in the polder areas of the city. These were therefore excluded from the analysis. If available datasets lack data for parameters that are static in time, additional data are collected by field measurements. Details about the used data are provided in Section 4.3.

Table 1
The datasets from water management authority AGV and the municipality of Amsterdam that are used for application of the suitability indices in Amsterdam. The datasets are not publicly published.

Dataset, source	Details
Water quality, AGV	Water quality data at point locations based on field and laboratory measurements in samples from 0.3 m depth. Samples are taken at least monthly during daytime, at some locations only during summer months. Due to the known high spatial variability of some parameters, water quality data are not assigned to HUs but processed for point locations unless otherwise stated in Section 4.3.
Discharge, AGV	Discharge data are generated by a hydraulic SOBEK model (https://download.deltares.nl/en/download/sobek/) for line segments in the centre axis of waterways. Data from the line segments are assigned to the HUs that they cross. The dataset contains average values and percentiles for each line segment based on discharge at every 15 min in the period June to August 2016–2019.
Navigation, municipality	Dimensions of waterways in transects between bridges. Data are based on field measurements between 2004 and 2016 and are still valid. Depth and air draft are expressed in a unit that requires correction for water level. This is done with water level data from AGV. Movable bridges are identified using the information from the national navigation map (vaarweginformatie.nl) and open water is identified using Google Maps Satellite images (maps.google.nl).

4. Results

4.1. Suitability indices for thermal energy extraction, transport and recreation

4.1.1. Suitability index for thermal energy extraction (SI TEE)

Thermal energy extraction (TEE) from surface water can be used for cooling or heating of buildings with a water-to-water heat pump. SI TEE is targeted at heat extraction. The current common practice in The Netherlands is to extract heat during the three warmest months, store warm water in the subsurface – in an aquifer thermal energy system -

and use it in winter. Therefore, SI TEE is designed for heat extraction during the warmest summer months.

Step 1: Parameter selection

Suitability for TEE primarily depends on the heat extraction capacity (HEC) of the water. We selected three parameters that are positively correlated with HEC: width, discharge and water temperature (Table 2). Studies on using surface water for heat extraction show the importance of water surface area [19,21]. Larger surface areas receive more solar radiation. As Dutch urban surface water consists mainly of canals and channelized rivers, we use width of the water body as indicator for surface area. Discharge influences replenishment and therefore effective intake volume rates. TEE requires sufficient water depth to accommodate intake and discharge pipes. Therefore, a minimum water depth is set as precondition.

Consulted practitioners state that chemical or microbiological water quality and the presence of flora and fauna, like shellfish or algae, influence the materials that can be used in equipment and the maintenance effort. However, this aspect is of minor influence and is not considered to significantly affect suitability of the water body for TEE. These parameter types are therefore not included in SI TEE.

Steps 2 and 3: Criteria definition for scores and integration

We define four levels of suitability related to the potential HEC (HEC calculated with the formula in [21]:

- Excellent (SI score = 4): TEE capacity of >40,000 GJ yr^{-1}
- Good (SI score = 3): TEE capacity of 4,000–40,000 GJ yr^{-1}
- Fair (SI score = 2): TEE capacity of 400–4,000 GJ yr^{-1}
- Low (SI score = 1): TEE capacity of <400 GJ yr^{-1}

These capacities relate to the typical heat demand of <10 to> 1,000 houses, based on a typical heat demand of 40 GJ yr^{-1} per house [25]. Relating SI scores to heat demand is illustrative and should be regarded as indicative.

Consulted practitioners state that water bodies are unsuitable for TEE if depth is <0.2 to 0.5 m. A depth of 0.5 m allows space for the pipes, a filter, some space above and below the pipes and allows for minor water level fluctuations. A minimum depth of 0.5 m is therefore set as precondition for TEE (Table 2).

Scoring criteria for width and discharge are derived by a rough estimate of the required values to reach the heat extraction capacity levels related to SI-classes 1–4. We start by estimating the required width and discharge to achieve the HEC value that relates to SI class 4. A width of approximately ≥100 m and discharge of ≥0.3 $m^3 s^{-1}$ is required. Each SI class lower relates to ten times lower HEC. A reduction of width with factor 10 results in a reduction of the HEC that relates to one suitability class lower. Therefore, width is considered as excellent (score = 4) if ≥100 m, good (score = 3) if 10 to 100 m, fair (score = 2) if 1–10 m, low (score = 1) if <1 m. A reduction of discharge with factor 10 results in a reduction of the extraction capacity that relates to one suitability class lower. Therefore, discharge is considered excellent (score = 4) if >0.3 $m^3 s^{-1}$, good (score = 3) if 0.03–0.3 $m^3 s^{-1}$, fair (score = 2) if 0.003–0.03 $m^3 s^{-1}$, and low (score = 1) if <0.003 $m^3 s^{-1}$. More details are provided in Supplementary material Text S1. Scoring water temperature is not straightforward since there is no direct relationship with HEC, which is calculated based on the temperature difference that results from heat extraction. In feasibility studies, a water temperature above 15 °C is considered ideal for heat extraction during summer months [21,34]. We assign the score of 4 to summer temperatures of ≥15 °C. The sub-score is reduced with one point at every 5 °C of temperature decrease. This is based on a rough estimate of the impact of lower water temperature on the heat transfer coefficient and on the maximum possible temperature change as a result of extraction.

If the precondition for water depth is met, the SI score is determined by integrating the sub-scores for width, discharge and temperature. A low value for one parameter can be counteracted by a high value for another parameter to some extent. Therefore, the integration method is the geometric mean of the sub-scores.

4.1.2. *Suitability index for transportation of goods (SI Transport)*

Step 1: Parameter selection

Studies on success factors for water transportation of freight to and within the city show that suitability for transportation depends on waterway dimensions. Three parameters that describe these dimensions are selected for the SI: width, depth and air draft (Table 3). Width, depth and air draft limit ship size [24]; the larger the waterway dimensions, the more vessel types can be used in a waterway. Wider waterways may also be less prone to congestion, if ships can pass each other, and thus increase reliability of water transportation. Maes et al. [24] and Van Duin et al. [41,42] emphasize that reliability of service is an important factor for water transportation to compete with road transportation. Absolute minimum dimensions are hard to define, as some urban freight vessels are especially designed or adapted for local urban circumstances [18,24]. However, a minimum level of depth is required for navigation. Depth is therefore used as precondition parameter and as parameter that will receive a sub-score. Air draft refers to the height between the water table and a structure above the water, usually a bridge. In case of movable bridges, air draft is often unlimited when the bridge is opened, depending on the type of opening system.

Besides waterway dimensions, connectivity or network density is mentioned in literature as important success factor for urban transportation [18,24,39]. As connectivity is more a characteristic of an entire water network rather than of a single water body, it is not selected as a parameter. Maes et al. [24] mention ice as a limiting factor. Consulted practitioners explain that in Amsterdam, the ice itself is not limiting as the vessels can break it. Occasional boating restrictions are aimed at protection of the ice surface for ice-skaters or to prevent damage to objects like houseboats by ice sheets that are pushed aside by ships. Since the trade-offs with other use functions are not included in the SI, ice thickness is not selected as parameter. Practitioners also state that water quality, and flora and fauna do not limit transportation. Cargo ships have engines strong enough to handle water plants in the ship's propeller.

Table 2

SI TEE. Criteria for sub-scores for the parameters that determine suitability for heat extraction. All criteria apply to the three warmest months of the year. Chem: chemical. Microbio: microbiological. n.a.: not applicable.

SI TEE							
Suitability	Score	Parameters					
		Quantity			Quality		Flora & Fauna
		Max. depth [m]	Width [m]	Discharge [$m^3 s^{-1}$]	Physical Temper-ature [°C]	Chem. & Microbio .	
Precondition		≥ 0.5	n.a.	n.a.	n.a.	n.a.	n.a.
Excellent	4	n.a.	≥100	≥0.3	≥15		
Good	3		10-<100	0.03-<0.3	10-<15		
Fair	2		1-<10	0.003-<0.03	5-<10		
Low	1		<1	<0.003	<5		

Table 3
SI Transport. Criteria for sub-scores for the parameters that determine suitability for urban freight transportation. n.a.: not applicable.

SI Transport						
Suitability	Score	Parameters				
		Quantity			Quality	Flora & Fauna
		Width [m]	Depth [m]	Air draft [m]		
Precondition		n.a.	≥0.35	n.a.	n.a.	n.a.
Excellent	4	≥45.6	≥6.3	≥9.1[a]		
Good	3	20.2–<45.6	3.1–<6.3	4.0–<9.1		
Fair	2	8.4–<20.2	1.4–<3.1	1.7–<4.0		
Low	1	<8.4	0.35–<1.4	<1.7		

[a] This also applies to open water or movable bridges without air draft constraints.

Steps 2 and 3: Criteria definition for scores and integration

SI scores relate to the vessel types that can use a waterway, based on the required waterway dimensions for these vessel types:

- Excellent (SI score = 4): Large Rhine vessel with maximum beam of 11.4 m, draft 4.5 m and air draft 9.1 m as described in CEMT class Va [11]. This is the largest vessels that we expect to be used for urban freight transport.
- Good (SI score = 3): Barge with maximum beam of 5.05 m, draft 2.2 m and air draft 4 m. This is the smallest inland vessel type in the CEMT classification [11].
- Fair (SI-score = 2): Smallest operational vessels for urban freight transport that are described in literature [18,24], with a beam of 4.2 m, draft 1.1 m and air draft 1.65 m.
- Low (SI score = 1) refers to the situation that the requirements for class 'fair 'are not met.

A minimum water level of 0.35 m is set as precondition for depth (Table 3). This is defined after consultation with the builder of the smallest vessel, especially designed for urban freight transport, that we identified. The sub-scores for depth, width and air draft relate to the required waterway dimensions for different ships based on national and international guidelines. For suitability scores 4 and 3, criteria are based on the dimensions for a 'normal profile' as defined in the guidelines for waterways by the Dutch national water authority Rijkswaterstaat [31]. The minimum depth for these suitability classes is calculated by multiplying draft of the normative vessel with a factor 1.4; for width, the ship beam is multiplied by 2. Required waterway dimensions for suitability score 2 are based on 'single lane or tight profile' in the same guidelines. The minimum depth criterion is calculated by multiplying ship draft with a factor 1.3; for width, the ship beam is multiplied by 2. Low suitability (score = 1) refers to the situation that the requirements for class 'fair 'are not met. Supplementary material Text S2 provides more details about the sub-score criteria. The minimum operator approach is used for integration of the sub-scores because unsuitable conditions for one parameter cannot be counteracted by another.

4.1.3. Suitability index for primary contact recreation (SI Recreation)

Step 1: Parameters selection

SI Recreation is targeted at swimming in freshwater by adults. Studies describing WQIs for primary contact recreation show that swimmers' safety is the most important aspect that determines suitability for swimming. Safety is limited by risk of infection by pathogens, skin and eye irritation, and the risk of limited visibility hiding submerged dangers [3,27]. We use three parameters from the WQI's by Azevedo Lopes et al. [2,3] and Nagels et al. [27] that relate to swimmers' health safety: *Escherichia coli* bacteria (*E. coli)*, pH and clarity (Table 4). *E.coli* is the common indicator for faecal pollution in freshwater in Europe. For clarity, secchi disk visibility is chosen as indicator because it shows vertical visibility depth and it is commonly monitored in The Netherlands. Several studies show that clarity is also an important indicator for perceived water quality [43]. Azevedo Lopes et al. [2,3] added cyanobacteria which is included as fourth parameter because cyanobacteria blooms are common in the Netherlands and certain species cause health problems. Parameters related to flora and fauna, other than microorganisms, are not included in the existing WQI's. Although flora or fauna may be a nuisance to swimmers, high risks are not expected and the SI thus excludes this type of parameters.

Water quantity characteristics are not included in the existing WQI's even though physical conditions do impact safety for swimmers. Examples of physical risk factors are a steep bottom floor or dangerous current [10]. We expect that in Dutch urban waters, potential physical dangers are mainly related to strong current (in rivers), deep water in combination with vertical quay walls without ladders (larger canals and channelized rivers), objects under water (e.g. bicycle wrecks), and shipping. The risk of injuries by underwater objects is indirectly included in the SI through the parameter clarity; poor clarity increases the risk that objects are not seen. Dangers of shipping are excluded in this SI because trade-offs between uses are not taken into account. Other dangers can be prevented to a large extent if swimmers can stand on the bottom with their head above water. Therefore, we use water depth as indicator for physical safety. As swimming is physically impossible if water depth is not sufficient, water depth is also set as precondition.

Table 4
SI Recreation. Criteria for sub-scores for the parameters that determine suitability for swimming by adults. n.a.: not applicable.

SI Recreation							
Suitability	Score	Parameters					
		Quality				Quantity	Flora & Fauna
		E.coli [cfu/100 ml]	Cyano-bacteria [ug/L]	pH	Clarity [m][a]	Depth [m]	
Precondition		n.a.	n.a.	n.a.	n.a.	≥ 0.75[b]	n.a.
Excellent	4	<500	<0.5	7–8	>4 or bottom visible	Designated bathing zone	
Good	3	500–<1,000	0.5–<12.5	6–<7 or >8–9	2–4	≤1.40[c]	
Fair	2	1,000–<1,800	12.5–≤75	5–<6 or >9–9.5	1.2–<2	>1.40[c]	
Low	1	≥1,800	>75	>9.5 or <5	<1.2	n.a.	

[a] Secchi-disk transparency.
[b] At deepest point.
[c] 1 m from shore.

Step 2 and 3: Criteria definition for scores and integration

Suitability scores relate to different levels of health safety for swimmers, ranging from very limited expected risk to relatively high risk by the assessed parameters:

- Excellent (SI score = 4): No or very low health risk
- Good (SI score = 3): Low health risk
- Fair (SI score = 2): Moderate risk
- Low (SI score = 1): High risk

Criteria for sub-scores are based on Dutch and European guidelines, if available. For other parameters, the scoring is based on literature on WQI's for contact recreation.

A minimum depth of 0.75 m is set as precondition (Table 4). This criterion is based on a simple field test that showed that the average Dutch male, with a height of 1.81 m and taller than an average woman [9], needs at least 0.75 m water to swim. Sub-scores for *E. coli* relate to target values for inland waters in the European Bathing Water Directive [12] and the related signal value issued by the Dutch Steering Committee for Bathing Water. Criteria for sub-scores 4 and 3 are equal to target values for the respective classes 'excellent' (<500 cfu/100 ml) and 'good' (<1000 cfu/100) in the Directive. Sub-score 2 is related to the signal value (1,800 cfu/100 ml) and higher values result in sub-score 1. Sub-scores for cyanobacteria are based on the national protocol for cyanobacteria at designated bathing sites; this protocol includes target values for chlorofyl-a associated with cyanobacteria [30]. Since monitoring is only initiated at sites where a risk of cyanobacteria blooms is expected, values below detection limit lead to sub-score 4. The target value of <12.5 ug/l for the lowest risk level is used as criterion for sub-score 3. Criteria for sub-score 2 equal the value range (12.5–75 ug/l) at which swimmers need to be warned. Sub-score 1 relates to concentrations (>75 ug/l) that lead to a negative swimming advice or prohibition. For pH, sub-scores 4, 3, 2 and 1 are based on the values that Nagels et al. [27] consider as respectively ideal, suitable, marginally suitable and unsuitable in their WQI for primary contact recreation. For clarity, the only available criterion of ≥1.2 m secchi disk visibility for recreational water from Health Canada [17] is used as boundary between sub-scores 1 and 2. This value is comparable to the black disk visibility that Nagels et al. [27] set as lower boundary for marginal suitability. Sub-scores 3 and 4 are related to their 'suitable' and 'eminently suitable' visibility ranges. The parameter depth, an indicator for physical safety, is only assigned criteria for sub-scores 2 and 3, based on the maximum depth that allows the average Dutch woman of 1.68 m [9], to stand with her head above water. Physical dangers are in principle neglectable at officially designated inland bathing sites. Therefore, we use the status of designated swimming site as indicator for excellent suitability (score = 4). Sub-score 1 is not used for this parameter, assuming that dangers for which depth is used as an indicator are not high enough to lead to low suitability in Dutch urban waters. Supplementary material Text S3 provides more detailed motivation of the criteria for sub-scores. For calculation of the SI, the minimum operator method is applied because each parameter limits suitability, and high risk by one parameter cannot be compensated by another.

4.2. Application of three SIs for the city of Amsterdam

4.2.1. SI TEE

To assess suitability for TEE, data are required for depth, width, discharge, and temperature. From the navigation database, we use minimum depth in the fairway and maximum width as the best available data. From the discharge dataset, we use the 75th percentile of decreasing values to ensure that the values used for the analysis are valid most of the time. This was chosen, since a 95th percentile of decreasing values in many HUs results in (near-) zero discharge due to flow direction variation. For temperature, we use the water quality dataset and select the 74 locations with at least one measurement per month. For all these locations, average temperature and the 95th percentile value is above 15 °C. Even when taking into account that night-time temperatures are expected to be at most 1 °C lower [37] (www.waterinfo.rws.nl) than the daytime values, the 24 h average is still ≥15 °C. Therefore, we assume that in all HUs, temperature is ≥15 °C. For 296 HUs, data are available for all parameters. These HUs are included in the suitability for TEE analysis. Apart from temperature, data availability is mostly limited by lack of depth and width data. Depth and width are available for respectively 335 and 347 HUs; discharge is available for 468 HUs.

In 98% of the HUs (289 HUs), suitability for TEE is at least good (score = 3 or 4, see Table 5). This means that the assesed waterbodies could provide sufficient thermal energy for heating at least a large appartment buidling of >100 apartments. In 2% of the HUs (7 HUs), suitability is fair (score = 2), which is the lowest score in the analyzed waters. Sub-scores show that suitability is most frequently limited by width and/or discharge. The sub-score for temperature is always 4 and therefore does not limit the suitability for TEE.

The spatial patterns of the SI scores (Fig. 3) are roughly comparable to the patterns in a modeling study for TEE potential in Amsterdam (https://waternet.omgevingswarmte.nl/waternet; [38]), where larger waterways have higher potential for TEE than smaller waterways. That modeling study provides more detailed information about the estimated amount of extractable thermal energy for specific areas.

4.2.2. SI Transport

Data are required for depth, width and air draft. From the navigation database, we use the data on minimum depth in the fairway, minimum width and minimum air draft. Movable bridges without air draft restrictions and open water are treated as locations with infinite air draft. For 319 HUs, data are available for all three parameters. These HUs are included in the suitability for transportation analysis. Data availability is mostly limited by lack of air draft data. Air draft is available for 324 HUs, which is somewhat less than for depth (335 HUs) and width (348 HUs).

Suitability is low (score = 1), fair (score = 2) or good (score = 3) in respectively 17% (55 HUs), 76% (244 HUs) and 6% (20 HUs) of the HUs (Table 6). This means that most of the assessed waterways are accessible for the smallest active urban freight vessels. Suitability is most frequently determined by depth in combination with air draft as limiting parameters.

The SI analysis provides spatial information on the suitability for urban transport (Fig. 3). The SI assessment includes waterways that are not part of the national and international waterway network for which CEMT-class information is pubicly available (www.vaarweginformatie.nl). The spatial coverage of a navigation map of the municipality with its own waterway classification [13] is larger than the extend of the SI assessment (see Supplementary material Figure S1b for full map). That municipalities' map is based on the same dataset that was used for the SI analysis and on system knowledge of the municipality. The SI sub-scores show which parameter(s) limit the suitability for transportation. The municipaly's navigation map and the accompanying report [13] however do not provide details about air draft while the SI results show that this is often a limiting parameter.

Table 5
The frequency (number of HUs) of sub-scores and SI scores for SI TEE. n.a.: not applicable.

Score value	Frequency of sub-score per parameter				Frequency of SI score
	Depth	Width	Discharge	Temperature	
0	0	n.a.	n.a.	n.a.	0
1	n.a.	0	7	0	0
2	n.a.	11	18	0	7
3	n.a.	277	201	0	216
4	n.a.	8	70	296	73
TOTAL	296	296	296	296	296

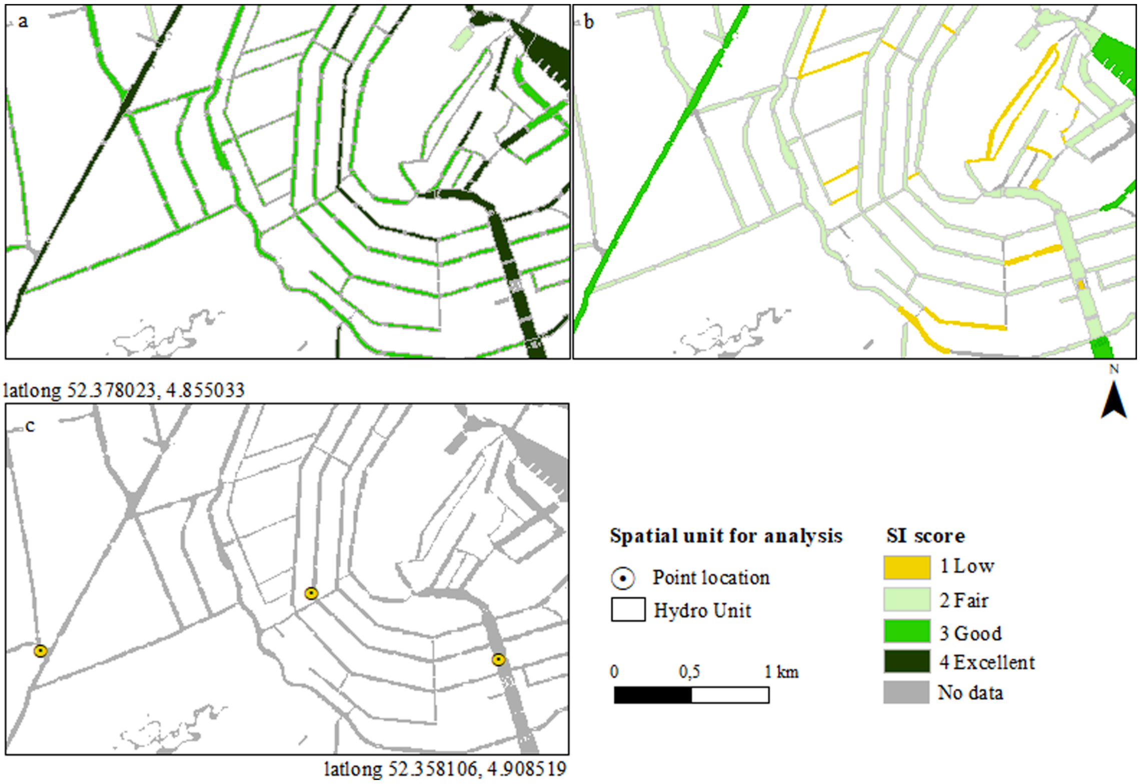


Fig. 3. Application of the SIs provides spatial information about the suitability of urban surface water for individual use functions in a comparable way. This is illustrated by the SI scores for TEE (a), Transport (b) and Recreation (c) for part of the city centre of Amsterdam. See Supplementary material Fig. S1 for full maps and Supplementary material DS1 for all data per HU or point location.

Table 6
The frequency (number of HUs) of sub-scores and SI scores for SI transport. N.a.: not applicable.

Score value	Frequency of sub-score per parameter			Frequency of SI score
	Depth	Width	Air draft	
0	0	n.a.	n.a.	0
1	26	27	21	55
2	263	126	244	244
3	30	155	3	20
4	0	11	51	0
TOTAL	319	319	319	319

4.2.3. SI Recreation

Data are required for the water quality parameters *E. coli*, cyanobacteria, pH and clarity, and for depth. For the water quality parameters, we use the water quality dataset and select data from the swimming season 1 April–1 October. We include all locations with at least 3 years of data for each parameter since for only 5 locations all parameters are available in all 4 years. Data availability is most limited by *E. coli* and cyanobacteria data. Cyanobacteria samples are only taken and analysed in case of visible algae blooms or a suspicion of cyanobacteria problems. For locations where cyanobacteria data are lacking, we therefore assume that cyanobacteria are not present. Water managers from AGV confirm that cyanobacteria blooms are absent or very rare at these locations. For depth, field measurements, by means of a lead line, were performed to retrieve depth information specifically for 1 m from the shore and at the deepest point in the waterways' profile since this information in not included in the dataset. For practical reasons, depth was measured in January 2021. At two locations, water level, and therefore water depth, is variable during the year. The water level data from AGV show a maximum fluctuation of 0.4 m. Measured depth values differ >0.4 m from the sub-index boundaries. Therefore, the measured depths can be used for determining the sub-scores for depth even though they are measured in January.

The resulting dataset contains data for 19 locations for analysis of the suitability for recreation. Seven of these locations are designated bathing zones (zwemwater.nl). Six locations are located outside the municipalities' administrative borders. Since these sites belong to the same surface water system, they border urban areas and they lie within the areas used by citizens from Amsterdam for recreation, these locations are included in the analysis.

At 2 locations, the precondition for maximum depth is not met (Table 7). These are children's wading areas. All 17 other locations have a low suitability due to limited clarity, at 9 locations in combination with low scores for other parameters. If the clarity sub-score is excluded from calculation of the SI score, suitability scores range from 1 (low) to 3 (good). Apart from clarity, the most frequently limiting parameter for the SI score is *E. coli*. Each of the parameters has at least once the lowest sub-score and thus determines the SI score at a location.

Application of the SI provides information about suitability for swimming at locations that are not all included in the standard monitoring and evaluation system for designated bathing water sites as prescribed by the European Bathing Water Directive (publicly available at www.zwemwater.nl). For the seven designated bathing sites, SI scores cannot be compared to the safety profiles for these sites (as published on zwemwater.nl) as these profiles are based on historic data until 2016 or before.

5. Discussion

5.1. Use of the protocol for parameters selection and definition of scoring criteria

The SIs in this study were developed for TEE, transportation, and recreation (Section 4.1) because previous research showed that

Table 7
The frequency (number of HUs) of sub-scores and SI scores for SI Recreation. 'SI score ex. clarity.': SI score if the sub-score for clarity is not taken into account. n.a.: not applicable.

Score value	Frequency of sub-score per parameter						Frequency SI score	Frequency SI score ex. clarity
	Depth max.	*E. coli*	Cyano-bacteria	pH	Clarity	Depth shore		
0	2	n.a.	n.a.	n.a.	n.a.	n.a.	2	2
1	n.a.	9	4	0	18	0	17	9
2	n.a.	1	3	3	0	4	0	5
3	n.a.	5	11	14	0	8	0	3
4	n.a.	4	1	2	1	7	0	0
TOTAL	2	19	19	19	19	19	19	19

increasing demand is most prominent for these human use functions [40]. For all three SI's, water quantity related parameters were identified as relevant limiting factors for suitability and two SIs include water quality parameters. None of the developed SI's include flora and fauna parameters, that are mentioned in the protocol for SI development (Section 2.1). However, it is expected that for some other uses of urban surface water the SI should include these types of parameters such as for sports fishing or open water aquaculture.

The protocol provided useful guidance for the selection of parameters and definition of scoring criteria based on literature, guidelines and individual expert consultation. However, it may not always possible to define criteria for sub-scores in this way for other use functions or in other regions. An alternative approach could be expert consultation such as the Delphi Method [22]. This iterative process in which an expert panel finds consensus about criteria is used by several authors when developing WQIs for contact recreation [3,27].

For some parameters, the criteria for sub-scores of the SIs developed in this study need to be adjusted if the SIs are used in another context than urban surface water in the Netherlands. For example, SI Recreation is designed for swimming by adults; sub-indices for water quantity related parameters are based on the average Dutch adult. For assessing suitability for swimming by adults in other countries, or by children, the SI protocol can be used to adjust the criteria. The SI for thermal energy in this study is targeted at summer extraction of heat in combination with seasonal storage. The protocol can also be used to define alternative SIs for other types of thermal energy extraction such as cooling water extraction or all year harvesting of heat.

Our SIs indicates four discrete levels of suitability. As a result, minor changes in functional water quality may either remain hidden when they do not result in another suitability class, or they may be exaggerated when a small change leads to another suitability class. A higher number of classes would make small changes in suitability more visible. This could be achieved by interpolating between the criteria for the four classes as in the suitability-for-use curves by Azevedo Lopes et al. [3] and Nagels et al. [27]. Yet uncertainty in the data due to monitoring errors and variability over time can introduce false accuracy if discriminating among more levels of suitability. For SI scores that are based on the average of the sub-scores, unrounded scores could be used to determine whether suitability of a location is close to another SI class.

5.2. *Applicability of the SIs*

The SIs for TEE, transportation and recreation can be applied to at least part of the water system of Amsterdam (Section 4.2). The available datasets enable analysis of the suitability of medium sized, locally managed urban waters like canals and channelized rivers in central Amsterdam. If the analysis could be extended to the largest national waterways that cross the city and the smallest waters like ponds and ditches, a larger spread in SI scores is expected for TEE and transportation.

Data availability is most limited for SI Recreation, especially as depth is required at specific locations in the water bodies' profile and because *E. coli* and cyanobacteria are not regularly monitored outside designated bathing areas. Moreover, these parameters are known to be highly variable in space and time, which makes it difficult to interpolate data. Required data for SI Transport and SI TEE relate to more commonly available parameters such as temperature and waterway dimensions. However, the available datasets do not match exactly with the desired data. For example, maximum width from the navigation database was the closest to average width that is required for SI TEE. Over- or underestimation of sub-scores will have a higher impact on aggregate SI scores that are based on the minimum operator approach, than those where the geometric average is used as aggregation method. It is expected that, as in Amsterdam, in most cities data will not be available for all parameters at all sites.

To deal with limited data availability, three strategies could be applied to enhance applicability of the SIs. For parameters with no or limited temporal variability, one field campaign or GIS analysis can fill data gaps (see depth measurements in Section 4.2.3). For other parameters, a frequent monitoring campaign is necessary. For locations where the precondition is met and data is available for some but not all other parameters, the sub-score for parameters without data could be set to 1 until data becomes available. For example, if no indicator for faecal pollution is monitored, risk of infection to swimmers cannot be ruled out. Suitability for recreation may improve by better monitoring of water quality. In general, urban surface water monitoring programs may be improved by targeting parameters that determine suitability for relevant human use functions.

5.3. *Added value of the SI approach*

The advantage of the SI approach is that it enables a suitability assessment for different types of use functions. To the best of our knowledge, no methodologies are available to determine suitability of urban surface water for important urban water uses in a consistent manner. This study demonstrates that suitability of urban surface water for TEE and transportation could not be assessed with a traditional water quality assessment (e.g. [1,32,35]) because literature and experts indicate that physical characteristics of surface waters determine their suitability (Section 4.1). Existing WQIs for contact recreation [3,27] are developed for designated recreational waters. SI Recreation shows that besides important water quality parameters from these indices, indicators of physical dangers should be analysed for urban waters that are not pre-screened and designated as official bathing water. The SI approach is developed for urban surface water but it may also be useful for rural areas.

6. Conclusions

We present suitability indices (SIs) as a new way to characterize functional quality of urban surface water. A SI evaluates suitability of urban water bodies for a specific use function based on the water bodies' characteristics that limit suitability. The proposed protocol for SI development provides a generic method that is designed to be applicable for a wide range of use functions in a wide range of urban areas. In this study we demonstrated that the protocol can be applied to different types of use functions by developing SIs for thermal energy extraction (TEE), transportation of goods and primary contact recreation in the geographic context of The Netherlands. The three SIs were successfully applied in the city of Amsterdam. Using existing datasets from local authorities, it was possible to determine suitability for a large part of the network of canals and channelized rivers. Sub-scores per parameter showed which characteristics are most limiting suitability for these three functions. The geographic extent of the analysis could be enlarged by additional data gathering and field measurements. The protocol is now ready to be used for development of SIs for other use functions and to be tested in other cities.

The added value of the SI approach is related to three features. Firstly, the SI's evaluate suitability of a water body for single use functions. This enables assessment of functional quality of surface water for those uses that are considered relevant in a specific urban context. Secondly, the generic protocol for SI development supports consideration of key characteristics of a water body that determine suitability, including physical parameters. This enables a suitability assessment for different types of use functions, including those that do not, or not only, depend on water quality. Thirdly, the SI protocol also enables assessment of suitability for different kinds of use functions in a consistent manner. This new approach to surface water assessment can support function-oriented planning, design and maintenance of urban surface water systems. For setting priorities for water use or investments in water management, a next step would be to analyse demand for specific use functions and to analyse trade-offs among uses and between use functions and ecological goals.

CRediT authorship contribution statement

E.S. van der Meulen: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition, Project administration. **P.R. van Oel:** Conceptualization, Writing – review & editing, Supervision. **H.H.M. Rijnaarts:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **N.B. Sutton:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **F.H.M. van de Ven:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

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Data availability statement

Data archiving is underway. If the manuscript is accepted for publication, data will be made available through the 4TU.ResearchData repository. For the review process, data are provided as Supplementary material.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2022.100079.

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