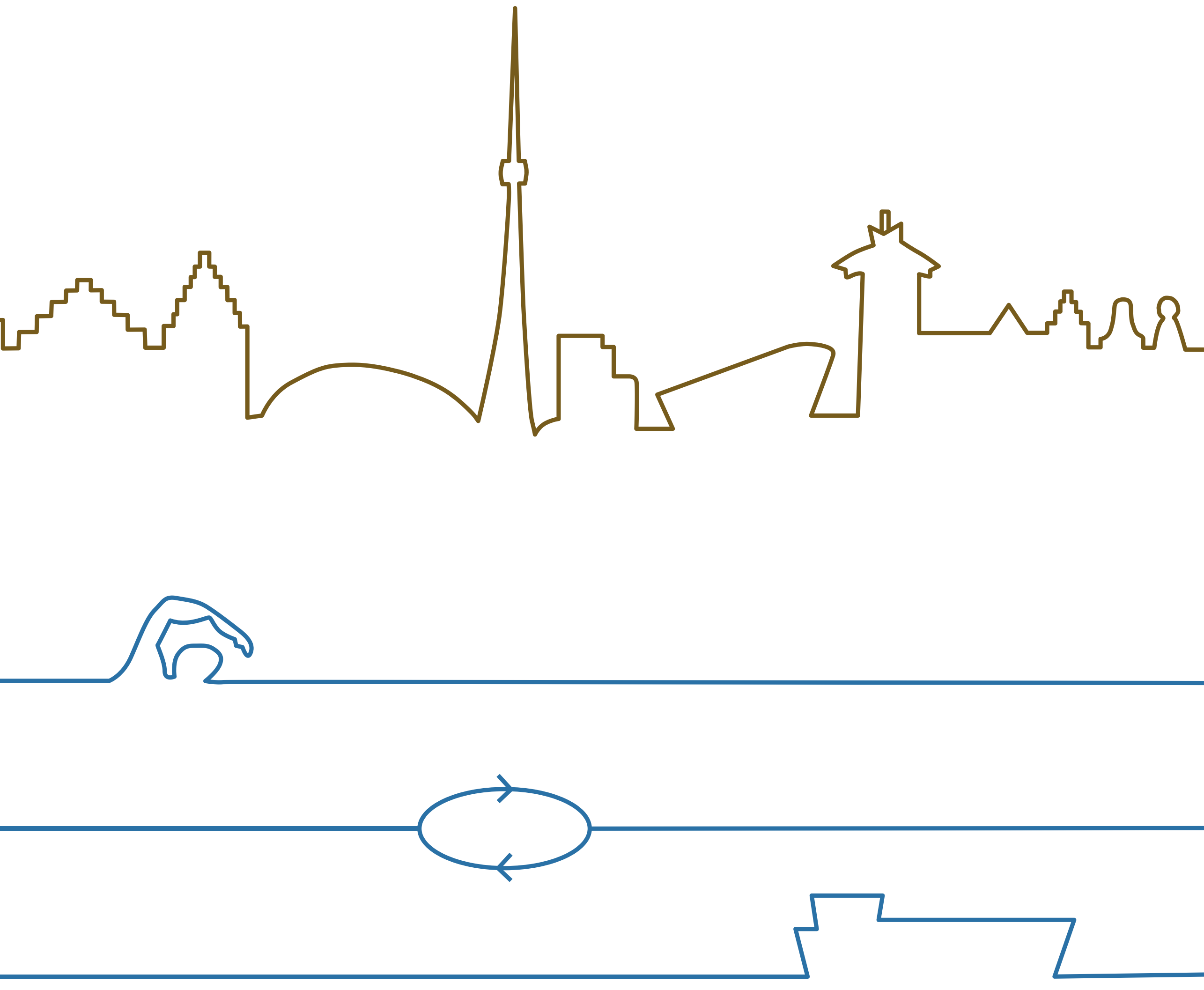
Functional quality of urban surface water

Suzanne van der Meulen



Propositions

1. Sustainable water management requires setting goals for ecological and functional quality of urban surface waters.
   (this thesis)

2. Limited space on and in surface water is a bigger problem for urban dwellers in water-rich European delta cities than water quality issues.
   (this thesis)

3. Adding propositions to a PhD thesis fosters the idea that science is just an opinion.

4. Predicting scientific impact in research proposals is as reliable as fortune telling.

5. The fear of authorities to share all environmental data with citizens is unjustified.

6. Creating more mid-career PhD positions increases the impact of scientific research.

Propositions belonging to the thesis, entitled

Functional quality of urban surface water

Suzanne van der Meulen
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Functional quality of urban surface water

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Suzanne van der Meulen

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List of abbreviations

CEMT	Classification of European inland waterways by the European Conference of Ministers of Transport
CICES	Common International Classification of Ecosystem Services
E. coli	*Escherichia coli*
ESS	Ecosystem services
HEC	Heat extraction capacity
HU	Hydro unit
SI	Suitability Index
TEE	Thermal energy extraction
UWRM	Urban water resources management
WWTP	Wastewater treatment plant
WQI	Water quality index


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Chapter 1
Introduction

1 Background

1.1 Urban surface water

Surface water is a key element of the resources and space in urban areas. It comprises natural waters like rivers, lakes or creeks, and manmade or highly modified water bodies such as canals, canalized rivers, reservoirs, ponds and ditches. Many urban water bodies were altered or created to serve human needs such as transportation, drainage of storm water and wastewater, or sand excavation. As a consequence, the ecological quality of urban aquatic ecosystems is limited by pollution and loss of water-related habitats, especially through flow control measures and canalization of rivers (Breuste, 2021; Lafont et al., 2008).

Many urban water bodies were filled in or covered in the nineteenth century, as a response to low water quality or to create more space on land, for example for roads and parking (Buchholz & Younos, 2007; Conradin & Buchli, 2003; Hintz et al., 2022; Lin et al., 2020; Napieralski & Welsh, 2016). The current trend, especially in North America and Europe, is to create new urban surface water bodies and reopen previously filled in or covered waterways (Khirfan et al., 2020; Wild et al., 2019). Canals and ponds are created as part of the green-blue infrastructure in new urban development or regeneration areas where they provide water storage, drainage, aesthetic and recreational services. Formerly culverted or filled-in rivers and canals are reopened since the 1970's to restore aquatic habitats, to improve water retention, and other aims such as creating aesthetic value (Boffey, 2020; Buchholz et al., 2016; EC Green City Tool, 2021; EEA, 2016b; Khirfan et al., 2020; Pinkham, 2000; VRT, 2018; Wild et al., 2011). Recent examples include the deculverting, or 'daylighting', of river Aarhus in Aarhus, Denmark (completed in 2015), daylighting of Harbor Brook in Meriden, USA (completed in 2016), reopening of the historic canal Reep in Ghent, Belgium (completed in 2018) and reopening of the canal Catharijnesingel in Utrecht, The Netherlands (completed in 2020). Local governments are planning to reopen more waterways to improve quality and climate resilience of the urban environment (MVRDV, 2020; VWW & Stad Gent, 2018).

1.2 Increasing societal interest to use urban surface water

The reopening of urban waterways illustrates that cities increasingly acknowledge the value of surface water in the urban environment. Societal interest to use urban surface water for different human use functions is growing and the use of urban waters is expected to change and to intensify. This is influenced by urban population growth and redevelopment, water quality improvements and ambitions to provide multiple benefits when creating or restoring water bodies.

As urban populations grow and cities face densification, the pressure on urban surface waters to be used for multiple human uses is increasing due to larger population numbers and lack of space (Day et al., 2008). The type of use functions will likely also change due to urban redevelopment. An example of ongoing urban redevelopment in many European and Northern American water-rich cities, is the transformation of former industrial harbour areas into residential areas and cultural hotspots (Feilberg & Mark, 2016; bostonplans.org; portofrotterdam.com). With this land use change, it is likely that industrial water extractions and shipping of bulk products will decline, while the new residents may want to use the water for recreation, as thermal energy source or for irrigation of green space.

Local water quality improvements in Europe and Northern America create new opportunities for human use of urban surface waters. Since a few decades, attempts have been made to restore urban aquatic habitats through renaturalization of water courses and to reduce pollution (Booth et al., 2016; EEA, 2016b). Many restoration projects involve the creation of more natural river courses surrounded by green space such as the Don river mouth restoration project in Toronto (www.trca.ca) and the restoration of Mayes Brook in London (EEA, 2016b). Emissions of contaminants into surface water were mainly reduced through improvements in the collection and treatment of urban waste water, which result in reductions in faecal pollution of the water (EEA, 2016b; Keiser & Shapiro, 2019). The improvements in ecological quality of urban waters may create new opportunities of certain human uses of the water, for example through increased attractiveness for recreation (Souliotis & Voulvoulis, 2021).

The use of urban surface water may also be influenced by the ambition to provide multiple societal benefits when creating or restoring water courses. A multifunctional design is expected to improve financial and moral support for these projects (EEA, 2016a; Wild et al., 2011) and multifunctional use potential is an important motivation for choosing nature based blue-green infrastructure over grey infrastructure (EC, 2014). For example, storm water detention ponds may be created as climate change adaptation measures with the primary aim to attenuate surface runoff. With the proper design, they may also serve water treatment and recreation (http://nwrm.eu/measures-catalogue) and thus provide additional value to society. If water bodies are designed to enable multiple use functions, the use of these waters will likely increase.

1.3 Urban water management

The key urban water management concept is sustainable or integrated Urban Water Resources Management (UWRM). This concept promotes integration of water management and spatial planning for holistic management of all parts of the water cycle, including both natural and technical water infrastructure (Feilberg & Mark, 2016; Hering & Vairavamoorthy, 2018; Kirshen et al., 2018). The integration of water management and urban spatial planning is also advocated in the United Nations' New Urban Agenda (UN, 2017). Integrated management requires knowledge of each component of the water system (Mosleh & Negahban-Azar, 2021); surface water is one such component. To create the best possible water management outcomes for the entire community, water should be planned in a proactive instead of reactive manner (Guthrie et al., 2020). This includes management of water demand and supply, considering the quality of water for the intended use (Hering & Vairavamoorthy, 2018; Mosleh & Negahban-Azar, 2021). This 'fit for purpose' principle pleads for function-oriented water management.

2 Problem statement

2.1 The need for insight into the functional quality of urban surface water

With growing ambitions to use urban surface water, water managers and spatial planners are faced with the challenge of managing multifunctional use of the water and making or maintaining water bodies fit for purpose. For example, the city of Amsterdam, The Netherlands, is densifying to prevent urban sprawl. This leads to conflicting claims on the limited space on water, as urban actors increasingly want to use the water for floating buildings, like houses or bicycle parking, and for navigation (Gemeente Amsterdam, 2016; Het Parool, 2012, 2021). Similar conflicts are also reported for London, United Kingdom (The Guardian, 2019). Another example is that in many cities, bathing in non-designated urban waters in increasing. City councils like those of Exeter in The United Kingdom, Ghent in Belgium and Amsterdam in The Netherlands, are concerned about the health and safety of citizens who swim in urban waters that are not (yet) suitable for this type of recreation (De Standaard, 2021; De Volkskrant, 2021; Exeter City Council, 2020). At the same time, political and societal groups in Europe and the USA are urging authorities to create more opportunities to swim in surface water (Mouchel et al., 2020; Ruby & Shinohara, 2019). These examples illustrate the need for proactive and function-oriented planning, design and maintenance of urban surface waters.

To support function-oriented urban surface water management, insight is needed into the functional quality of these waters. *Functional quality* is defined here as the suitability of a water body for specific human use functions. This perspective on the quality of urban surface waters can be used parallel to the ecological perspective on water quality. Insight into the actual and required functional quality of urban surface water bodies can support function-oriented planning, design and maintenance of these waters. Identification of use opportunities in planning processes can help to prioritize use functions based on demand and potential supply. The priorities may guide temporal and spatial delineation of conflicting uses and guide investments (Day et al., 2008; Gemeente Amsterdam, 2016). Major investments are needed in high income countries to renovate water infrastructure in the next decades (UNEP, 2013); this provides a window of opportunity to optimize surface waters as part of this infrastructure for the desired use functions of the future. When demand exceeds the potential of surface water to provide the desired functionality, it is also important to understand how suitability of water bodies for the desired functions can be increased. Such insight can be used to improve design and maintenance of these waters.

Strategic planning, design and maintenance of urban surface waters should take into account all use functions that are relevant in a specific urban setting. In this thesis, *use functions* refers to all human uses of surface water and can be distinguished in *extractions* and *in situ* uses. Water extractions are typically included in UWRM studies on supply and demand of urban water. Other extractions and in situ uses are described in literature on aquatic ecosystem services. Examples of extractions are water withdrawals for domestic use, irrigation or industrial use (Exall & Vassos, 2012; Padowski & Gorelick, 2014), and extraction of fish for consumption (Joosse et al., 2021). In situ use refers to surface water uses that do not involve extractions of water or other materials from the water system. Examples are recreational boating, swimming or waterborne transportation (Haase, 2015; Van der Meulen et al., 2016). Although UWRM and ecosystem services literature provide examples of urban surface water use, a comprehensive insight into the actual use of these waters or demand for use functions in the near future is not available. This knowledge gap needs to be resolved because an evidence-based insight into use and demand of urban surface water is needed to guide research on the functional quality of urban surface waters.

2.2 The lack of an assessment framework for functional quality

To date, there is no method available to review functional quality of urban surface waters in a consistent way for all types of uses. A widely applied method to evaluate water quality is the water quality index (WQI). A WQI describes water quality with a single value and is based on the integration of sub-scores for relevant parameters. The advantages of the WQI model are that an index is simple and easy to understand by a broad audience (Borges Garcia et al., 2018; Lumb et al., 2011; Sarkar & Majumder, 2020), requires a modest amount of input data, and an integrated index provides more information than a single water quality parameter (Azevedo Lopes et al., 2016).

WQIs however cannot be used to review functional quality of urban surface water for the full range of single use functions. WQIs are mainly targeted at ecological water quality and/or suitability of water for drinking water production and irrigation (Alvareda et al., 2020; Borges Garcia et al., 2018; Lumb et al., 2011). Because of this focus, WQIs typically classify water quality as grade of pollution or purity. For many urban surface water uses, traditional water quality parameters related to pollution or naturalness are not sufficient to determine the suitability of the water for these use functions. For example, suitability of the water for thermal energy extraction or recreation is expected to rely on more or other characteristics of surface water, like water depth or water temperature. The ecological focus of common water quality concepts is likely a major reason for the underrepresentation of manmade waters in water quality research and policy (Koschorreck et al., 2020). This focus may also explain why in scientific publications that stress the importance of blue space or blue-green infrastructure for human health and well-being (e.g. Bell et al., 2022; Dall'O', 2020; Geneshka et al., 2021), surface waters and their potential for human use functions of them is hardly considered (Beck et al., 2018; Joosse et al., 2021). Therefore, a new assessment framework is needed that considers all relevant characteristics of surface waters, beyond traditional water quality parameters.

Another limitation of many WQIs is that they score water quality based on the number of uses for which the water is considered suitable (Alvareda et al., 2020; Lumb et al., 2011; Shree & Brema, 2019). However, following the UWRM principle that water should be fit for purpose, the functional quality of an urban surface water body is the quality needed for its intended use. This intended use is context specific, and in most cases will involve multiple use functions. Each use function has its own functional quality requirements. Therefore, an assessment framework for functional quality should review the suitability of surface waters for single use functions. No adequate instruments exist to assess the suitability of urban surface water for different kinds of use functions in a unified way. This knowledge gap needs to be resolved to enable structured analysis of current functional quality of urban surface waters and the impact of changes in these waters on functional quality.

3 Research aim and objectives

The overall aim of this research is to develop an assessment framework for functional quality of urban surface water. The framework should be applicable to all kinds of surface water use functions that are potentially relevant in an urban setting. To achieve this aim three research objectives are defined:

1) Identify current uses of urban surface water and future demand for human use functions to determine which use functions are relevant to include in the assessment framework
Actual use of surface water and expected demand in the next decades is assessed in two different urban contexts to solve the lack of evidence-based knowledge on the use of urban surface water.

2) Develop a method for assessing functional quality of urban surface water, building on existing approaches for water quality and ecosystem services assessment
This method will define the assessment framework for functional quality that enables review of the suitability of water bodies for single use functions, taking into account the water body characteristics that determine suitability.

3) Determine applicability and added value of the assessment framework
The assessment framework is applied in case studies to test applicability and demonstrate added value of the assessment framework.

4 Research approach and context

4.1 Overall research approach

The generic model for the assessment framework is developed through integration of knowledge from the fields of water quality research and aquatic ecosystem services. Water quality literature provides the basic model for the assessment framework and ecosystem services literature provides insight into the relevant parameters of functional quality. To ensure that the assessment framework is targeted at relevant use functions, the actual use of urban surface water and expected demand by 2040 is assessed through an in-depth study for two cities. By focussing on the period until 2040, this research can be relevant for water management in the next decades. The study is based on documented water use and expert knowledge. The assessment framework is also applied in two cities to test applicability, especially with regard to data availability, and to demonstrate added value for researchers and practitioners.

4.2 Research context: water-rich cities with relatively high water quality

This research is targeted at water-rich cities with relatively high water quality, such as in Europe and Northern America, because their surface water system can support a broad spectrum of water uses. The study areas for in-depth assessments in this thesis are the cities of Amsterdam in The Netherlands (Europe), Ghent in Belgium (Europe) and Toronto in Canada (Northern America). Amsterdam serves as study area in each phase of the research, while Ghent and Toronto are used as study area for specific research activities.

The assessment of the current use of and future demand for urban surface water use functions is conducted for Amsterdam and Toronto. These cities are selected because they represent cities on different continents, with different climates and geographic characteristics, including different types of surface waters (Table 1.1). This variation broadens the relevance of this study. Amsterdam and Toronto are medium sized cities with respectively 854,047 and 2.96 million inhabitants. This is a relevant size class for studying urban surface water use and demand because most city dwellers in Europe and Northern America live in cities with a population of respectively 500,00 to 5 million inhabitants and 1 to 10 million inhabitants; this is expected to continue through 2030 (UN, 2019). In both cities, urban redevelopment leads to land use change and densification. Together with local water quality improvements, especially reductions of nutrient concentrations and faecal pollution (AGV, 2015; Dahmer et al., 2018; Edge et al., 2018; Howell et al., 2018; TRCA, 2019), these developments may increase ambitions to use surface waters.

For testing and demonstrating the assessment framework, the cities of Amsterdam and Ghent are selected as study areas. While the general approach of the assessment framework is expected to be widely applicable, the parameters that are reviewed and their scoring criteria are expected to be context specific. Therefore, it is important to apply and test the framework for a comparable specific context. Amsterdam and Ghent are both delta cities in North-western Europe with comparable climate, social-economic context and highly managed surface water systems dominated by canals and canalized rivers (Table 1.1). These similarities provide a homogeneous research context. The two cities also provide a good research climate because of the benevolence of local water authorities to share available data.

Table 1.1: Characteristics of the study areas
(Beck et al., 2018; City of Toronto, 2019; Copernicus Land Monitoring Service, s.a.; EEA, 2021a; Federale Overheidsdienst Binnenlandse Zaken, 2018; Gemeente Amsterdam, 2018b, 2018c; Metropoolregio Amsterdam et al., 2018; Stad Gent, s.a.; Statistics Canada & Ontario Ministry of Finance, 2018; Wang et al., 2015).

Characteristics	**Toronto (Canada)**	**Amsterdam (The Netherlands)**	**Ghent (Belgium)**
Geography[a]	Hills along Lake Ontario, 1.7% water + Lake Ontario	Low land delta 25-35% water + adjacent lakes and waterways	Low land delta 2.1% water
Surface water	Rivers, creeks, shallow and deep lakes, ponds	Rivers, canals, shallow and deep lakes, ponds	Rivers, canals, deep lake, ponds
Climate	Warm-summer humid continental climate	Moderate sea climate	Moderate sea climate
Population density	4,651 per km^2 (land area)	3,850 per km^2 (total surface area) 5,178 per km^2 (land area)	1,643 per km^2 (total surface area)
Population 2018	City: 2.96 mln Greater Toronto Area (GTA): 6.3 mln	City: 854,047 Metropolitan region (MRA): 2,5 mln	City: 259,570
Population 2040	GTA +52%	City +18%, MRA +13%	Projection for 2030: +3% (no data for 2040)

[a] Percentages refer to the part of the surface area that is covered by water within the municipal boundaries. In Amsterdam, part of the large lake IJmeer that borders the city is included in this figure.

5 Thesis outline

After this introduction chapter (**Chapter 1**), the thesis includes three research chapters (Chapters 2-4) that describe all research methods and outcomes in detail. The thesis is concluded by a discussion chapter (Chapter 5). Figure 1.1 provides a visual representation of all chapters and the connections between them.

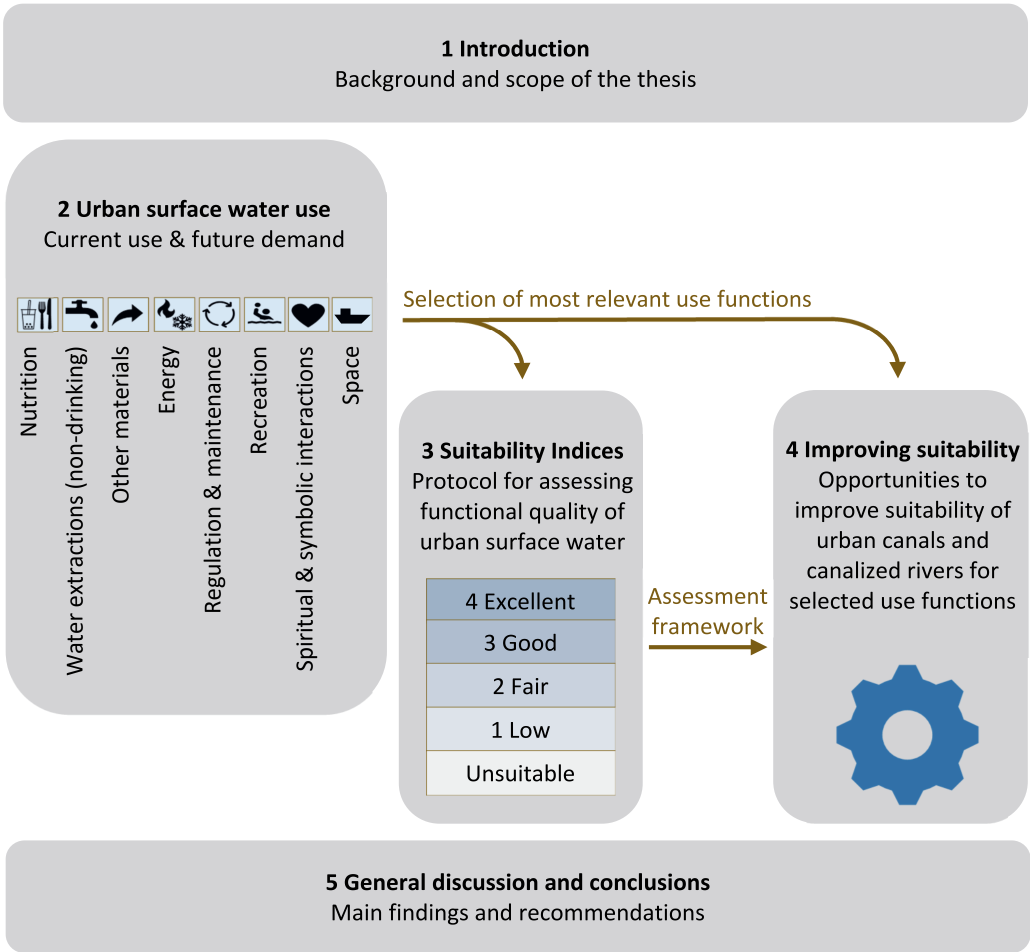

Figure 1.1: Overview of the chapters in this thesis and the connections between chapters.

Chapter 2 describes the assessment of the current use of urban surface water and the expected future demand for use functions of these water bodies. Analysis of water related policy documents and technical reports for Amsterdam and Toronto provides evidence for the actual use of urban surface water in these cities. In-depth interviews with water managers and spatial planners reveal trends in demand for specific use functions towards 2040 and the drivers of these trends. The results of this assessment show which use functions are most relevant to assess in the next steps of the research.

In **Chapter 3**, Suitability Indices (SIs) are proposed as assessment framework for functional quality of urban surface water. A protocol for SI development is defined building on literature on WQIs and ecosystem services. The protocol is used to develop SIs for three use functions in the context of the Netherlands. The SIs are targeted at thermal energy extraction (TEE), transport and recreation because these are the three use functions for which Chapter 2 shows the most prominent increase in demand. The SIs are applied for the case of Amsterdam to test applicability and added value compared to existing information on the suitability of the urban surface water for the selected use functions.

Chapter 4 shows how the assessment framework can be used to identify opportunities for improving suitability of urban surface waters for specific use functions. First, the SIs from Chapter 3 are applied in Amsterdam and Ghent to determine current suitability of urban canals and canalized rivers for TEE, transport and recreation. Next, the impact of higher sub-scores on the SI scores is analysed. The results show which alterations in the water bodies are required for improving their suitability for TEE, transport and recreation. The assessments for Amsterdam and Ghent provide novel insights into the functional quality of urban surface waters and on the applicability, added value and limitations of the assessment framework.

Chapter 5 provides a discussion of the main findings of the research and the novel contributions to the field of urban water management. This final chapter continues with recommendations for practical water management and for future research. The chapter ends with general conclusions.

Chapter 2
Trends in demand of urban surface water extractions and in situ use functions

A slightly modified version of this chapter has been published as:
Van der Meulen, E.S., Sutton, N.B., van de Ven, F.H.M., van Oel, P.R., Rijnaarts, H.H.M., 2020. Trends in demand of urban surface water extractions and in situ use functions. Water Resources Management 34, 4943–4958. https://doi.org/10.1007/s11269-020-02700-7

Abstract

Scientific literature currently lacks comprehensive understanding of urban surface water use functions. This hampers sound analysis of the demand and potential supply of these functions. This study provides a comprehensive overview of potential use functions, by integrating knowledge from ecosystem services and integrated urban water management fields. Analysis of water-related management plans for Toronto and Amsterdam shows that surface water is currently being used for a variety of functions related to nutrition, energy, water regulation, recreation, symbolic use, transportation and floating buildings. Notably, many use functions involve in situ use, rather than water extractions. Interviewed water managers and spatial planners in both cities expect demand for most use functions to increase by 2040, especially demand for thermal energy extraction, recreation and transportation. Some identified novel demands, such as climate regulation and reuse of waste products from waterway maintenance. Increasing demand is mainly driven by urban growth, climate change and sustainability ambitions. This study found urban surface water uses that are usually not acknowledged in scientific literature on urban water management. This comprehensive overview supports planning, design, and maintenance of urban surface waters, laying the foundation for future research on supply and demand of urban water use functions.

1 Introduction

Surface water is an important resource and part of the public space in urban areas. Water use will increase due to population growth in European and Northern American cities. Urban surface water use may change with, for example transformation of former industrial sites and harbour areas into residential areas and cultural hotspots (Feilberg & Mark, 2016; bostonplans.org; portofrotterdam.com). Recently, urban water quality has improved across Europe (EEA, 2016b) and North America (McPhearson et al., 2014), opening new opportunities to use these waters. Strategic planning, design and maintenance of urban surface water systems can be optimized by taking into account all relevant use functions. Here *use functions* refers to all human use of water bodies, and can be distinguished in *extractions* (e.g. water for drinking or fish for nutrition) and *in situ* uses (e.g. swimming or transportation). Scientific literature supports function-oriented water management, describing drivers of water demand and supply, and the effectiveness of measures to influence these. Literature from the field of urban water resources management (UWRM) usually focusses on water extractions by different sectors. UWRM thus neglects demand and supply of in situ water use and the extraction of materials from water bodies beyond water itself.

This study therefore provides a comprehensive overview of all use functions of urban surface water, based on literature and in-depth analyses for two cities: Amsterdam (Netherlands) and Toronto (Canada). While many studies focus on water management challenges in water-scarce urban regions (e.g. Haak & Pagilla, 2020), our research is focused on water-rich cities in the western world. We focus on areas where ample water and a relatively high water quality support a broad spectrum of water uses. Managing supply and demand of the water use functions is key to ensure and improve quality of life in these cities. This study provides a comprehensive perspective on urban water use by combining the fields of UWRM and Ecosystem Services. Besides a theoretical overview of potential uses of urban water, we reveal actual use of these waters in two cities and the expected changes in demand by 2040.

2 Conceptual approach

We integrate knowledge from two scientific fields to develop a comprehensive understanding of urban surface water uses: UWRM and Ecosystem Services (ESS). The concepts of integrated and sustainable UWRM promote holistic management of all parts of the urban water cycle (Kirshen et al., 2018). These concepts also link water management and spatial planning, and they integrate natural water bodies and technical infrastructures (Feilberg & Mark, 2016; Hering & Vairavamoorthy, 2018). Moreover, sustainable UWRM includes both quantitative management of water supply and water quality management considering the intended use (Hering & Vairavamoorthy, 2018). In most UWRM literature on water supply and demand, water use is described as withdrawal for uses that are defined like agriculture; environment; urban or municipal water; or residential, domestic or household use and industrial water (Ali et al., 2017; Exall & Vassos, 2012; Ghavidelfar et al., 2017; Giacomoni & Berglund, 2015; Haak & Pagilla, 2020; Padowski & Gorelick, 2014; Sharvelle et al., 2017).

The ESS field provides a broader view on urban water use. ESS explains how ecosystems provide goods and services that are used by humans and contribute to their wellbeing and welfare (WRI, 2003). The Common International Classification of Ecosystem Services (CICES) distinguishes three main categories of ESS: Provisioning, Regulating & Maintenance and Cultural (www.cices.eu). A few studies provide information about potential uses of urban surface water (Blicharska & Johansson, 2016; Haase, 2015), urban lakes (Hossua et al., 2019) or the entire urban water system (Garcia et al., 2016). Maes et al. catalogued suitable indicators for mapping and assessing ESS in freshwater ecosystems (Maes et al., 2014) and urban ecosystems (Maes et al., 2016). For urban ecosystems, we selected information on the service providing units watersheds, water bodies, wetlands or waterways from their publication. A similar approach was performed for a publication on ESS in New York City (McPhearson et al., 2014). While most publications provide a theoretical overview of ESS, Persson (2012) gives some concrete examples of actual use of urban ponds. Habitat or ecological functions (Blicharska & Johansson, 2016; Garcia et al., 2016) influence the potential of ecosystems to deliver services (Potschin & Haines-Young, 2011). If natural ecosystems are used by humans, this is included in our study as a specific use function. Nature in itself is not a human use function and is therefore not included in this study.

We identify some additional functions that are usually not included in UWRM or ESS studies. While not included in CICES, we include spatial use of water as carrier for human activities (Haines-Young & Potschin, 2018), with water transportation (Haase, 2015; Van der Meulen et al., 2016) and floating housing being well-known examples of urban water uses. Similarly, we include energy-related uses including thermal energy extraction (TEE) from surface water (Laanearu et al., 2017), energy production from salinity gradients (Swinkels et al., 2010), and kinetic energy like hydropower.

Based on literature and practical knowledge, we compiled a long list of potential use functions (Table 2.1). The main structure is based on the three CICES sections and an additional section covering spatial use of water. Supplementary Information 1 provides a detailed explanation for each use function. Within categories, use functions are differentiated to an appropriate level to prevent overlooking functions and to differentiate use functions with different water quality requirements. In this way, the list can support assessment of potential supply of the use functions.

Table 2.1: Potential use functions of urban surface water; short notations for graphs and tables

Section	Category	Use function (short notation)
Provisioning	Nutrition	Fishing for consumption (Fishing)
		Catch of other surface water-related animals for consumption (Other animals)
		Harvest of aquatic plants or algae for consumption (Plants or algae)
		Water extractions for drinking water production (Drinking water)
	Water extraction for non-drinking purposes	For irrigation of crops (Irrigation agriculture)
		For irrigation of other vegetation (Irrigation other)
		For industrial processes
		For firefighting
		For filling ponds
		For other non-drinking purposes (Other)
	Other materials	Harvest of biomass for non-food purposes (Biomass)
		Extraction of abiotic materials (Abiotic materials)
	Energy	Thermal energy extraction (Thermal energy/TEE)
		Energy production using salinity gradient in water (Energy salinity)
		Energy production using kinetic energy (Energy kinetic)
Regulation & maintenance	Regulation & maintenance	Managing water quality
		Managing water quantity
		Global climate regulation
		Local climate regulation
Cultural	Recreation	Primary contact recreation (Primary contact)
		Secondary contact recreation (Secondary contact)
		Recreational boating (Boating)
		Sport fishing
		Hunting aquatic animals (Hunting)
		Enjoying a landscape characterized by surface water (Landscape)
		Ice-skating
	Spiritual & symbolic interactions	Designation of cultural heritage value (Cultural heritage)
		Religious use
Space	Space	Building on water (Building)
		Under water storage/infrastructure (Under water storage)
		Transporting goods
		Transporting persons
		Using water as a barrier (Physical barrier)

3 Method

3.1 Study areas

Toronto, Canada and Amsterdam, The Netherlands are intermediate sized cities with significant amounts of surface water. They provide the opportunity to assess a wide array of water body types, water uses and water users. Both cities face densification. Former industrial harbour areas are redeveloped into new residential, cultural, leisure, and business areas. The cities are located on different continents, have different climates and represent varying geographic characteristics, thus broadening the study's validity (Table 2.2).

Table 2.2: Characteristics of the study sites. Tav: average temperature, Prec: precipitation (Beck et al., 2018; City of Toronto, 2019; Gemeente Amsterdam, 2018a; Metropoolregio Amsterdam et al., 2018; Statistics Canada & Ontario Ministry of Finance, 2018; Wang et al., 2015)

Characteristics	**Toronto**	**Amsterdam**
Geography	Hills along Lake Ontario, 1.7% water + Lake Ontario	Low land area 25-35% water + adjacent lakes and waterways
Surface water	Rivers, creeks, shallow and deep lakes, ponds (fresh water)	Rivers, canals, shallow and deep lakes, ponds (fresh to brackish water)
Population density	4,651 per km² (land area)	3,850 per km² (total surface area) 5,178 per km² (land area)
Population 2018	City: 2.96 mln; Greater Toronto Area (GTA): 6.3 mln	City: 854,047; Metropolitan region (MRA): 2,5 mln
Population 2040	GTA +52%	City +18%, MRA +13%
Climate	Warm-summer humid continental climate T max. -0.7 °C (Jan) to 26.6 °C (Jul) Precipitation 831 mm	Moderate sea climate T max. 5.8 °C (Jan) to 22.1 °C (Aug) Precipitation 897 mm
Climate change towards 2050	Tav + 4.0 to 4.7 °C Prec. + 4.6 to 10.2 % Intensity of rainfall storms increase	Tav. + 1 to 1.5 °C Prec. +4.5 to 5.7 %. Frequency and intensity of rainstorms increase; water deficit in spring and summer equal or increase

Toronto lies on the shores of Lake Ontario, a fresh water lake with a surface area of 18,960 km² and maximum depth of 244 m (EPA, 2019). The city's hillsides are covered by river and creek watersheds that discharge into Lake Ontario. Other urban surface water bodies include storm water ponds and aesthetic ponds. Amsterdam is situated in a low delta area. Water enters the city through channelized rivers and large canals and, depending on tide, water is discharged through a large canal into the North Sea. The city contains a fine network of connected smaller canals, ponds and five deep (35 m) lakes (AGV, 2014), relics of sand excavation. Amsterdam borders lake IJmeer with a 80 km^2 surface and 2.6 m depth (Rijkswaterstaat, 2019).

Toronto is assigned as Area of Concern according to the Great Lakes Water Quality Agreement (TRCA, 2019). Road salt-related chloride issues are persistent while the situation for nutrients, faecal pollution and habitat diversity is locally improving (Dahmer et al., 2018; Edge et al., 2018; Howell et al., 2018; TRCA, 2019). Chemical and ecological water quality in Amsterdam is generally “bad” to “moderate” according to European Water Framework Directive water quality classification (AGV, 2014; AGV, 2018; HHNK, 2018; Ministerie van Infrastructuur en Milieu, 2018). Chemical pollution problems are persistent while faecal pollution and eutrophication are locally declining (AGV, 2015).

3.2 Documents analysis and interviews

To verify actual use of urban surface water, water-related policy documents and technical reports were analysed from all relevant authorities involved in water management and spatial planning in the study areas. The documents were scanned for evidence of urban surface water use for the functions in the long list (Table 2.1). For use functions that were not mentioned in the policy documents, additional information sources have been searched in Scopus, Google and Deltares’ and Wageningen University’s libraries using the specific use function or ‘water’ in combination with the study areas or their region as keywords.

For several use functions, like smaller water extractions, current use is not documented. In other cases, use data are more than five years old. For most use functions, future demand is not documented. Therefore, we conducted structured in-depth interviews with local water managers and spatial planners to check the validity of older documented information and to retrieve non-documented information on water use and future demand towards 2040.

Eleven participants, six in Amsterdam and five in Toronto, were interviewed individually in July-October 2019. They represent all authorities involved in water management and have supplementary knowledge on water use based on their different positions and fields of expertise. Six interviewees live in Amsterdam or Toronto. Anonymized transcripts are used for analysis. See Supplementary Information 2 for more details on the interview procedure.

4 Results

4.1 Current use

Urban surface water in Toronto and Amsterdam is used for a broad range of functions (Figure 2.1). Data on specific uses from the analysed documents and the interviews is provided in Supplementary Information 3.

Surface water is used for several categories of provisioning functions (Figure 2.1). Nutrition is extracted as locally caught fish in both cities. In Toronto, Lake Ontario is the main source of drinking water; in Amsterdam, surface water is not used for this purpose. In both cities, surface water is extracted for irrigation of food crops and other vegetation. Water extractions for other purposes are less frequently documented. Extraction of other materials for non-consumption purposes is uncommon. However, there is an experiment in Amsterdam with bio-composite production from mowed aquatic plants. In both cities, TEE from deep lakes is used for cooling office buildings. In Amsterdam, surface water from deep and shallow lakes, rivers and canals is also used for industrial cooling, for heating and cooling of houses or for cooling of bridges to prevent expansion in summer.

Surface water bodies are intentionally used for water regulation and maintenance in both cities, but in different ways. Storm water management ponds are widely applied in Toronto to manage runoff water quality and quantity before these enter rivers or creeks.

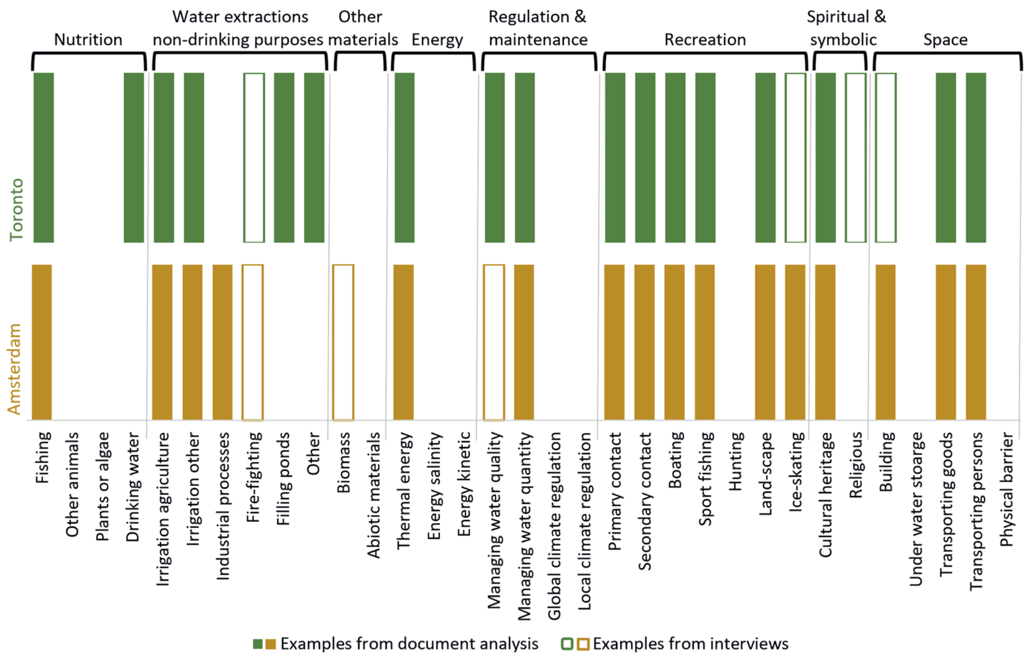

Figure 2.1: Current use of urban surface water in Toronto (above) and Amsterdam (below)

Amsterdam's surface water network is actively managed to control water discharge and retention. The water inflow from Lake IJmeer and a large canal into the water system of Amsterdam is regularly increased to mitigate inflow of saline water through another canal that connects Amsterdam and the sea or through seepage water.

Surface water use for cultural functions mainly involves recreational activities. Amsterdam and Toronto have officially designated areas in lakes for primary contact recreation. Especially in Amsterdam, swimming also occurs outside these areas in all types of water. Secondary contact recreation like canoeing, rowing and sailing takes place on various water bodies in both cities. In Toronto, these activities are mostly concentrated on Lake Ontario. Sport fishing is also popular in both cities, and urban dwellers enjoy surface water as an important landscape element. Recreation along the water is common in both cities, but this type of use is not extensively documented. Although winter temperatures usually do not allow for it, ice-skating is considered an important use function of Amsterdam's canals. No documented examples were found for ice-skating on Toronto's surface waters. Interviewees mentioned that ice-skating does happen on some ponds although it is not allowed. Spiritual and symbolic use of surface water is more prevalent in Toronto than in Amsterdam. Symbolic use is demonstrated by the World Heritage status of Amsterdam's inner canal system and designation of Humber River in Toronto as Canadian Heritage River. Religious use of surface water is not documented, although one interviewee in Toronto observed religious or funeral ceremonies along the shores and on the water of Lake Ontario, and at some ponds.

The space provided by water is intensively used in Amsterdam to accommodate houseboats and other floating buildings like bicycle shelters. In Toronto, this use of the water surface is rare. The few houseboats that interviewees observed are not mentioned in water management documents. Surface water in both cities plays an important role in transportation of goods and persons. In Toronto, Lake Ontario accommodates international cargo transport lines and in Amsterdam the larger canals, rivers and Lake IJmeer provide important waterways for national and international transportation of goods. The same waters are also used by cruise ships. Waterborne public transport is mainly focussed on transporting pedestrians or cyclists and is limited to destinations that cannot be reached otherwise.

Interviewees were asked to add to the list of use functions. Several interviewees stated that this list was already more extensive than expected, including use functions that they did not think of before. Six interviewees suggested to include the nature or habitat function. One interviewee mentions that local surface water is also used as a scientific research object.

4.2 Future trends in demand

For most provisioning use functions, demand is expected to remain equal or increase and new uses may emerge (Figure 2.2). An exception to this pattern is that interviewees in Toronto foresee equal or declining demand for water extractions for non-drinking purposes. Notably, interviewees have most information and relatively high certainty about extractions for drinking water, irrigation, and TEE (Figure 2.3). Toronto's increase in TEE demand is limited mainly to cooling of buildings with Lake Ontario water. Potential emerging demand is reported for consumption of undesired species, like exotic Crayfish, in both cities. Emerging demand is also reported for non-edible use of biomass and abiotic waste products from waterway maintenance works such as dredged sediments or mowed aquatic plants. Another emerging demand in Amsterdam is surface water extraction for decentralized drinking water production. Local water managers

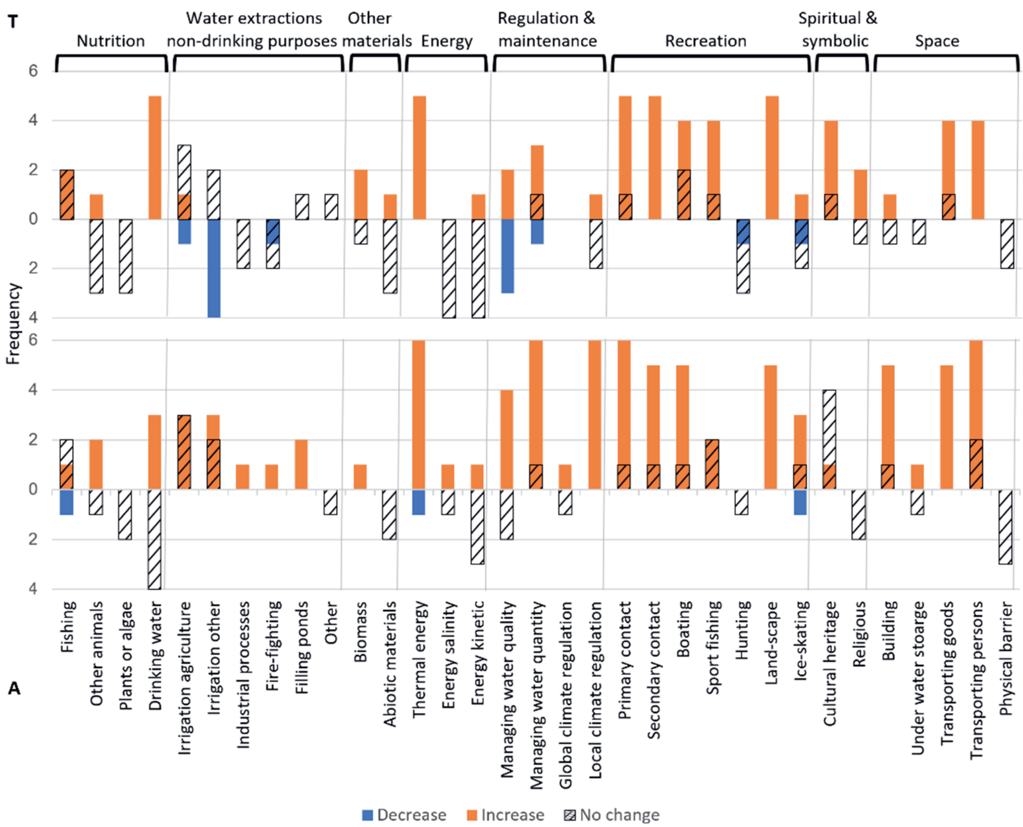

Figure 2.2: Expected trends in demand by 2040 in Toronto (above) and Amsterdam (below). 'No change' bar directed downwards: function is currently not used and interviewees expect no demand in the future. 'No change' bar directed upwards: function is currently being used and interviewees expect no change in demand. Frequency of a trend may be higher than the number of interviewees, since some mention two trends for the same use function, e.g. 'equal or increase'

receive requests by private parties, such as a cultural site, who want to produce their own drinking water from local surface water. Most interviewees consider the local water system unsuitable for energy production by using kinetic energy or osmotic processes relying on salinity gradients. Some interviewees think that demand may also emerge for these activities.

In the category maintenance and regulation functions, several interviewees in both cities expect increasing demand for water quality and quantity regulation. In Toronto, however, demand for storm water ponds may diminish or decline due to lack of space, high land prices and the preference for low impact development to reduce storm water runoff. Most interviewees have no information about the use of surface water to influence global climate. For the intentional use of surface water to influence local climate, all interviewees from Amsterdam and one in Toronto report emerging demand.

Demand for most cultural functions is expected to increase, especially for recreation. In the case of primary contact recreation, this is not limited to officially designated swimming areas; especially in Amsterdam demand for swimming grows for all kinds of waters.

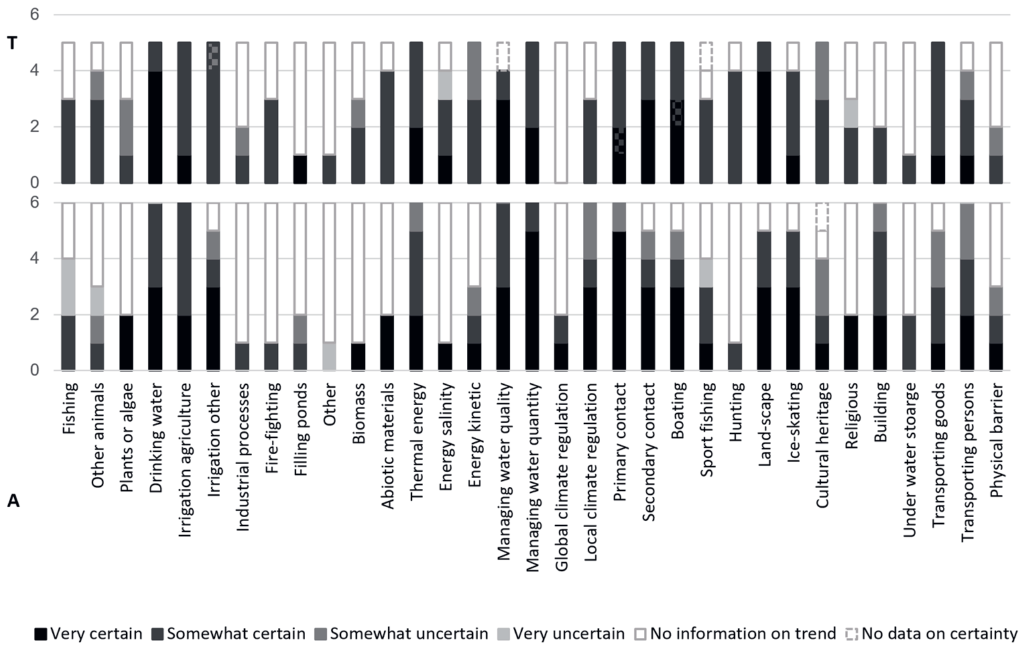

Figure 2.3: Degree of certainty that interviewees have for the trend in demand and the number of interviewees that have no information about specific use functions. T: Toronto, A: Amsterdam. Checkerboard pattern: interviewee mentioned different levels of certainty for different aspects of a use function

In Toronto, the increasing demand for secondary contact recreation and boating is mainly foreseen on Lake Ontario since boating opportunities on rivers and creeks are limited due to low water levels. Hunting is expected to remain absent and not allowed in both cities. Some interviewees in both cities expect demand for ice-skating to decrease due to higher temperatures. Spiritual and symbolic interactions with the urban surface water system seem to become more important in Toronto than in Amsterdam. In Toronto, several interviewees report increasing demand for religious practices.

Spatial use of surface water for transportation is expected to increase in both cities. Increasing demand for transport of goods in Toronto relates to local and international transport on Lake Ontario. In Amsterdam, national and international transportation will increase through the large waterways and local transportation via smaller canals. Demand for transportation of passengers will grow mainly due to intensification of cruises in both cities. Interviewees also expect more intense use of the few existing public transport lines and possibly a few new routes in specific areas where waterborne transport is faster than road or rail. Growing demand for floating buildings or other structures is mainly limited to Amsterdam. Under-water space is currently unused in both cities, and most interviewees have no information about future demand for this. One interviewee in Amsterdam reports interest to lay electricity cables at the bottom of large canals as opposed to the subsurface where space is becoming scarce. Finally, the use of water as a physical barrier is considered to be outdated, and interviewees do not expect demand to emerge before 2040.

4.3 Drivers explaining future increasing demand

Interviewees indicated an overall increase in demand for urban surface water use by 2040. The most frequently mentioned categories of drivers for both cities are urban growth, climate change, sustainability ambitions and social trends (Table 2.3). Urban growth and redevelopment are expected to result in increased demand for nearly all categories of use functions, especially due to an increasing number of users (Supplementary Information 4). Densification leads to a higher concentration of users and a lack of space on land, both of which drive increasing demand for spatial water uses. Redevelopment near water improves accessibility of the water and introduces new users. Climate change influences demand for several categories of use functions. Drought may increase demand for some water extractions, especially in Amsterdam, and more extreme rainfall patterns drive demand for water quality and quantity regulation. Temperature increase mainly influences demand for local climate regulation and recreation. Sustainability ambitions mainly drive demand for TEE and transportation. Circularity ambitions drive emerging demand for beneficial use of biotic or abiotic waste materials from waterway maintenance works. In Amsterdam, the ambition to reduce drinking water consumption may lead to increasing demand for surface water as an alternative source for irrigation or firefighting. Social trends are mainly expected to drive demand for nutrition, recreation and transportation of persons. For example, preferences for local

Table 2.3: The most frequently mentioned drivers for increasing demand of urban surface water use functions. For original quotes see Supplementary Information 4. Frequency of the answers in brackets

Toronto		**Amsterdam**	
Driver category	Specific drivers	Driver category	Specific drivers
Urban growth & redevelopment (67)	Population growth (36) Redevelopment close to water (15) Urbanization/land use change (8) Lack of space on land (4) Densification (3) Limits to transportation on land (1)	Urban growth & redevelopment (55)	Population growth (26) Densification (12) Limits to transportation on land (7) Redevelopment close to water (5) Lack of space on land (4) Urbanization/land use change (1)
Climate change (10)	Temperature increase (6) Rainstorms more intense (3) Dry periods longer/more frequent (1)	Climate change (44)	Temperature increase (25) Dry periods longer/more frequent (14) Rainstorms more intense (5)
Water quality improvements (10)	Water quality improvement (10)	Welfare increase (24)	People have more free time (9) People live longer (5) Welfare increase (5) Tourism growth (5)
Sustainability ambitions (9)	Sustainability ambitions (7) Circular economy/re-use of waste streams ambitions (2)	Sustainability ambitions (19)	Sustainability ambitions (12) Saving drinking water ambitions (4) Circular economy/re-use of waste streams ambitions (3)
Social trends (8)	Popularity of the activity (6) Local products trend (2)	Social trends (16)	Popularity of the activity (13) Local products trend (2) Self-sufficiency ambitions (1)

products may cause an increase in fishing for consumption or decentralized drinking water production.

Some drivers are frequently reported in only one city. In Toronto, several interviewees expect that water quality improvements will result in increased demand for nutrition and recreation. Only in Amsterdam, welfare growth is frequently mentioned as driver for increased demand for recreation and cruises. Besides the six main categories of drivers, there are less frequently mentioned drivers like intentions to save on costs, local developments in specific sectors or infrastructure and technological developments (Supplementary Information 5).

Changes in demand for specific use functions are the result of a combination of drivers. This is illustrated for TEE and recreation. Increasing TEE demand is mainly driven by sustainability ambitions to reduce fossil fuel use for cooling or heating. Cooling demand may increase due to climate change, to local growth in specific sectors like energy production and data centres, or to opportunities to link demand and supply due to redevelopment near water. TEE demand is further pushed by local developments that differ per city. Demand for recreation increases mainly due to population growth and transformation of former industrial areas near water into residential and cultural hotspots. Demand is further pushed by an increasing need for warm-weather recreation due to climate change and by the popularity of water sports and other outdoor activities. Locally, welfare growth results in more people that have time and/or financial resources for water recreation. Furthermore, water quality improvements and measures may improve opportunities for recreation.

5 Discussion

5.1 Structured assessment reveals broad use of urban surface water in theory and practice

By integrating knowledge on UWRM and ESS, we compiled a comprehensive long list of potential use functions of urban surface water (Table 2.1). Our analysis of cities in North America and Europe shows that actual use is even broader than what is usually included in scientific literature on urban water use (e.g. Haase, 2015; Padowski & Gorelick, 2014; Persson, 2012). Most use functions involve in situ use of urban surface water rather than water extractions.

Document analysis in Toronto and Amsterdam revealed that surface water in both cities is used for a variety of functions related to nutrition, energy, water regulation, recreation, symbolic use, transportation and space for buildings (Figure 2.1). For several use functions from the long list, no examples of actual use were found in reviewed documents. However, this does not ensure that water is not used for these functions. This information gap was resolved to a great extent by interviewing spatial planners and water managers. Their professional knowledge, and in many cases additional local knowledge as a citizen, resulted in a more complete overview of actual urban surface water use. The uses that were uncovered in this way, like water extractions for fire-fighting and religious use, probably are relatively small-scale applications. This assessment of actual use of surface water provides additional insights beyond those estimating ESS provisions using modelling (e.g. Grêt-Regamay et al., 2020).

There are many similarities between surface water use in Amsterdam and Toronto (Figure 2.1). The most notable differences may be explained by characteristics of the local water system (Table 2.2). The presence of Lake Ontario provides Toronto with a large reservoir of drinking water, while the smaller water bodies in Amsterdam are less reliable than sources outside the city. Spatial use of the water's surface is more common in Amsterdam than in Toronto. Amsterdam's location in a low delta area with calm waters and a dense network of canals across the entire city provides many opportunities for spatial uses like floating buildings. Toronto's topography with mainly free flowing rivers and creeks and a city centre with less open surface water area provides less opportunities for this type of water use. It is plausible that the spatial use of urban surface water will generally be higher for cities with a relatively large surface area of calm waters.

5.2 Future trends by 2040: intensification of urban surface water use

In-depth interviews with water managers and spatial planners provided insight in changes in demand for urban surface water before 2040 in Amsterdam and Toronto. The results reveal three main patterns in both cities: 1) increasing demand for many use functions; 2) high confidence in expectations on increasing demand for TEE, different types of recreation and transportation; 3) broadening of the range of uses through emerging demand for new use functions (Figure 2.2 and Figure 2.3). This reveals that urban surface water use can be expected to further intensify.

Changes in demand may seem less relevant for use functions for which only one or two interviewees foresee a change. However, interviewees are sometimes certain about the trend based on their contacts with stakeholders. Such situations often involve functions that are currently not, or not widely, used like extraction of biomass for non-consumption purposes or local climate regulation. It seems logical that fewer interviewees have knowledge about future demand for these use functions than for more common functions.

Interviewees sometimes report conflicting trends, which shows that visions on specific use functions vary among the stakeholders. However, a high degree of consistency exists for the three main patterns in future demand within and between the two cities. It is therefore expected that another group of professionals covering all relevant fields of expertise would validate these patterns.

5.3 Common drivers of increasing demand

The main drivers of demand identified by interviewees are developments applicable to other western, water-rich cities (Table 2.3). For example, urban population growth, densification and redevelopment near water are common trends (e.g. Feilberg & Mark, 2016; UN 2018). Increasing temperatures, more extreme rain storms and drought periods are common aspects of climate change in the Northern Hemisphere (Meehl et al., 2007). Sustainability ambitions are set in international agreements and policies such as the Paris Agreement (UN, 2015) and the European Circular Economy Action Plan (EC, 2020). The widespread occurrence of these developments indicates that the main trends in demand as identified in Toronto and Amsterdam are likely relevant to other comparable cities.

Some reported drivers are known from literature. For example, population growth is known to be the key driver for current and future projected participation rates in outdoor, water-related recreation (Bowker et al., 2012; Cordell, 2012). Blue-green infrastructure is widely proposed as climate adaptation measure (Altvater et al., 2011; WHO, 2017), which confirms our finding of increasing demand for water and climate regulation functions as a response to climate change. The city of Copenhagen, Denmark provides an example outside our study areas where water quality improvement led to increased recreational water use, even for swimming (EEA, 2016b). Beyond known drivers, our study provides insight into combinations of drivers that cause trends in demand specifically for urban surface water use functions, including less studied use functions like TEE.

While more universal developments strongly impact demand for urban surface water use, specific local circumstances and developments are decisive in some cases. For example, differences in developments in Amsterdam and Toronto result in differences in demand for water extractions. Interviewees in Toronto expect decreasing demand, emphasizing that farmers and golf courses, the main users of extracted surface water, leave the city. Conversely, some interviewees in Amsterdam see new water users, such as hydrogen factories, moving into the city. Another example is that more interviewees in Amsterdam than in Toronto foresee growing demand for beneficial use of waste products from waterway maintenance works. This difference may be explained by the larger number of waterways in Amsterdam requiring dredging and mowing to facilitate navigation and water discharge. Exploring more cities across Europe and North America using the method developed in this study will further highlight universal and context dependent trends in demands for urban water use.

5.4 Implications for future research and water management

The results of this study motivate a broader perspective on urban surface water use in science and water management. Our long list of potential use functions can guide future research on supply and demand. Interviewees indicated that they would not have thought about some use functions spontaneously even though they did have information about them (section 4.1). This demonstrates that using the list helps to prevent overlooking use functions.

Several authors (section 2) and interviewees suggest to include ecological functions, or ‘nature’ or ‘habitat functions’, to the long list. However, ecological functions do not comply with the scope of this study on *human* use functions and thus were not addressed.

Assessment of ecological ecosystem quality can be performed in parallel to research on demand and potential supply of human use functions. Such an integrated analysis enables assessment of trade-offs between ecological water quality and the potential supply of human use functions, supporting management choices by water managers and spatial planners. In some ESS studies, authors include the role of water bodies as an object of scientific research and educational activities. Only one interviewee mentioned scientific research as a use function. This indicates that scientific and educational use of surface water have low relevance for practical urban water management.

For three potential functions from the list, no evidence was found for current use or future demand in the study areas: harvesting aquatic plants or algae for consumption, hunting and water as a physical barrier. Additional assessments in other cities may reveal the relevance of these functions in an urban context.

6 Conclusions

By combining UWRM and ESS literature, we developed a comprehensive overview of potential use functions of urban surface water. This overview contains use functions that are often lacking in UWRM literature, as many studies are focussed on water extractions. Analysis of actual use of surface water systems in two cities demonstrates that many use functions involve in situ use rather than water extractions.

The study also reveals that demand for existing and new use functions is expected to increase. This will result in an increased pressure on urban surface water systems to deliver multiple services. These findings motivate a broader perspective on the use of urban surface water in science and in water management. The overview of potential use functions that was developed in this study can guide future research on supply and demand of these functions.


CITY SUPPLIER

Chapter 3
Suitability Indices for assessing functional quality of urban surface water

A slightly modified version of this chapter has been published as:
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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 SIs 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 (Haase, 2015; Persson, 2012; Van der Meulen et al., 2020). Research in the cities of Toronto and Amsterdam demonstrated that demand for most use functions is expected to increase towards 2040 (Van der Meulen et al., 2020). 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. (2020) 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 (Borges Garcia et al., 2018; Lumb et al., 2011; Sarkar & Majumder, 2020), requiring a modest amount of input data, and understandable for a broad audience of non-specialists (Azevedo Lopes et al., 2016). A composite index is also considered to provide a more accurate reflection of water quality compared to a review of single water quality parameters (Noori et al., 2019). 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 (Lumb et al., 2011). This relates to the emphasis of the WQIs, even those designed for urban water (e.g. Alvareda et al., 2020), on ecological water quality and suitability for drinking or irrigation. For many relevant urban water 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 (Shree & Brema, 2019). 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. (2011) 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 (Mohebbi et al., 2013) or recreation (Azevedo Lopes et al., 2016; Nagels et al., 2001). 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 (Figure 3.1). 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 (Lumb et al., 2011; Sarkar & Majumder, 2020). Consulted experts must include users of the use function. Parameters of the SI should be specific and

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

Figure 3.1: Protocol for the development of a 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.

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 & Fauna (Figure 3.1).

According to Brauman et al. (2007) and Hallouin et al. (2018), 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. (2018) 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 & 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 (Borges Garcia et al., 2018; Lumb et al., 2011). 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 (Brown et al., 1970).

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 (Azevedo Lopes et al., 2016). 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:

SI=$Min(S_{i=1}^{n})$, 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 (1989) and is used in WQIs for primary contact recreation by Azevedo Lopes et al. (2016) and Nagels et al. (2001). 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: $SI = (\prod_{i=1}^{n} Si)^{1/n}$. 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. (1973) to solve the lack of sensitivity in arithmetic averaging in the NSFWQI, and is also applied by e.g. Bhargave (1986) 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 (Van der Meulen et al., 2020). 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 (Kruit et al., 2018). 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 (Van der Meulen et al., 2020).

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 (Gemeente Amsterdam, 2016). 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 (Figure 3.2). 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 part of local and world cultural heritage (Van der Meulen et al., 2020).

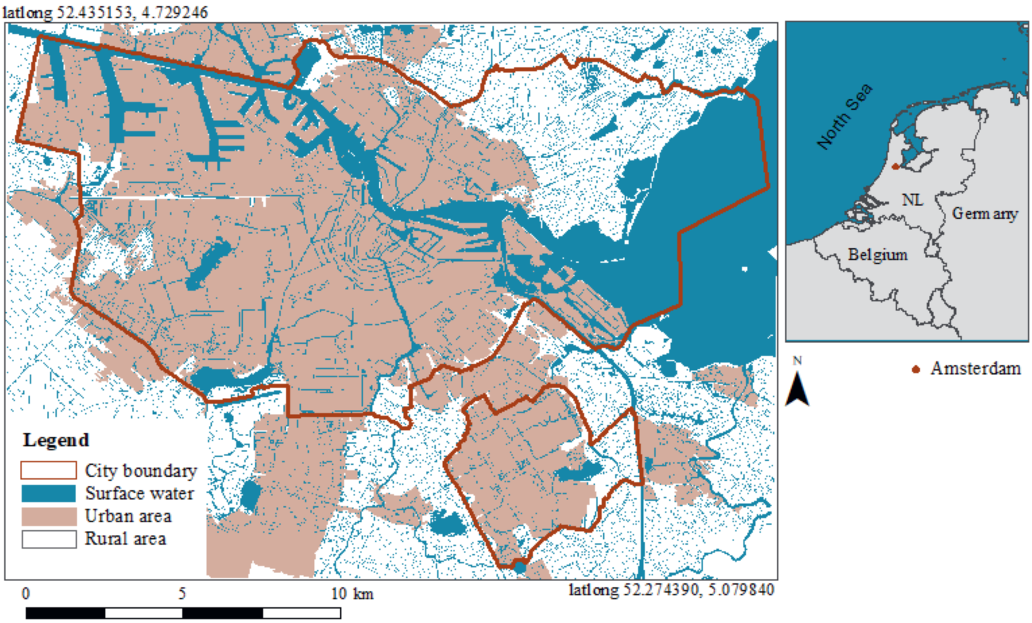

Figure 3.2: The surface water system of Amsterdam, The Netherlands (NL). City boundary indicates the municipal administrative boundary until 24 March 2022.

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 95^{th} or 5^{th} 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 3.1). 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 4.2.

Table 3.1: 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 4.2.
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 minutes 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 3.2). Studies on using surface water for heat extraction show the importance of water surface area (Kindaichi et al., 2015; Kruit et al., 2018). 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 Kruit et al., 2018):

- 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 less than 10 to more than 1,000 houses, based on a typical heat demand of 40 GJ yr^{-1} per house (Menkveld, 2009). Relating SI scores to heat demand is illustrative and should be regarded as indicative.

Table 3.2: 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
					Physical	Chem. & Microbio.	
		Max. depth [m]	Width [m]	Discharge [m^3 s^{-1}]	Temper-ature [°C]		
Precondition		≥ 0.5	n.a.	n.a.	n.a.		
Excellent	4	n.a.	≥100	≥0.3	≥15		
Good	3		10-<100	0.03-<0.3	10-<15	n.a.	n.a.
Fair	2		1-<10	0.003-<0.03	5-<10		
Low	1		<1	<0.003	<5		

Consulted practitioners state that water bodies are unsuitable for TEE if depth is less than 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 3.2).

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 to 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, and 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 Information 6 (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 (Kruit et al., 2018; Scholten & Van der Meer, 2016). 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 3.3). Width, depth and air draft limit ship size (Maes et al., 2012); 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. (2012) and Van Duin et al. (2017; 2014) 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 (Janjevic & Ndiaye, 2014; Maes et al., 2012). 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.

Table 3.3: 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.		
Excellent	4	≥45.6	≥6.3	≥9.1[a]		
Good	3	20.2-<45.6	3.1-<6.3	4.0-<9.1	n.a.	n.a.
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

Besides waterway dimensions, connectivity or network density is mentioned in literature as important success factor for urban transportation (Janjevic & Ndiaye, 2014; Maes et al., 2012; Van der Does de Willebois, 2019). 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. (2012) 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.

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 (Classification of European Inland Waterways) class Va (ECA, 2015). 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 (ECA, 2015).
- Fair (SI-score=2): Smallest operational vessels for urban freight transport that are described in literature (Janjevic & Ndiaye, 2014; Maes et al., 2012), 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 3.3). 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 (2017). 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 Information 6 (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: Parameter 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 (Azevedo Lopes et al., 2016; Nagels et al., 2001). We use three parameters from the WQI's by Azevedo Lopes et al. (2020; 2016) and Nagels et al. (2001) that relate to swimmers' health safety: *Escherichia coli* bacteria (*E. coli)*, pH and clarity (Table 3.4). *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 (West et al., 2016). Azevedo Lopes et al. (2020; 2016) 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.

Table 3.4. 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 $100ml^{-1}$]	Cyano-bacteria [ug L^{-1}]	pH	Clarity [m][a]	Depth [m]	
Precondition		n.a.	n.a.	n.a.	n.a.	≥ 0.75[b]	
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]	n.a.
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

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 (DHV, 2008). 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 from 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.

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 3.4). 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 (CBS, 2008), 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 (EC, 2006) 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^{-1}) and 'good' (<1,000 cfu 100 ml^{-1}) in the Directive. Sub-score 2 is related to the signal value (1,800 cfu 100 ml^{-1}) 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 (RIVM, 2020). 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^{-1} 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 ugl^{-1}) at which swimmers need to be warned. Sub-score 1 relates to concentrations (>75 ug l^{-1}) 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. (2001) 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 (2012) is used as boundary between sub-scores 1 and 2. This value is comparable to the black disk visibility that Nagels et al. (2001) 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 (CBS, 2008), 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 Information 6 (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 (Solverova et al., 2019; www.waterinfo.rws.nl) than the daytime values, the 24 hour 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 3.5). This means that the assesed waterbodies could provide sufficient thermal energy for heating at least a large appartment buidling of more than 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.

Table 3.5: 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

The spatial patterns of the SI scores (Figure 3.3) are roughly comparable to the patterns in a modelling study for TEE potential in Amsterdam (Syntraal, 2020; https://waternet.omgevingswarmte.nl/waternet), where larger waterways have higher potential for TEE than smaller waterways. That modelling study provides more detailed information about the estimated amount of extractable thermal energy for specific areas.

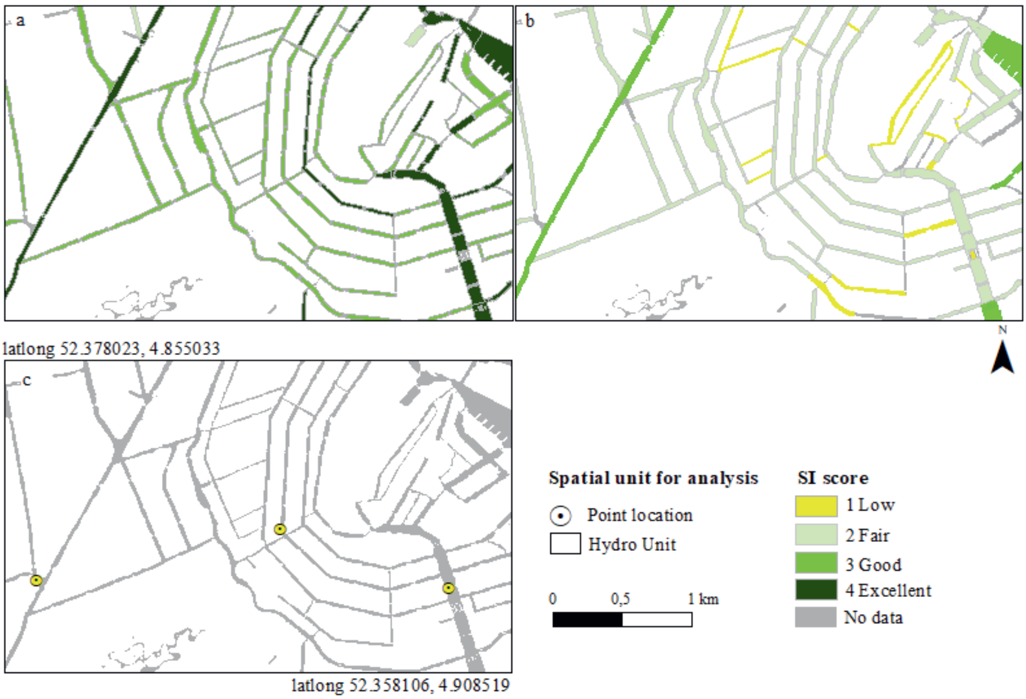

Figure 3.3: Application of the SIs provides spatial information about the suitability of urban surface water for individual use functions in a comparable way. This is illustrated by the SI scores for TEE (a), Transport (b) and Recreation (c) for part of the city centre of Amsterdam. See Supplementary Information 6 for full maps (Figure S1) and for all data per HU or point location (Dataset DS01).

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 3.6). 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.

Table 3.6: 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

The SI analysis provides spatial information on the suitability for urban transport (Figure 3.3). 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 (Gemeente Amsterdam, 2009) is larger than the extend of the SI assessment (see Supplementary Information 6, 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 (Gemeente Amsterdam, 2009) however do not provide details about air draft while the SI results show that this is often a limiting parameter.

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 to 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 more than 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 3.7). 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.

Table 3.7: 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

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 increasing demand is most prominent for these human use functions (Van der Meulen et al., 2020). 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 & 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 (Linstone & Turoff, 1975). This iterative process in which an expert panel finds consensus about criteria is used by several authors when developing WQIs for contact recreation (Azevedo Lopes et al., 2016; Nagels et al., 2001).

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 indicate 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. (2016) and Nagels et al. (2001). 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. Alvareda et al., 2020; Saha & Paul, 2021; Shree & Brema, 2019) because literature and experts indicate that physical characteristics of surface waters determine their suitability (section 4.1). Existing WQIs for contact recreation (Azevedo Lopes et al., 2016; Nagels et al., 2001) 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.

Chapter 4
Improving suitability of urban canals and canalized rivers for transportation, thermal energy extraction and recreation in two European delta cities

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Abstract
Canals and canalized rivers form a major part of surface water systems in European delta cities and societal ambitions to use these waters increase. This is the first assessment of how suitability of these waters can improve for three important uses: transportation, thermal energy extraction (TEE) and recreation. We assess suitability with Suitability Indices (SIs) and identify which alterations in the water system are needed to improve SI scores in Amsterdam, The Netherlands, and Ghent, Belgium. The results show spatial variability in suitability scores. Current suitability for transportation is low (SI score=1) to excellent (SI score=4), for TEE fair (SI score=2) to excellent (SI score=4), and suitability for recreation is low (SI score=1). Suitability could improve by enlarging specific waterway dimensions, increasing discharge and clarity, and by enhancing microbiological water quality. The same methodology can be applied to optimize designs for new water bodies and for more water uses.

1 Introduction

After decades of investments in water quality, through improved wastewater treatment and stormwater management, cities are rediscovering their urban surface water as an important functional and aesthetic asset (EEA, 2016b). This is also reflected by the growing attention for ‘blue space’ in urban planning and public health sciences (Bell et al., 2022; Dall'O', 2020; Georgiou et al., 2021; Smith et al., 2021). The urban surface water system includes many highly modified or manmade water bodies such as canals and canalized rivers. In the remainder of this article, we will use the term ‘*canals*’ to refer to canals and canalized rivers. While the ecological status of these waterbodies is relatively low, they provide important use functions, or ecosystem services, to citizens and businesses in European delta cities. Function-oriented design and maintenance of these water bodies will become increasingly important. Firstly, this is due to increasing use of urban surface water for human use functions, mainly driven by urban growth and regeneration, climate change, water quality improvements and sustainability ambitions (EEA, 2016b; Van der Meulen et al., 2020). Secondly, there is the ambition to provide multiple societal benefits when creating or restoring urban water courses (EEA, 2016b; Wild et al., 2011).

Research in Amsterdam, The Netherlands and Toronto, Canada, has shown that demand for many use functions of urban surface water is expected to increase in the next decades (Van der Meulen et al., 2020). This increasing demand is most clear for transportation, thermal energy extraction (TEE), and different types of recreation including swimming. These trends were also reported by other authors. Janjevic & Ndiaye (2014) and Hallock & Wilson (2009) describe increasing demand for waterborne urban freight transportation, driven by road congestion and by ambitions to reduce greenhouse gas emissions from freight transport. In its New EU Urban Mobility Framework, the European Commission (2021) proposes better utilization of urban waterways for the ‘first and last mile’ in the Trans-European Transport Network (TEN-T) that is being developed until 2050. TEE from surface water is considered as one of the renewable alternatives for fossil fuel heating in Europe (www.ec.europa.eu/cip/iee). The most favourable conditions for surface water based district heating are expected in urban areas close to surface water (Moller, 2015). The potential of this heat source is significant: 43% of the total urban heat demand in the Netherlands can be extracted from surface water in an economically feasible way (Kruit et al., 2018) and in England, the entire heat demand of smaller urban areas along larger rivers can be obtained from the river (Department of Energy & Climate Change, 2015). Increasing recreational use of urban water is illustrated by a substantial increase in the number of designated urban bathing sites in Europe in the last decade (EEA, 2020). Additionally, swimming at non-designated sites is increasingly popular due to water quality improvements and higher water temperatures (EEA, 2020). Swimming events in urban canals are also gaining popularity (Hintaran et al., 2018) such as the Big Jump in Ghent, Belgium (www.gentsmilieufront.be), the Amsterdam City Swim (www.amsterdamcityswim.nl) and Swim-In in Leiden (www.swiminleiden.nl), The Netherlands. Several political and societal groups in Europe and the USA are advocating for more opportunities to swim in urban surface water (Mouchel et al., 2020; Ruby & Shinohara, 2019).

Besides the increasing ambitions to use urban surface waters, there are ambitions to add use potential when restoring urban rivers or canals for ecological or water detention purposes. Many restoration projects in cities involve restoration of smaller urban waters (EEA, 2016b). In some cases, formerly culverted or filled in waterways are recently reopened, or 'daylighted', such as Aarhus River in the city of Aarhus, Denmark (completed in 2015) or the historic canal Reep in Ghent (completed in 2018), Belgium. Policy documents and explorative studies indicate that more waterways will be reopened in the near future (e.g. MVRDV, 2020; VWW & Stad Gent, 2018). A multifunctional design that includes benefits in terms of use functions, or ecosystem services, is expected to increase financial and moral support for restoration projects (EEA, 2016b) and may lead to greater sustainability (Wild et al., 2011). The European Commission considers the multiple benefits that natural water retention measures, such as open water, can provide as the primary justification for choosing green infrastructure over grey infrastructure measures (EC, 2014). Among the potential co-benefits are provision of human use functions such as recreation (http://nwrm.eu/measures-catalogue; https://oppla.eu/nbs/case-studies).

With increasing ambitions to use urban water for human uses, it is important to understand how to improve suitability of existing and planned water bodies for desired functions. Such insight can be used to improve design and maintenance of these waters. To date, there have been no studies described in scientific literature that clarify how suitability of urban canals can be improved for transportation, TEE and recreation. Therefore, the aim of this study is to identify which characteristics of urban canals in European delta cities should be adapted to improve suitability of the water bodies for these three use functions. To reach this aim, we first assess the suitability of urban canals for transportation, TEE and recreation in two delta cities by applying Suitability Indices (SIs) for these uses (Van der Meulen et al., 2022). Next, we analyse the impact of alterations in the water system on the SI score for each use function to identify the required alterations for improving suitability. We use the cities of Amsterdam in The Netherlands, and Ghent in Belgium, as study sites. The results of the analysis provide novel insight in how suitability of urban canals for the selected human uses can be improved.

2 Method and study areas

2.1 Method

To analyse how suitability of urban canals can be improved for transportation, TEE and recreation, we analyse which alterations are needed to improve the Suitability Index score for these use functions. We use existing SIs that were developed for the biophysical and socio-economic context of the Netherlands (Van der Meulen et al., 2022). SI Transport is targeted at urban freight transportation, which includes transport of goods to and withing the city. SI TEE is targeted at heat extraction during warm summer months, seasonal storage and use of the thermal energy in winter (See Supplementary Information 7, Appendix S1, for a detailed explanation of the heat extraction process). SI Recreation is targeted at swimming by adults. A SI consists of parameters that describe water bodies' characteristics that determine suitability for a single use function. The parameters are each rated by a sub-index score and sub-index scores are integrated into the SI score. Parameters include chemical, microbiological and physical characteristics of surface waters (Table 4.1). Suitability is rated on a five-class scale: unsuitable (SI score=0), low (SI score=1), fair (SI score =2), good (SI score=3) or excellent (SI score=4). Water is unsuitable if use of the function is physically impossible. See Supplementary Information 7 (Appendix S1) and Van der Meulen et al. (2022) for more details about the SIs, including target values for the sub-scores.

Our analysis consists of a simplified optimization process in four steps to identify which alterations of the SI parameters are needed to increase the SI score by at least one class. First, the SIs are applied to determine current suitability of urban canals in our study areas for transportation, TEE and recreation. Secondly, we apply a local search algorithm to explore and evaluate the impact of hypothetically higher sub-scores on the SI score for each use function. The result shows which alterations in sub-scores lead to an increase of the SI score by (at least) one class. For this first analysis, we raise sub-scores by one class. For most parameters, this is expected to be more realistic to achieve in practice than larger sub-score improvements. 4 is the maximum for sub-scores and overall SI scores (Table 4.1). This procedure is repeated for all parameters of the SI. The procedure is also repeated for all possible combinations of two or more parameters. Finally, we indicate the order of magnitude of the required changes in the parameter values to reach a higher sub-score. To this end, we compare the average values of the parameters with the required values that lead to a higher sub-score. The calculation of the sub-scores and overall SI scores is done with ArcGIS and MS Excel software. Sub-scores are calculated by Boolean expressions that compare the parameter values to the scoring criteria. Overall SI scores are calculated by applying the integration method that is defined per SI (see Table 4.1).

Table 4.1: Characteristics of the Suitability Indices. The SI score is based on the integration of sub-scores for parameters that significantly influence the suitability for a specific use function. Target values for the sub-scores and the preconditions are given in Supplementary Information 7 (Appendix S1).

SI Characteristics	Suitability Index (SI)		
	SI Transport	SI Thermal Energy Extraction (TEE)	SI Recreation
Suitability based on:	Maximum possible ship size[a] for urban freight transport	Heat extraction capacity related to typical heat demand per house (40 GJ yr^{-1})	Health risk for adult swimmer
SI score classes:			
4 Excellent	Large Rhine vessel	≥ 1,000 houses	No or very low risk
3 Good	Barge	100-1,000 houses	Low risk
2 Fair	Specialized urban vessel	10-100 houses	Moderate risk
1 Low	Smaller than urban vessel	< 10 houses	High risk
0 Unsuitable	Precondition not met	Precondition not met	Precondition not met
Parameters (correlation with sub-score):	Depth (+) Width (+) Air draft (+)	Width (+) Discharge (+) Water temperature (+)	Depth at shore (-) *E. coli* (-) Cyanobacteria (-) pH (optimum at 7-8) Clarity (+)
Precondition:	Minimum depth in fairway	Minimum depth	Maximum depth
Integration: method	Minimum operator[b]	Geometric mean[c]	Minimum operator[b]

+: higher values for the parameter lead to higher sub-score

-: lower values for the parameter lead to higher sub-score

[a] See Supplementary Information 7 (Appendix S1) for ship dimensions

[b] $SI = Min(S_{i=1}^{n})$, where S_i is the sub-index score of the i-th parameter

[c] $SI = (\prod_{i=1}^{n} Si)^{1/n}$ where S_i is the sub-index score of the i-th parameter

2.2 Study areas

The cities of Amsterdam and Ghent are selected as study sites because they provide a comparable topographic, biophysical and socio-economic context, and an extensive network of canals and canalized rivers. Conducting the analysis in two cities, instead of one, will broaden the validity of this study. It is important that the study areas have a comparable climate, socio-economic context and geography because the SIs are context specific with respect to the parameters that are reviewed and their scoring criteria. Amsterdam and Ghent are low lying delta cities in North-western Europe with a moderate sea climate (Table 4.2). The two cities have highly managed surface water systems dominated by canals and canalized rivers. This provides ample opportunities to assess suitability of different types of canals and canalized rivers. Both cities face

Table 4.2: Characteristics of the study areas. T max.: maximum temperature, prec.: yearly precipitation (Beck et al., 2018; Copernicus Land Monitoring Service, s.a.; EEA, 2021a; Federale Overheidsdienst Binnenlandse Zaken, 2018; Gemeente Amsterdam, 2018b, 2018c; KMI, s.a.; Metropoolregio Amsterdam et al., 2018; Stad Gent, s.a.)

Characteristics	**Amsterdam (The Netherlands)**	**Ghent (Belgium)**
Geography[a]	Low land delta 25-35% water + adjacent lakes and waterways	Low land delta 2.1% water
Surface water	Rivers, canals, shallow and deep lakes, ponds	Rivers, canals, deep lake, ponds
Climate	Moderate sea climate T max. 5.8°C (Jan) to 22.1 °C (Aug), Prec. 897 mm	Moderate sea climate T max. 6.7°C (Jan) to 23.4 °C (Jul-Aug), Prec. 876 mm
Population density	3,850 per km² (total surface area), 5,178 per km² (land area)	1,643 per km² (total surface area)
Population 2018	854,047	259,570
Projected population growth	+18% by 2040	+3% by 2030:

[a]Percentages refer to the part of the surface area that is covered by water

population growth and densification (Table 4.2). Together with drivers like water quality improvements and climate change, this increases ambitions to use the surface water for uses like transportation, recreation or thermal energy extraction (Van der Meulen et al., 2020; VWW & Stad Gent, 2018).

The increasing ambitions for waterborne transportation are mainly targeted at local freight transportation, such as building materials or waste; ambitions to increase waterborne public transport are limited (Van der Meulen et al., 2020; VRT, 2021; VWW & Stad Gent, 2018). Water-related recreation includes, amongst others, swimming, canoeing, fishing and boating. In both cities, water-related recreation is important as a social, cultural and economic factor for both inhabitants and visitors. Demand for swimming in urban canals is increasing, even though they are not designated as bathing waters (PZC, 2020; Van der Meulen et al., 2020; VWW & Stad Gent, 2018). Demand for thermal energy extraction is especially increasing in Amsterdam, where the water is used for both heating and cooling (Van der Meulen et al., 2020).

Amsterdam is located in the Rhine-delta (Figure 4.1). Canals and rivers, such as Amstel River, transport water to the city. A large canal discharges into the North Sea, 25 km west of the city; this canal is also the main artery of the sea harbour. A fine network of smaller canals, with the highest network density in the historic city centre, covers the entire city.

Figure 4.1: Location of Amsterdam and Ghent in the Rhine- and Scheldt deltas

Ghent is located in the Scheldt-delta (Figure 4.1). Surface water enters and leaves the city through canals and the rivers Leie and Scheldt that confluence in the city centre. Other major waterways are the ring canal around the city and a large canal that leads from the harbour in the north of the city to the Scheldt estuary, approximately 30 km north of the city centre. Several smaller and larger canals connect the main waterways. Most canals and canalized rivers in both cities have vertical quay walls and some have a sloping bank with paved or unpaved slope and hard bank protection (Figure 4.2). Water levels in both cities are managed at a fixed level in almost all parts of the water system included in this research (VWW & Stad Gent, 2018; unpublished water levels map from AGV).

Respectively 99.9% and 96.6% of waste water is collected by the sewer system in Amsterdam and Ghent (VMM, 2022; Waternet, 2016), more than the average of 90% in Europe (EEA, 2021b). In 75% of Amsterdam, wastewater and storm water are collected separately (Waternet, 2016). In these separated systems, storm water is discharged directly into surface water and wastewater is transported to wastewater treatment plants (WWTPs). Area's developed before 1923, in the city centre, have a combined sewer system that transports all water to WWTPs (Waternet, 2016). In Ghent, most areas have a combined wastewater and storm water sewer system (Sumaqua, 2021). In both cities, combined sewer overflows occur during heavy rainfall.

Chemical and ecological water quality of the Amsterdam canals and river system is "bad" to "moderate" according to the European Water Framework Directive water quality classification (AGV, 2018; Ministerie van Infrastructuur en Milieu, 2018). While faecal pollution and eutrophication are locally declining, chemical pollution remains persistent (AGV, 2015). In Ghent, the physico-chemical status is "bad" to "insufficient", mainly due to eutrophication, and the ecological status is "bad" to "moderate" (Bekkensecretariaat Bekken van de Gentse Kanalen, 2016).

Figure 4.2: Most canals and canalized rivers have vertical quay walls (right, Schippergracht in Amsterdam), some have sloping banks with hard bank protection (left, Coupure in Ghent).

2.3 Data for Suitability Index analysis

Data are obtained from Dutch and Belgium water management authorities. Most data for Amsterdam are provided by the regional water authority Amstel, Gooi en Vecht (AGV) and the Municipality of Amsterdam. Most data for Ghent are provided by, or obtained from, the municipality Stad Gent, Vlaamse Waterweg (VWW) and Vlaamse Milieu Maatschappij (VMM).

The surface water system is divided into Hydro Units (HUs) by local authorities. HUs represent sections in a waterway with unique properties. If data are available for larger spatial units than the original HUs, they are merged into new HUs. In Amsterdam, length of the HUs varies between approximately 50 m and 300 m; in Ghent, length varies between approximately 100 m and 3 km. The analyses are performed for HUs with sufficient data. SI scores for transportation are calculated for respectively 319 and 41 HUs in Amsterdam and Ghent, and for TEE in 296 (Amsterdam) and 42 (Ghent) HUs. Due to the known high spatial variability of some water quality parameters, SI scores for recreation are calculated for point locations (12 locations in Amsterdam and 7 in Ghent). The available datasets in Amsterdam lack information for some of the largest national waterways that cross the city and the adjacent sea harbour. In Ghent, we also exclude the sea harbour outside the primary city area to support comparison with Amsterdam and to focus on urban waters.

For temporally variable parameters, we use available data from a recent 4-year period. We use the (interpolated) 5th or 95th percentile of the values, in order of increasing value, at a location to ensure that the suitability score represents the minimum suitability that is valid in 95% of the time. The analyses were first performed for Amsterdam with a dataset covering the period 2016-2019. To broaden the validity of this study, Ghent was later added as second study area. The available dataset covered 2018-2021, which is partly overlapping with the period covered by the Amsterdam dataset. In Amsterdam, most water quality parameters are measured at least monthly and we include locations with at least three years of data. In Ghent, such frequent monitoring is only available for three locations. Therefore, we also include locations with at least 3 days of water quality data. For discharge in Amsterdam, we use the 25th percentile because the 5th percentile is near zero in many locations due to flow direction variation. Because of the seasonal character of the activities, only data for the summer months April to September are used for SI Recreation, and data from the three warmest months are used for SI TEE.

Available datasets lack information for particular parameters. Cyanobacteria samples are only taken and analysed in case of a suspicion of cyanobacteria problems, e.g. visible algae blooms. For locations in Amsterdam where cyanobacteria data are lacking, water managers from AGV confirm that cyanobacterial blooms are absent or very rare. We therefore assume that cyanobacteria are not present. In Ghent, regular observation of potentially high concentrations only takes place at the recreational canal Watersportbaan. As the cyanobacteria registration contains no notifications for this water body, we assume that cyanobacteria are not present. For all other locations we assign a sub-score of 1 because the online register and local experts indicate that cyanobacterial blooms occur in many parts of the water system, so potential high concentrations cannot be ruled out. For clarity, the Ghent dataset includes less than three days of data outside three intensively monitored locations. However, at all locations the sub-score for this parameter is 1 based on available data. Because of the limited spatial and temporal variability of this parameter, we assume that the sub-score for clarity is always 1 in Ghent. Discharge data are not available for HUs in our analysis in Ghent. Therefore, we made indicative calculations for SI TEE with four scenarios for discharge. To retrieve depth information specifically for 1 m from the shore and at the deepest point in the waterways' profile, additional field measurements were performed by means of a lead line in Amsterdam and Ghent. See Supplementary Information 7 (Appendix S2) for more details on data and the complete dataset that was used to calculate SI scores.

3 Results and Discussion

3.1 Suitability and required interventions to improve the SI scores

3.1.1 Transport

In Amsterdam, suitability for transportation is fair in most waterways (Figure 4.3). Suitability is low (SI score=1), fair (SI score=2) or good (SI score=3) in respectively 17% (55 HUs), 76% (244 HUs), and 6% (20 HUs) of the HUs. Most HUs with low suitability represent short sections within waterways with fair suitability in the city centre. In Ghent, suitability for transportation of most waterways within the city centre is low (SI score=1) or fair (SI score=2), like in Amsterdam (Figure 4.3). Outside the centre, suitability ranges from low (SI score=1) to excellent (SI score=4). The ring canal around the city and a few sections in the southern part of the harbour have a good suitability (SI score=3). Canals with excellent suitability (SI score=4) are all located in the sea harbour in the north.

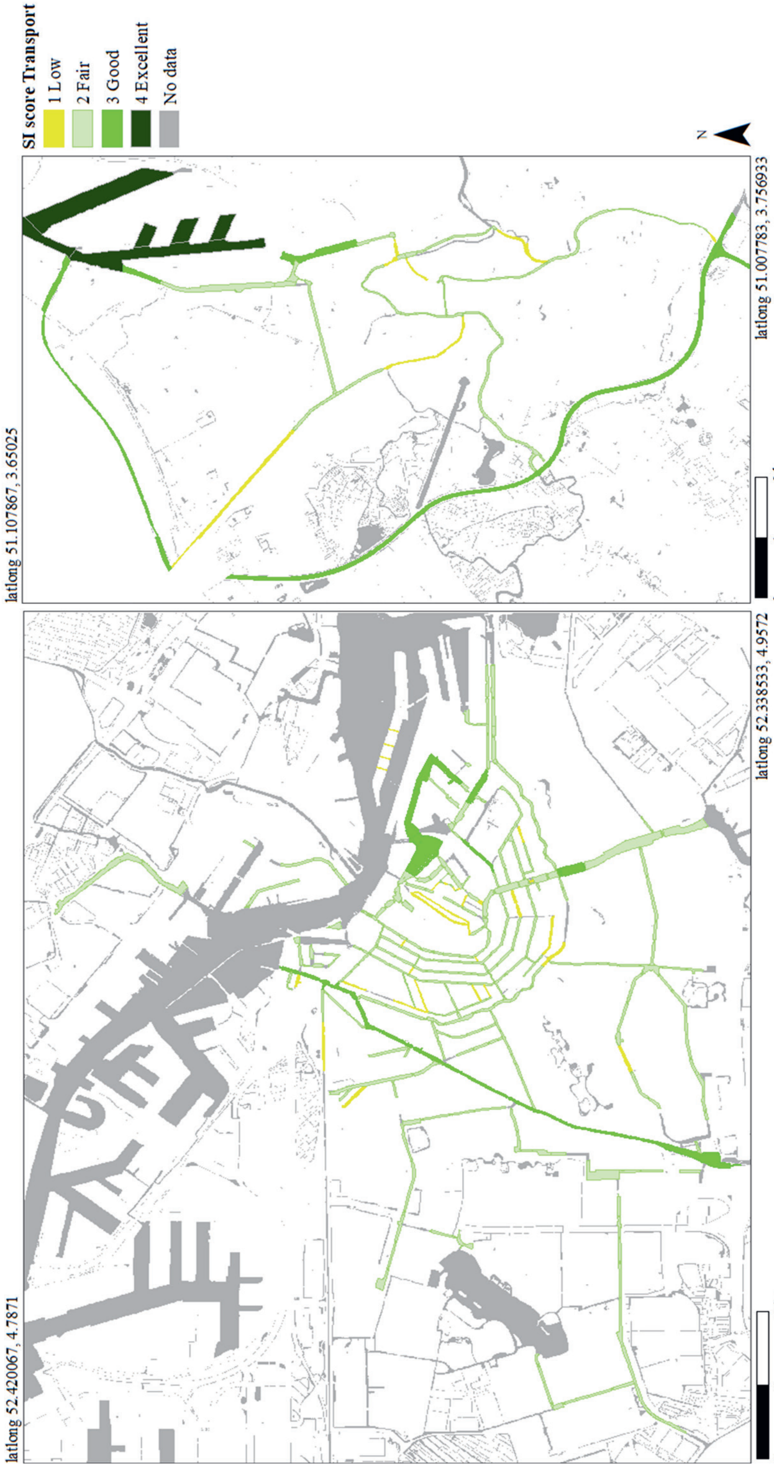

Figure 4.3: SI Transport scores in Amsterdam (left) and Ghent (right). The map for Amsterdam was previously published, with minor alterations, in Supplementary Information in Van der Meulen et al. (2022)

For all HUs with a SI score lower than 4, the impact of raising sub-scores by one class for depth, width and air draft is assessed. In Amsterdam, improving suitability for transportation usually requires higher sub-scores for multiple parameters (Figure 4.4). HUs with low suitability (SI score=1) are an exception to this. In 65% of these HUs, the SI score can be raised by improving just one parameter; elsewhere a combination of increased depth, width and/or air draft is required. On average, the required increase is 0.3 m for depth, 1.9 m for width and/or 0.5 m for air draft in HUs where these parameters are limiting the SI score to 1. To increase suitability from fair (SI score=2) to good (SI score=3), both depth and air draft need to be increased in most cases (Figure 4.4). In many HUs (38%), mostly in the inner city (Supplementary Information 7, Figure S2), width needs to be enlarged as well. On average, the required increase is 1.0 m for depth, 5.7 m for width and/or 1.7 m for air draft in HUs where these parameters are limiting the SI score to 2. For HUs with good suitability (SI score=3), a combination of depth and width is most frequently (in 85% of the HUs) required to improve suitability further (Figure 4.4). On average, the required increase is 2.6 m for depth and 14.8 m for width in HUs where these parameters are limiting the SI score to 3.

In contrast to Amsterdam, air draft is not limiting suitability in HUs with low or fair suitability in Ghent (Figure 4.4). Some bridges are lower than 4 meters, the lower boundary for air draft sub-score 3, but these are movable bridges. To raise suitability from low (SI score=1) to fair (SI score=2) always requires increased width, mostly at locks (Figure 4.4). On average, the required increase is 1.6 m in HUs where width is limiting the SI score to 1. Improving suitability from fair to good (SI score=3) requires increased depth and width; in a few cases improving just one of these is sufficient (Figure 4.4). On average, the required increase is 1.0 m for depth and 5.9 m for width. In some HUs, the SI score will increase if width is enlarged at specific spots, usually engineering structures like bridges or locks; in other cases, the entire profile of the waterway should be enlarged. To improve suitability from good (SI score=3) to excellent (SI score=4) in the ring canal requires larger depth, in the southwestern section in combination with air draft and in

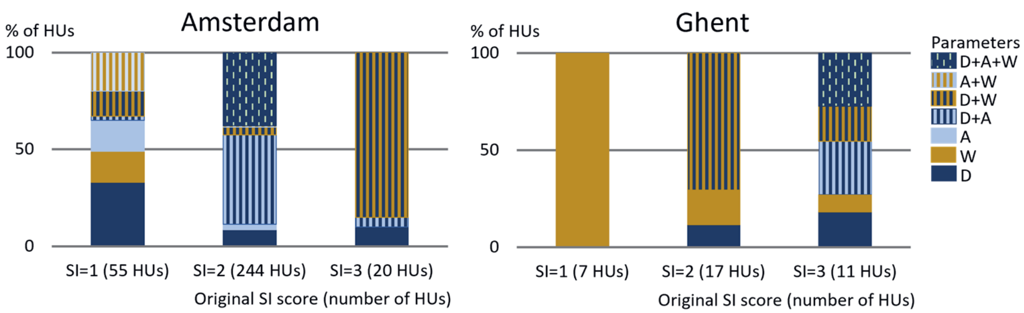

Figure 4.4: The percentage of HUs where improving the original SI score for Transport by one class requires increasing the sub-score for depth (D), width (W) and/or air draft (A) by one class. (Combinations of) parameters are not shown if raising their sub-score is not required or not sufficient to increase the SI score.

the northern section in combination with width at bridges and locks and sometimes also air draft (Figure 4.4). On average, the required increase is 2.4 m for depth, 11.3 m for width and 3.4 for air draft in HUs where these parameters are limiting the SI score to 3.

The results show that suitability for transportation can improve by increasing depth, width and/or air draft, with large variations within and between the study areas. Larger water depth may be achieved by dredging or by removing or adjusting under water structures. Water level management can be considered in transects where water level is controlled by locks or sluices. However, apart from short sections with low suitability in Amsterdam, the required increase of depth is quite large (>1 m) which may not be feasible in practice. Especially in Amsterdam, increasing water levels through water level management is not an option as suitability will only improve in many HUs by increasing both water depth and air draft. Raising the water level to increase water depth results in a decrease in air draft. To increase air draft, an alternative to raising or removing fixed bridges is to replace them by movable bridges. The benefits of movable bridges are illustrated by the fact that in Ghent, air draft is less frequently limiting the suitability score for transportation compared to Amsterdam. When assigning a suitability sub-score for air draft, movable bridges are treated the same as open water. However, depending on the operation practice their presence may lead to waiting times and thus longer travel time. Travel time is an important performance indicator for logistic operations (Van Duin et al., 2017) and therefore this aspect should be taken into account when a detailed assessment for investment decisions is made. The requirement to increase width sometimes involves widening of the channel, sometimes engineering structures like locks and bridge piers are limiting suitability. Widening of the channel (on average 2-15 m) may be challenging since space in an urban setting is limited, but it may be feasible at the expense of other uses of space like parking lots or sidewalks. Alterations to quay walls and engineering structures like bridges or locks may also be limited by technical constraints.

3.1.2 Thermal energy extraction

In Amsterdam, suitability for TEE is mostly good (Figure 4.5). Suitability is fair (SI score=2), good (SI score=3) or excellent (SI score=4) in respectively 2% (n=7), 73% (n=216) and 27% (n=73) of the HUs. Suitability in Ghent is uncertain due to a lack of discharge data. Calculations with different hypothetical discharge sub-scores show that, like in Amsterdam, suitability for TEE is expected to be at least fair (SI score=2). If we assume the worst-case scenario in which the sub-score for discharge is 1 everywhere, suitability for TEE is fair (SI score=2) in most canals in and around the city centre (Figure 4.5); suitability is good (SI score=3) in the largest canals in the south part of the sea harbour area.

For HUs with an original SI score lower than 4, the impact of raising sub-scores by one class for width and/or discharge is assessed. The sub-score for temperature is already 4,

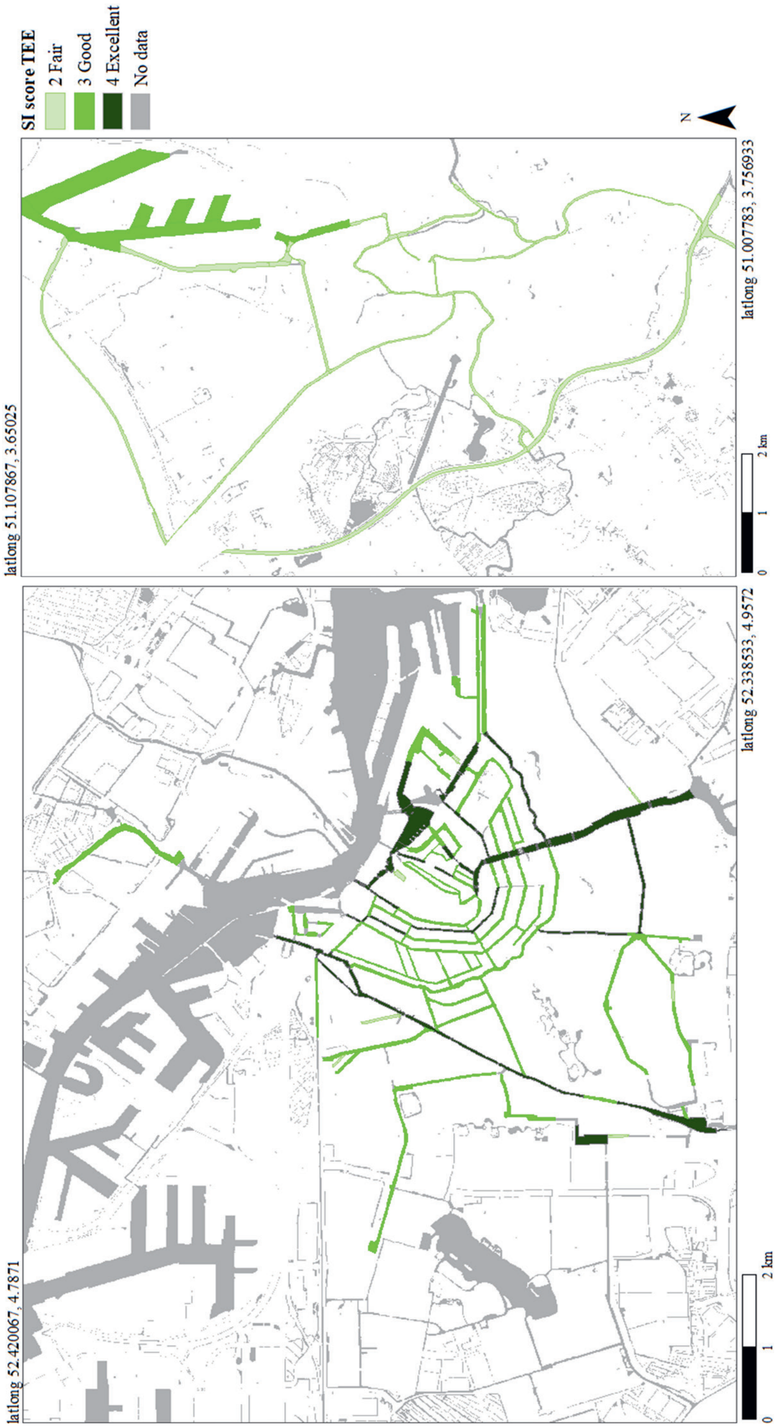

Figure 4.5: SI TEE scores in Amsterdam (left) and Ghent (right). SI TEE scores for Ghent are hypothetical scores based on the assumption that discharge sub-scores are 1 everywhere. The map for Amsterdam was previously published, with minor alterations, in Supplementary Information in Van der Meulen et al. (2022).

the maximum sub-score, in all HUs in both cities and therefore does not limit suitability. In most HUs in Amsterdam, improving suitability for TEE requires increasing either width or discharge, it does not matter which one of the two. For HUs with fair suitability (SI score=2), improving one of these parameters always results in a higher SI score (Figure 4.6). In 13% of the HUs with good suitability (SI score=3), the SI will only increase if both width and discharge are improved (Figure 4.6). Required changes for width and discharge are substantial. E.g., current width and discharge values in Amsterdam HUs with good suitability are on average 27 m (average sub-score width=3) and 0.14 m^3 s^{-1} (average sub-score discharge= 3). To raise the sub-scores for these parameters to 4, values need to increase to ≥ 100 m or ≥ 0.3 m^3 s^{-1} (see also Supplementary Information 7, Appendix S1).

In Ghent, we use different scenarios for discharge sub-scores to deal with the lack of discharge data. If the discharge sub-score is assumed to be 1, improving suitability from fair (SI score=2) to good (SI score=3) requires higher discharge or width, like in Amsterdam (Figure 4.6). Current width in HUs with fair suitability is on average 40 m (average sub-score width=3), assumed discharge is <0.003 m^3 s^{-1} (sub-score discharge=1); to raise the sub-scores by one class requires width to become ≥ 100 m or discharge > 0.003 m^3 s^{-1}. To raise suitability from good (SI score=3) to excellent (SI score=4), discharge should be raised at least two classes, which requires a value of > 0.03 m^3 s^{-1} (Supplementary Information 7, Appendix S1). In other discharge scenarios, the required alterations in the water system vary between higher discharge, discharge *and* width, and either discharge *or* width.

These results show that in most waterways, increasing width or discharge is required to improve suitability for TEE. Since width needs (on average) a factor 3 increase to achieve a higher SI score and space in limited in a city, increasing discharge may be a more feasible option. This may be implemented in specific waterways where demand for

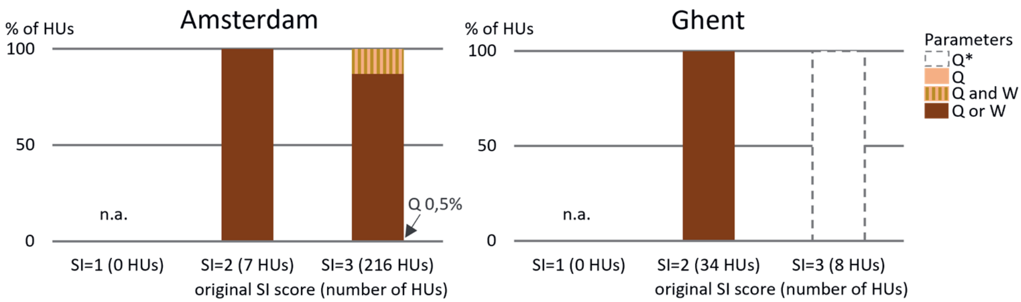

Figure 4.6: The percentage of HUs where improving the original SI score for TEE by one class requires increasing the sub-score for discharge (Q) and/or width (W) by one class. In Ghent HUs with originally SI score =3, increasing the SI score requires increasing the sub-score for discharge by 2 classes. (Combinations of) parameters are not shown if raising their sub-score is not required or not sufficient to increase the SI score. n.a.: not applicable.

thermal energy is higher than the potential supply. This measure was also suggested in a case study by Van der Brugge et al. (2022). Since European delta cities like Amsterdam and Ghent have highly managed water systems, it may be feasible to direct more water to specific waterways to increase flow. However, this opportunity may be limited during dry periods, as illustrated by reported temporal water shortages during summer in one of the canals that feeds the surface water system of Ghent (Sumaqua, 2021). Hydrological droughts are projected to become more frequent and severe in many parts of Europe including, but less strongly, in the temperate North-western Atlantic region (EEA, 2017). Alternatively, it might be sufficient to install a surface water circulation system rather than supply water from an external source to regenerate the temperature of the surface water after heat extraction. Local hydrological assessments can give more insight into the opportunities and constraints for managing discharge, which in a highly managed water system is strongly impacted by policy choices and prioritization of water use (Sumaqua, 2021).

3.1.3 Recreation

Suitability for recreation is low (SI score=1) at all assessed locations in Amsterdam and Ghent (Figure 4.7). The impact of raising sub-scores by one class for *Escherichia coli* (*E. coli)*, cyanobacteria, pH, clarity and depth is assessed.

In both cities, the SI score can only be raised from low (SI score=1) to fair (SI score=2) by improving the sub-score for clarity alone or in combination with other parameters (Figure 4.8). In Amsterdam, improving clarity only is sufficient in 50% of the locations; these locations are all situated outside the city centre (Supplementary Material 7, Figure S3). At five of the twelve locations (42%), the SI score will only improve by increasing sub-scores for clarity and *E. coli* (Figure 4.8). At one of these locations, the sub-score for cyanobacteria also needs to be improved to raise the SI. In Ghent, raising the sub-score for clarity alone leads to higher SI scores at two of the seven locations. These are located in a canal that is designated for recreation but not designated as bathing water (Supplementary Information 7, Figure S4). Elsewhere, improving suitability also requires better sub-scores for cyanobacteria, and in two cases also for *E. coli*. If cyanobacteria are monitored at all locations, some may receive a higher sub-score for this parameter.

On average, the required increase in clarity is >0.70 m in Amsterdam and >0.75 m in Ghent to reach at least 1.2 m clarity (measured as secchi disk transparency), which is required for sub-score 2. *E. coli* concentrations need to be reduced by approximately a factor of 2.9 (Amsterdam) and 1.6 (Ghent), from on average 3,020 cfu 100 ml^{-1} and 1,190 cfu 100 ml^{-1} respectively. At one location in Amsterdam, cyanobacteria need to be reduced by approximately 11%.

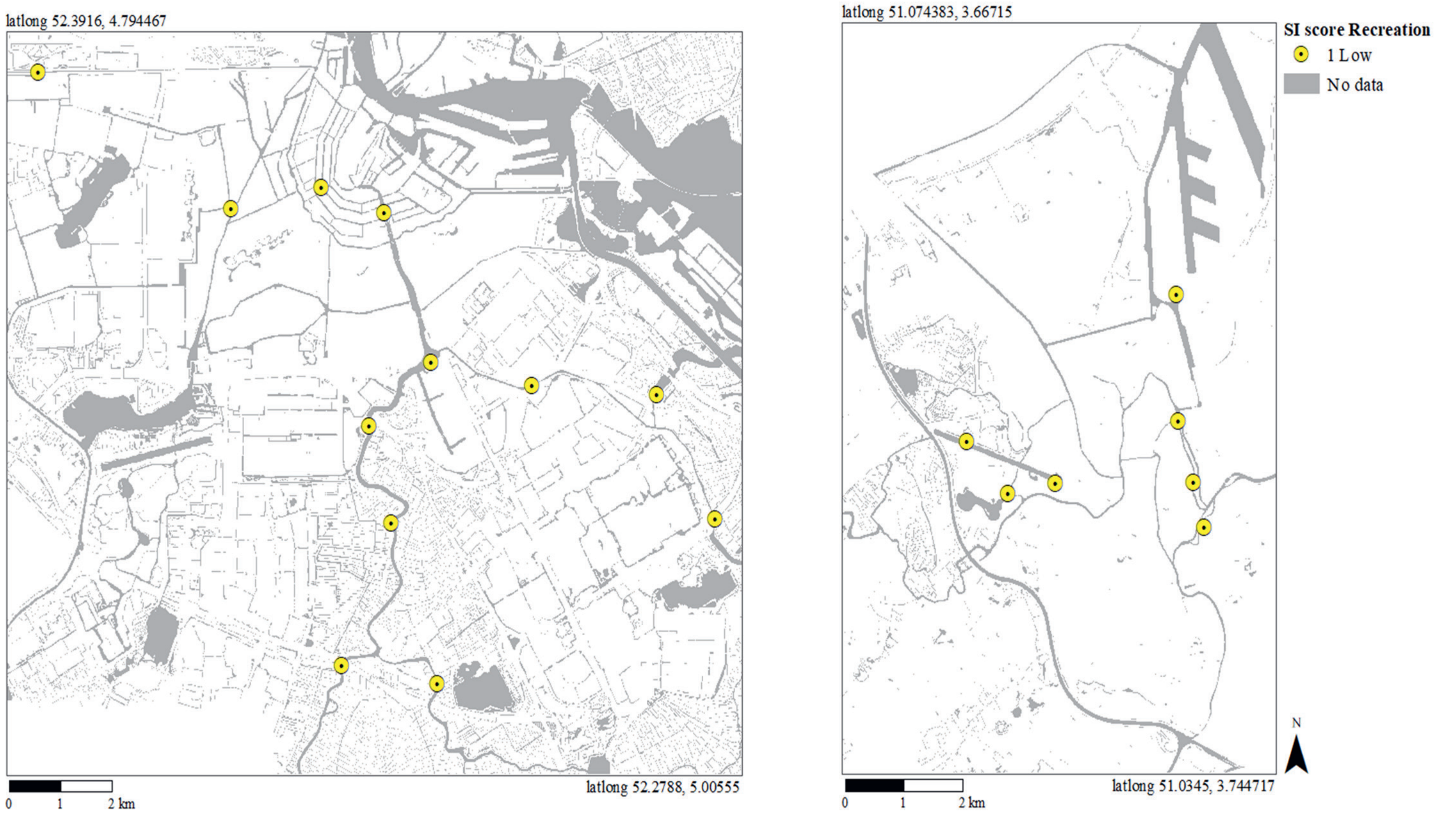

Figure 4.7: SI Recreation scores in Amsterdam (left) and Ghent (right). The map for Amsterdam was previously published, with minor alterations, in Supplementary Information in Van der Meulen et al. (2022).

Chapter 4

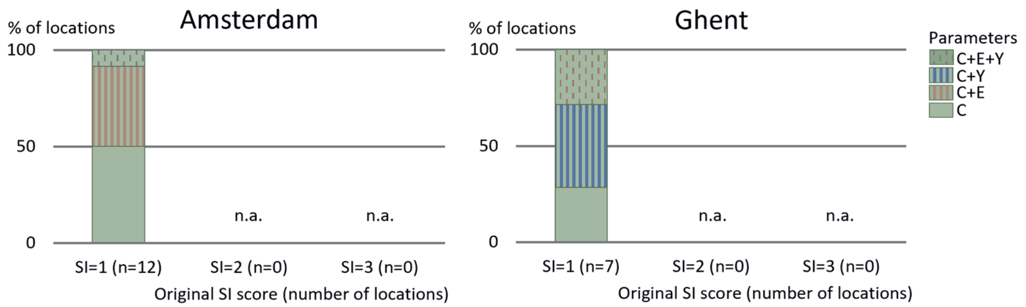

Figure 4.8: The percentage of HUs where improving the original SI score for Recreation by one class requires increasing the sub-score for clarity (C), *E. coli* bacteria (E) and/or Cyanobacteria (Y) by one class. Parameters, or combinations of parameters, are not shown if raising their sub-score is not required or not sufficient to increase the SI score. n.a.: not applicable.

Additionally, we also assessed which changes in sub-scores are needed to further increase the SI score to 3 (good) because improving sub-scores more than one class may be feasible for some water quality parameters. In Amsterdam, this requires larger improvements for clarity, *E. coli* and cyanobacteria and additionally, at some locations depth should be reduced. The same holds for Ghent. While in Amsterdam the sub-score for pH is never lower than 3, in Gent pH should be improved at one location to achieve a SI score of 3. There is a clear difference between the recreation canal Watersportbaan and the other waterways. At Watersportbaan, achieving good suitability (SI score=3) only requires raising sub-scores for clarity to 3.

The fact that clarity is limiting suitability for recreation at all locations may indicate that improving this parameter will be difficult. However, due to Covid restrictions that resulted in less boat traffic, clarity in Amsterdam canals improved from less than 1 m to more than 1.5 m at some locations in March-April 2020 (BNNVARA, 2020; H2O, 2020). The same phenomenon was observed in canals in Venice, Italy (The Guardian, 2020). This indicates that boating restrictions may help to improve clarity locally. Further local assessment is needed to identify the cause(s) of limited clarity. Besides resuspension of sediment by navigation, it may be caused by inflow of turbid wastewater or storm water, phytoplankton or aquatic humus (Davies-Colley et al., 2003). An example from Vienna, Austria, shows how restoration measures that reduced eutrophication of an urban lake resulted in higher clarity (Teubner et al., 2020). If it is not feasible to improve clarity, an alternative solution may be to assess and take away the risks that are not visible due to limited clarity such as sharp objects under water. This approach is implemented by organizers of the Big Jump swimming event in Ghent (Hannes Cosyns, personal communication, 8 juli 2021) and before the swimming season by water management organization Waternet in Amsterdam (Liesbeth Hersbach, personal communication). For reducing *E. coli* to improve its sub-score, permanent or intermittent sources of faecal pollution should be identified. Important potential sources of faecal pollution are WWTP discharge, combined sewer overflows, sewer system failures, or animals like birds (EEA, 2016a). If the sources are taken away, *E. coli* sub-scores can immediately raise more than one class. The potential effectiveness of measures to reduce bacteria concentrations can be simulated with models that take into account dilution and bacterial decay (Von Sperling & Von Sperling, 2013). General strategies to prevent cyanobacterial blooms include reduction of external and internal nutrient inputs, artificial mixing of stagnant water, increasing water flow to avoid stagnant water and reduce residence time, and biological control measures such as introduction of zebra mussels that filter out cyanobacteria (Huisman et al., 2018).

3.2 Compatibility of the required improvements for transport, thermal energy extraction and recreation

The required changes in the water system to increase suitability for transport, TEE and recreation are compatible with each other. The required changes per use function do not have an adverse effect on the SI sub-scores for the other functions. For example: improving suitability for recreation requires increased clarity. This is not a parameter that determines the SI score of TEE or transportation (see Table 4.1), thus changes will not affect suitability for these uses. There is one exception: if depth is enlarged to optimize for transportation, this may affect suitability for recreation. Especially when deepening close to the shore, the sub-score for depth in SI Recreation may decline. Opportunities for synergy exist as well; TEE and transport both benefit from enlarged width, although TEE needs a larger increase to achieve a higher sub-score than transport. Increasing discharge is beneficial to TEE and indirectly also to recreation as it may potentially improve water quality parameters like cyanobacteria concentration.

While the required alterations in the water system are mostly compatible between the three analysed use functions, simultaneous use in space and time may lead to conflicts. For example, shipping may induce reduced clarity and lead to collision risk to swimmers. Some trade-offs can be managed by temporal and/or spatial delineation of conflicting uses (Day et al., 2008; Gemeente Amsterdam, 2016). This strategy may also be implemented when human uses conflict with protection of ecological quality of aquatic ecosystems.

3.3 Novel insights

This study provides new insight into the suitability of urban canals for transportation, TEE and recreation in two delta cities, and identifies opportunities to enhance the suitability. Whereas other studies have provided insights into the feasibility of different urban water transportation concepts (Maes et al., 2012; Van Duin et al., 2017), this study shows how the canals themselves can be optimized for transportation of goods to and within the city. Maes et al. (2012) stated that scaling up of waterborne urban freight transportation is hampered by the dimensions of the existing infrastructure. In this study, we specify which dimensions have to be altered to improve suitability for transportation in Amsterdam and Ghent. Maes et al. (2015) state that adjusting vessels to reduce the required water depth and air draft is a better solution than expanding water capacity for transportation because of issues related to physical limitations, costs and potential environmental impact. We expect that these issues will be less of a bottleneck when improving suitability of short sections in the canal network. Our results show that in both study areas, the entire canal and river network can become suitable for existing special urban freight vessels by improving depth, width and/or air draft in short sections with low suitability.

This study shows that smaller to larger urban canals in two delta cities have a fair to excellent suitability for TEE. Additionally, our analysis shows how suitability of these waterways for thermal energy extraction may be improved by increasing width or discharge. These insights complement previous studies on surface water as a heat source that have shown the significant potential of heat extraction from inland waters at the regional or national scale, often targeting larger rivers, canals and/or lakes (e.g. Department of Energy & Climate Change, 2015; Kruit et al., 2018; Lund & Persson, 2016).

This is the first study that shows which characteristics of urban canals should be altered to improve suitability for primary contact recreation. To improve the low suitability in Amsterdam and Ghent to a fair level, clarity should be increased, often in combination with a reduction of faecal pollution (for which *E. coli* bacteria are used as indicator) and/or cyanobacteria. These findings are in line with a study in a tropical urban lake (Azevedo Lopes et al., 2020) that showed that suitability for contact recreation was most limited by low visual water clarity, faecal contamination and cyanobacterial blooms. The role of faecal pollution also has been reported in analyses of gastrointestinal illness outbreaks under urban canal or river swimmers in European cities (Hall et al., 2017; Joosten et al., 2017). Studies in designated bathing water typically focus on water quality parameters only (e.g. Azevedo Lopes et al., 2020; Nagels et al., 2001). Our study in urban waterways, that are not designated bathing waters, indicates that for further improvement of the suitability for primary contact recreation to a good or excellent level, more parameters need to be considered, especially depth close to the shore.

3.4 Limitations and suggestions for future research

We analysed the impact of increasing sub-scores lower than 4, the maximum score. In practice, enhancing parameters that are already classified as excellent (sub-score=4) may improve suitability for a use function. For example, SI TEE will not improve if water temperature increases since the sub-score for this parameter is already 4 in all locations. However, expected increase of water temperature of inland waters in Europe due to climate change (EEA, 2017) may extend the heat extraction season and hence enforce the opportunities for TEE.

Quality of the results is influenced by the reliability of the available data to calculate the current SI scores. Subsequently, this may influence which parameters are identified as limiting the suitability. First, SI parameter values in the available datasets may differ from the actual situation in the field. For example, the dataset in Amsterdam describes the smallest width of the canal itself, not taking into account smaller sections at engineering structures like bridge piers and locks. Especially in larger waterways, sub-scores for width could be lower if detailed bathymetric data could be used. Secondly, the available data in Amsterdam and Ghent are not entirely comparable for some parameters. This applies mainly to the data on waterway dimensions since data are collected by different methods and the varying lengths of the HUs. Thirdly, most uncertainty is related to the results for TEE and Recreation in Ghent due to the lack of discharge and cyanobacteria data. Sub-scores for cyanobacteria in Amsterdam are partly based on expert judgement which also reduces reliability.

As a consequence of the abovementioned issues, parameters may be wrongfully identified as the limiting factor for suitability of a use function. However, the average required change in parameter values to reach a higher sub-score are substantial (section 3.1.1-3.1.3). This indicates that the general insights from this study are valid.

The results from the two case studies indicate that enhancing suitability for transportation requires locally specific alterations in the canal system. For TEE and recreation, the parameters requiring improvements are more comparable between the two cities. This may indicate that the results are also relevant to other European delta cities. The insights from this study provide a solid foundation for more detailed local assessments to support management and planning decisions, and for future research in other cities and for more use functions. To improve knowledge on the functional quality of urban canals and how suitability can be enhanced, we advise to start targeted monitoring and/or modelling campaigns in multiple cities.

To support planning of urban water use, trade-offs between human uses, and between human uses and ecological conditions require further research. Studies from other surface waters cannot be translated directly to urban canals but provide a basis for further research. For example, studies on the impact of shipping on marine aquatic ecosystems or large rivers identify potential impacts of transportation (Jägerbrand et al., 2019; Que et al., 2020). The impact of TEE in the form of heat extraction and subsequent cold water discharge is hardly studied (Harezlak, 2021; Van Megchelen, 2017). General knowledge on the ecological impact of changes in water temperature and the impact of transport through filters on aquatic organisms can be translated into hypotheses for research on the impacts of TEE in urban canals (De Jong & Dionisio Pires, 2022; Ellwood et al., 2012; Harezlak, 2021; Thackeray et al., 2013). Research in non-urban streams showed that bathing activities result in environmental impacts like higher *E. coli* bacteria concentrations, reduced clarity, higher nutrient concentrations and habitat disturbance

(Butler et al., 2021; Phillip et al., 2009). It is likely that these impacts also occur in urban canals. This may be verified with research in urban canals with different environmental background conditions and bathing practices.

5 Conclusions

This study provides first insights on how suitability of urban canals and canalized rivers can be improved for transportation, thermal energy extraction and recreation in the cities of Amsterdam and Ghent. The required alterations for width, depth and air draft to improve suitability for transportation vary between and within these cities. However, in both cities the entire canal system can become at least suitable for specialized urban freight vessels if bottlenecks in short sections of low suitability are resolved. The canals have fair to excellent suitability for TEE; improving suitability for thermal energy extraction in most cases requires an increase in either width or discharge. The low suitability for recreation in both cities can only be improved by increasing clarity, often in combination with a reduction of faecal pollution and/or cyanobacteria. These results complement insights from studies in other water types and from studies that focus on factors other than water body characteristics that influence the use potential of urban water. In this study, we analysed how the Suitability Index scores of existing waterways can be increased by adapting parameters that limit suitability. The same methodology can be applied to designs for yet to be created waterways or to be reopened historic canals, in Ghent, Amsterdam and other cities.

Chapter 5
General discussion and conclusions

5.1 Introduction

Urban surface waters are rediscovered as important resources and part of the public space in urban areas. After a period of filling in and covering of urban surface waters, because of poor water quality and to create more space on land (Buchholz & Younos, 2007; Conradin & Buchli, 2003; Hintz et al., 2022; Lin et al., 2020; Napieralski & Welsh, 2016), canals and streams are now being reopened and restored (Buchholz et al., 2016; Khirfan et al., 2020; Wild et al., 2019). Also with ongoing urban development, new surface water bodies are created and the connection between land use and water is enforced. The latter is illustrated by waterfront development in many cities that follows from the transformation of former industrial harbour areas into residential areas and cultural hotspots (Feilberg & Mark, 2016; bostonplans.org; toronto.ca/city-government/planning-development/waterfront; portofrotterdam.com). It is likely that urban (re)development and population growth, together with local water quality improvements and multifunctionality ambitions will change and increase demand for human use functions of urban surface water.

To manage all different uses of urban water and to ensure that surface water is fit for purpose, it is important to take the desired functionality into consideration during planning, design, and maintenance of surface waters. Such function-oriented water management requires insight into the *functional quality,* the suitability for specific human use functions, of surface waters. To date, no assessment framework is available that enables structured analysis of the functional quality of urban surface waters and that is applicable to all kinds of individual human use functions. The widely used water quality indices (WQIs) are not suitable for this because of their focus on traditional water quality parameters. Another limitation of many WQIs is that water quality is defined by the number of potential uses (Alvareda et al., 2020; Lumb et al., 2011; Shree & Brema, 2019), thus ignoring the urban water resources management (UWRM) principle that water should be fit-for-purpose (Hering & Vairavamoorthy, 2018; Mosleh & Negahban-Azar, 2021). Research on the functional quality of urban surface water is also hampered by the limited insight into the actual use of urban surface waters and the demand for human use functions in the near future. Urban water supply and demand assessments are usually limited to water extractions, especially for drinking water production and irrigation (e.g. Exall & Vassos, 2012; Padowski & Gorelick, 2014). Ecosystem services literature highlights other potential uses of urban surface water (Blicharska & Johansson, 2016; Haase, 2015; Hossua et al., 2019; Persson, 2012; Van der Meulen et al., 2016) but almost all of these publications do not provide evidence for the actual use of the surface water.

The overall aim of this research was to develop an assessment framework for functional quality of urban surface water. To determine which use functions are relevant to include in the assessment framework, actual use of surface water and expected demand in the next decades were assessed in two different urban contexts (Chapter 2). To develop a framework that is well grounded in state-of-the-art water research- and management concepts, a method was defined building on existing approaches for water quality and ecosystem services assessment (Chapter 3). Applicability and added value of the assessment framework were determined by applying the assessment framework in two cities (Chapters 3 and 4). The next sections of this chapter provide a discussion on the novel contributions of this thesis to the scientific field of urban water management, the limitations of this research, recommendations for future research and recommendations for practical water management.

5.2 Contributions to the scientific field of urban water management

5.2.1 A novel assessment framework for functional quality of urban surface waters

This thesis contributes to the field of urban water management with a novel assessment framework in the form of Suitability Indices (SIs) for human use functions (Figure 5.1). The framework enables assessment of the functional quality of urban waters in addition to the classification of their ecological quality. Insight in functional quality provides an additional perspective to water research, for example for studies on the impact of changes in urban surface water systems due to climate change or management interventions.

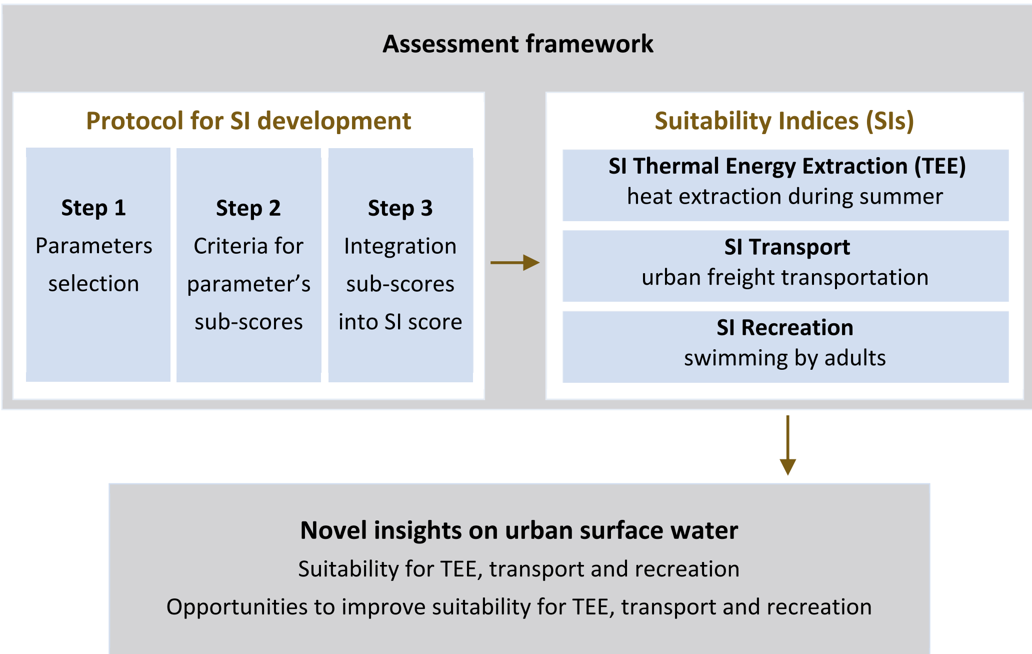

Figure 5.1: This thesis provides a novel assessment framework for functional quality of urban surface water in the form of Suitability Indices for single use functions. The protocol for SI development is used to develop three SIs. Application of these SIs has provided novel insights into the functional quality of manmade and highly modified urban surface waters.

The framework was developed by combining knowledge from the fields of water quality research and ecosystem services. A SI consists of parameters that describe the water body characteristics that determine suitability for a specific human use function. The basic model for SIs builds on the concept of widely applied WQIs (Borges Garcia et al., 2018; Lumb et al., 2011), with SI parameters that are each rated by a sub-score, and sub-index scores are integrated into the SI score. The generic protocol for SI development (Chapter 3) considers water quality, -quantity and flora & fauna parameters, based on the user requirements of hydrological ecosystem services (Brauman et al., 2007; Hallouin et al., 2018). This differs from WQI's, which typically use water quality parameters to classify water quality as a grade of pollution or naturalness (Alvareda et al., 2020; Borges Garcia et al., 2018; Lumb et al., 2011). As a result of the broader set of potential parameters, SIs can be used to review suitability of water bodies for all kinds of use functions in a consistent manner. This includes those that are not, or not entirely, dependent on traditional water quality parameters. Another advantage of the SI approach is the focus on single use functions. This enables assessment of the suitability for use functions that are relevant for a specific urban context and thus acknowledges the UWRM principle that water should be fit-for-purpose (Hering & Vairavamoorthy, 2018; Mosleh & Negahban-Azar, 2021).

In this thesis, the generic protocol for SI development is used to develop SIs for three use functions: SI Thermal Energy Extraction (TEE), SI Transport and SI Recreation (Figure 5.1). These use functions are selected based on their importance in the near future (Chapter 2). Application of the SIs for two cities shows how the framework makes it possible to gain new insights into the functional quality of urban surface waters and to identify opportunities to improve it.

5.2.2 New insights into the functional quality of canals and canalized rivers in European delta cities

This thesis contributes to the yet limited knowledge base on the functional quality of urban canals and canalized rivers. The focus on these manmade and highly modified waters is relevant because they are underrepresented in water research (Koschorreck et al., 2020), even though they form a major part of urban surface water systems. Application of SI TEE, SI Transport and SI Recreation provides novel insights into the suitability of canals and urbanized rivers for three use functions that are expected to become increasingly important in the near future (Figure 5.1).

The SI TEE assessments in Amsterdam and Ghent show that even relatively small and medium sized urban waters can play a role as a heat source in the ambitions (Chapter 2; ec.europa.eu/cip/iee) to use surface water as a source of thermal energy and to reduce fossil fuel use for heating in this way. In Amsterdam, suitability of canals and canalized rivers for TEE is mostly good to excellent; the indicative analysis in Ghent shows that suitability is at least fair in the worst-case scenario (Chapter 4). These insights complement the previously demonstrated potential for heat extraction from usually larger water bodies in regional or national studies (Department of Energy & Climate Change, 2015; Kruit et al., 2018; Lund & Persson, 2016). Suitability for TEE can be improved by increasing either waterway width or discharge. The latter is also suggested by Van der Brugge et al. (2022) in a regional Dutch case study. In a highly managed urban water system, increasing discharge seems more feasible than increasing width of the waterway as this requires a large increase and space is generally scarce. The results from Amsterdam and Ghent are also relevant to other cities with comparable climate and with canals and rivers of comparable width and discharge, because the conditions of the parameters of SI TEE will be comparable.

The SI Transport analyses in Amsterdam and Ghent show that in both cities, the entire canal and river system can become suitable for specialized urban freight vessels by increasing water depth, width and/or air draft in short sections of low suitability (Chapter 4). This is an interesting opportunity considering the growing demand for waterborne urban freight transportation, including the 'first and last mile', in response to road congestion and sustainability ambitions (Chapter 2; EC, 2021; Hallock & Wilson, 2009; Janjevic & Ndiaye, 2014). Low suitability is predominantly found in the historic city centres. Elsewhere, suitability for transport ranges mainly from fair to good or excellent. Improving suitability in that part of the water network requires alterations of multiple parameters in many long sections of the waterways. This observation supports the statement by Maes (2015) that adjusting vessels may be a more feasible solution than enlarging the waterways dimensions. As the same suitability pattern is found in both cities, it may be applicable to other cities. Moreover, it is plausible that manmade canals and engineering structures like bridges and locks from the same era in other cities have comparable designs.

It is notable that SI Recreation analyses in Amsterdam and Ghent show that suitability for recreation in the form of swimming by adults is low at all study sites (Chapters 3 and 4). This indicates that the growing number of swimmers in urban waters (De Jong et al., 2022; Hintaran et al., 2018) are faced with relatively high health and safety risks. Based on the low sub-scores for specific SI parameters, these risks are mainly related to low water clarity (which hides potential submerged physical dangers like sharp objects or potholes), faecal pollution (indicated by *E. coli* bacteria), and/or cyanobacteria (potentially producing toxins). To a lesser extent, suitability of urban canals and canalized rivers in Amsterdam and Ghent is limited by deep water close to the shore or sub-optimal pH values. Clarity, *E. coli* and cyanobacteria were also identified as limiting factors for the suitability of a tropical urban lake for primary contact recreation (Azevedo Lopes et al., 2020), and cyanobacteria blooms are identified as health risk in an urban lake in Greece (Gkelis et al., 2014). Faecal pollution was identified as potential cause of outbreaks of gastrointestinal illness amongst swimmers in urban canals (Joosten et al., 2017) and an urban river (Hall et al., 2017) in respectively Utrecht and Amsterdam (The

Netherlands) and London (UK). The similarities between Amsterdam and Ghent indicate that the suitability of urban waters, that are usually not designated and managed as bathing water, may also be low in other north-western European delta cities. This low suitability hampers the ambitions of societal actors to create more opportunities for bathing in these waters (Mouchel et al., 2020; Ruby & Shinohara, 2019; gentsmilieufront.be). Chapter 4 demonstrates how an optimization analysis for SI Recreation can be used to identify which alterations are required to improve the suitability for swimming at a specific site.

5.2.3 Future urban surface water demand

This thesis provides a broader view on urban water use than what is commonly considered in UWRM research. The assessment of urban surface water use in this research shows that especially in situ use functions, without water extraction, are often overlooked in urban water resources research. Chapter 2 provides a long list of potential use functions of urban surface water that is supported by UWRM and ecosystem services literature, and that is supported through evidence of use from two cities. While UWRM is focused on water extractions (Ali et al., 2017; Exall & Vassos, 2012; Ghavidelfar et al., 2017; Giacomoni & Berglund, 2015; Haak & Pagilla, 2020; Padowski & Gorelick, 2014; Sharvelle et al., 2017), this list also includes extractions of other goods from surface waters and in situ uses. For 30 of the 33 use functions on the list, evidence was found that urban surface water in Amsterdam and/or Toronto is actually being used for it (Chapter 2). This evidence mostly confirms the validity of theoretical listings of urban water uses in ecosystem services literature (Blicharska & Johansson, 2016; Garcia et al., 2016; Haase, 2015; Hossua et al., 2019) and complements the examples of the use of urban lakes and ponds in different cities as described by Persson (2012). This study also concretizes the role of surface water as an element of the blue-green infrastructure. Scholars often highlight the importance of blue-green infrastructure for human health and well-being (Bell et al., 2022; Dall'O', 2020; Geneshka et al., 2021), but surface waters and the actual or potential use of them is hardly considered as most attention goes to green spaces (Beck & Arauja Cruxen, 2019; Joosse et al., 2021; Veerkamp et al., 2021).

Future urban surface water use will likely be even broader and more intensive than today. Water managers and spatial planners expect that by 2040, demand for most current surface water uses will increase and demand for new use functions will emerge in Amsterdam and Toronto (Chapter 2). The most prominent and certain increase is expected for TEE, transportation of goods and different types of recreation, including swimming. Given the similarities between Amsterdam and Toronto, and because the major drivers of the trends are widely applicable, it is likely that these trends in demand also apply to other water-rich cities in Northern America and Europe. The most frequently mentioned drivers of increasing demand for urban surface water use functions relate to urban growth and redevelopment, climate change and sustainability ambitions (Chapter 2). Urban population growth, densification, and redevelopment near water occur in many cities throughout the World (Feilberg & Mark, 2016; UN, 2017; 2018); these developments are expected to increase demand for many use functions of urban surface water. The climate trends that are expected to influence water uses like irrigation and recreation in Amsterdam and Toronto, are similar for other regions in the Northern Hemisphere (Meehl et al., 2007). Sustainability ambitions that mainly drive the increasing demand for TEE and transport are set in international policies (EC, 2020; UN, 2015). The insights from this thesis on combinations of drivers that influence demand for specific use functions (Chapter 2 and Supplementary Information 5), including less studied use functions like TEE and urban freight transportation, can be used in future studies on demand management.

5.3 Recommendations for water management

5.3.1 Proactive function-oriented water management

To deal with the increasing demand (Chapter 2; Chapter 4, section 1), water managers are advised to proactively manage functional quality and the use of urban surface water. This may prevent undesirable situations like conflicting use and surface water not being fit for purpose (Chapter 1, section 2.1). The list of potential use functions and the assessment framework for functional quality of urban surface water from this thesis provide information to support function-oriented water management.

The long list from Chapter 2 (Table 2.1) prevents overlooking of relevant use functions. Interviewed water managers and spatial planners from Amsterdam and Toronto stated that they forgot about certain surface water uses until they found them on the list (Chapter 2). The broader view on surface water use may also support collaboration between water managers and spatial planners. This collaboration is one of the pillars of UWRM (Feilberg & Mark, 2016), but water managers are mostly focused on water extractions and spatial planners predominantly focus on land use planning.

Case studies in Amsterdam and Ghent (Chapters 3 and 4) illustrate how the assessment framework (Chapter 3) is used to explore the suitability of urban waters, including waters that are not formally designated for the use functions of interest. Such insight may support prioritization of conflicting water uses and guide investments to improve functional quality. The SI scores can also provide a common information ground for water managers and spatial planners, as the idea of integrated indices is known from the fields of both water management and spatial planning. Examples are the indices for surface water quality (Borges Garcia et al., 2018; Lumb et al., 2011) and suitability indices that are used in spatial planning to identify target locations for specific land uses (Finn & McKenzie, 2020), for habitat protection for flora and fauna (Tang et al., 2021), or to review walkability of a city (D'Alessandro et al., 2016). Application and evaluation of the SIs in a larger set of case studies will provide more insight into their applicability and added value for practical water management.

5.3.2 Monitoring functional quality of urban surface waters

I advise water managers to extend surface water monitoring schemes with additional parameters and new monitoring locations within urban areas. This will improve the possibilities to assess and monitor functional quality of urban surface waters. The case studies with application of SI TEE, SI Transport and SI Recreation in Amsterdam and Ghent have illustrated data gaps that may exist in other urban regions as well.

Application of the SIs was mainly limited by data availability for parameters of SI TEE and SI Recreation with high temporal variability. A lack of data for these parameters cannot be solved with a single measuring campaign. For SI TEE, lack of discharge data was limiting the analysis the most. Discharge is only monitored at locations outside the urban study areas (Chapters 3 and 4). This lack of field data can be solved with hydraulic model generated data, as was done in Amsterdam. It is recommended to locate monitoring stations in the urban water system and use the data to calibrate a hydraulic model to generate data for all surface waters. Application of SI Recreation is mainly limited by data availability for *E. coli* and cyanobacteria. Monitoring locations and monitoring frequency of these parameters outside designated bathing areas are limited, especially for cyanobacteria (Chapters 3 and 4). This is also shown by a recent inventory for 32 popular non-designated bathing areas in urban surface water in The Netherlands and Belgium. For 50% of these sites, some monitoring data for *E. coli* and/or cyanobacteria are available, ranging from a few measurements to extensive monitoring campaigns (De Jong et al., 2022). At most sites, these measurements are not combined with monitoring of the other parameters of SI Recreation: pH, clarity and water depth. It is recommended to combine measurements of all these parameters at the same location.

5.3.3 Opportunities to improve functional quality of urban surface waters

SIs can be used to identify the required alterations to urban surface waters to improve their suitability for specific use functions. A first insight can be retrieved by identifying which parameters have relatively low sub-scores (Chapter 3). A more comprehensive insight is achieved by an optimization process to assess how alterations to the SI parameters, expressed by their sub-score, impact the SI score. Case studies for canals and canalized rivers in Amsterdam and Ghent (Chapter 4) show how such an analysis provides spatially explicit information that can be used to target measures. Chapter 4, section 3.1 provides examples of potential measures to improve suitability of canals and canalized rivers for TEE, transport and recreation.

If it is not feasible (yet) to achieve structural improvements, and suitability is limited by temporally variable parameters with low sub-scores during short periods of time, flexible use management may be considered. In case of flexible use management, users are warned for temporal reduced suitability to improve the use potential for the rest of the time. This approach is known from bathing water management (EC, 2006; Kistemann et al., 2016) and the relevance of this option is explained with an example from this study. The SI Recreation assessments in Amsterdam (Chapters 3 and 4) show that the low suitability of urban surface waters for swimming is caused by low clarity, and at some locations also by high *E. coli* bacteria and/or cyanobacteria concentrations. The sub-scores for these parameters are based on high percentiles which means that even occasional unfavourable conditions reduce the suitability score. A scan of the datasets in Amsterdam shows that especially *E. coli* and cyanobacteria sub-scores are strongly impacted by short term pollution events at some locations. High temporal variability was also reported for *E. coli* and cyanobacteria in studies on recreational waters (EPA, 2010; STOWA, 2000). Additionally, variability of *E. coli* is found to be higher in urban areas than in rural areas (Chen & Chang, 2014; Desai & Rifai, 2010) and is strongly related to rainfall events (Chen & Chang, 2014). If, in the example of Amsterdam, clarity is improved, or mitigation measures are implemented (see Chapter 4, section 3.1), and suitability remains low due to short term faecal pollution, flexible bathing management could be considered to improve safe swimming during most of the season.

The early warning system that is required for such flexible bathing management can include a combination of targeted monitoring and prediction models to warn the public or organizers of swim events for high-risk circumstances. Recent and ongoing research on rapid detection methods (e.g. Angelescu et al., 2018; Bramburger et al., 2015; Noble et al., 2010; Noble & Weisberg, 2005) and prediction models for *E. coli* (e.g. Bachmann-Machnik et al., 2019; Chen & Chang, 2014; Naloufi et al., 2021) and cyanobacteria (e.g. Giere et al., 2020; Heddam et al., 2022; Luo et al., 2017) can improve reliability of early warning. In situ automated sampling and analysis (e.g. Angelescu et al., 2018) enables high sampling frequencies, which is useful for local variability assessments of *E. coli* values. This information helps to identify potential sources of *E. coli*, and to support prediction model development and calibration. I recommend pilot studies in different urban settings including 'wild-swimming' locations, that are not designated as bathing waters, to gain more insight into the feasibility of different monitoring and prediction techniques for practical water management.

5.4 Limitations of this research and directions for future research

5.4.1 Trade-offs

A key challenge for future urban water management is to meet demand for different human use functions and ecological ambitions (Brown et al., 2009; Day et al., 2008). To prevent conflicts and unsustainable use, and to identify opportunities for multifunctional water use, it is important to understand trade-offs among use functions, or among use functions and ecological ambitions. Trade-offs are negative relationships that occur in space or time (Aryal et al., 2022; Karimi et al., 2021). The SIs in this thesis do not consider use restrictions to prevent trade-offs among use functions or between use functions and ecological goals. The reason for this is that prioritization of use functions and ecological ambitions are context specific, often local, political planning decisions. This goes beyond the scope of this thesis. The SIs provide input to the planning process with insight into the suitability of urban surface water for single uses. I recommend further research to gain insight into trade-offs to support multifunctional water management.

Trade-offs may refer to the impact of a specific water use on the surface water conditions that limit the suitability for another use function. This type of trade-offs can be assessed in future research by relating knowledge about the impact of specific water uses on environmental conditions to the parameters of SIs. This is illustrated for the impact of waterborne transport and TEE on environmental conditions. Knowledge on the impact of waterborne transport in urban water systems is limited. Studies in other aquatic environments such as marine ecosystems or large rivers are useful to identify potential trade-offs of urban waterborne transportation. Some of the impacts, like dispersion of non-indigenous species and light pollution (Jägerbrand et al., 2019), are probably less relevant in case of urban freight transport as transport routes are short and the urban environment is already impacted by artificial light. Other impacts are likely more relevant, such as pollution, resuspension of sediments and habitat disturbance (Jägerbrand et al., 2019; Que et al., 2020). These impacts may influence suitability of the water for human use functions like recreation (through reduced clarity) and ecological quality. Research in different types of urban waters is needed to verify the environmental impacts, also since the type of vessels and navigation patterns are different compared to non-urban shipping. The environmental impact of TEE in the form of heat extraction, and subsequent discharge of cooler water, is hardly studied. However, insights from studies on the ecological impact of changes in water temperature and the impact of transport through filters on aquatic organisms can be translated into hypotheses for future research on this topic. Decreasing surface water temperatures during the heat extraction season can have a complicated web of direct and indirect changes in aquatic chemistry, species composition and phenology (Ellwood et al., 2012; Harezlak, 2021; Thackeray et al., 2013; Van Megchelen, 2017). Additionally, transport through water filters and heat exchanges is expected to harm biota (De Jong & Dionisio Pires, 2022). Amongst the potential impacts is reduced growth of cyanobacteria (Harezlak, 2021). This is beneficial to aquatic biodiversity and may improve suitability for recreation, as SI Recreation is negatively correlated with cyanobacteria density (Table 4.1). This example shows that besides trade-offs, synergies may also exist.

Sustainable and fair use of a specific function is also limited by the impact of the use on potential supply of the same use function at another location or in the future. For example, thermal energy extraction will reduce the heat extraction capacity at downstream locations. Another example is provided by the environmental impacts of bathing activities. Bathing in non-urban tropical streams was shown to result in higher *E. coli* bacteria concentrations, reduced clarity, higher nutrient concentrations and habitat disturbance (Butler et al., 2021; Phillip et al., 2009). These effects are increased through wading (Butler et al., 2021; Phillip et al., 2009). It is likely that these impacts also occur in urban waters in different regions, especially in case of thick sediment layers. Comparison of these effects with SI Recreation (Chapter 3) shows that swimming activities themselves can reduce the suitability of the water for this function, as higher *E. coli* concentrations and lower clarity values are negatively correlated with suitability for swimming. Moreover, higher nutrient concentrations may lead to higher cyanobacteria concentrations (Huisman et al., 2018). I recommend further research to verify the impacts in urban waters with different environmental background conditions and bathing practices.

There are other types of trade-offs between use functions, that are not related to the suitability of the water body itself. This is illustrated with examples from practice. Transport and swimming cannot be combined without zoning in place and time due to collision risk between vessels and swimmers (De Jong et al., 2022). Houseboats limit accessibility of the water for recreationists and for cargo-transhipment between freight vessels and the land. Angling and other recreational activities are conflicting in small waters as canoes and boats interfere with fishing lines. These examples show that many conflicts are related to competition for space and accessibility of the water. This underlines the importance of collaboration between water managers and spatial planners and the need for research that supports spatial planning of the urban blue space.

5.4.2 Applicability of the SI-protocol for diverse use functions

The protocol for developing SIs for specific use functions was successfully applied to develop SIs for TEE, transport and recreation (Chapter 3). Although this is a limited set of SIs, the protocol is likely also suitable for other use functions. This broad applicability stems from the diversity of parameters that are considered in the protocol, the suggested process for parameter selection and criteria definition, and the consideration of two different methods for integrating sub-scores into SI scores.

The protocol considers parameters from the groups ‘water quality’, ‘water quantity’ and ‘flora & fauna’ for inclusion in an SI. Based on ecosystem services literature (Brauman et al., 2007; Hallouin et al., 2018), it is expected that these groups cover all characteristics of surface waters that significantly limit their suitability for human use functions. The development of SI TEE, SI Transport and SI Recreation for the context of The Netherlands confirmed the importance of ‘water quality’ and ‘water quantity’ parameters. These types of parameters were identified as factors that significantly limit suitability for respectively two and three use functions (Chapter 3). None of the three SIs include parameters from the ‘flora & fauna’ group. However, it is obvious that this group is relevant for other use functions like fishing (relying on fish species and abundance) or for the same use functions in other contexts, such as dangerous aquatic animals limiting suitability for water recreation. I recommend developing SIs for more use functions to verify whether the suggested parameter groups sufficiently cover all surface water characteristics that determine suitability for human use functions.

The protocol suggests using scientific literature, guidelines and/or expert judgement for parameter selection and definition of scoring criteria for the parameters. Expert consultation broadens the applicability of the protocol as this enables SI development for use functions for which limited, or no, scientific knowledge or guidelines are available. This is likely the case for several use functions of urban surface waters, given the limited available knowledge on the potential use of, or ecosystem services supply by, urban waters (Beck & Arauja Cruxen, 2019; Joosse et al., 2021; Luederitz et al., 2015; Veerkamp et al., 2021). Expert consultation includes interviews or surveys amongst individual experts (Hennink et al., 2011) or methods aimed at finding consensus through group sessions or an iterative process like the Delphi method (Azevedo Lopes et al., 2016; Linstone & Turoff, 1975; Nagels et al., 2001). Expert interviews showed to be helpful in this research for defining preconditions for SI TEE and SI Transport, and for selecting parameters for these SIs (Chapter 3).

Offering two methods for integrating sub-scores instead of prescribing one method for all SI's, also broadens the applicability of the protocol. The development of SI TEE, SI Transport and SI Recreation illustrates the need for different integration methods. Averaging sub-scores is the most obvious method to calculate the SI score. This is a suitable approach for SI TEE, as low values for one parameter can be compensated by high values for other parameters that determine heat extraction capacity (Chapter 3). For some other use functions, each parameter alone strongly limits suitability. If the parameters' sub-scores are averaged, a low sub-score for one parameter is masked by higher scores for other parameters (Smith, 1989). This is the case for SI Transport and SI Recreation. For example, small width of a waterway cannot be compensated by higher water depth or discharge. And health risks due to high concentrations of cyanobacteria cannot be counteracted by the absence of faecal pollution. Therefore, the protocol proposes two methods for integrating sub-scores into the SI score: the geometric mean is used for use functions where low sub-scores for one parameter can be compensated to at least some extent by higher sub-scores for others, and the minimum operator approach is used for SIs in which each parameter alone strongly limits suitability. If more SIs are developed in future research, I advise to evaluate the suitability of the two integration methods for other SIs.

5.4.3 Applicability context of SI TEE, SI Transport and SI Recreation

SIs are context specific, which means that they are valid for a specific geographic, socio-economic and temporal context. SIs are also targeted at a specific definition of a use function for which they classify suitability of the surface water. The three SIs in this thesis (SI TEE, SI Transport and SI Recreation) are developed for urban surface water in the Netherlands, and they are also tested in Ghent, Belgium. The SIs are expected to be valid for other North-western European low-lying cities like Hamburg due to the similarities in their surface water systems, wastewater and surface water management practices, climate and socio-economic context (Chapter 1; Chlebek et al., s.a.).

For application in other regions, some SI parameters and/or criteria for their sub-scores need adjustment. For example, additional parameters may be needed for SI Recreation to take into account local health risks in other regions of the World, such as harmful micro-organisms that are abundant in other climatic regions (WHO, 2021). Another example is provided by the sub-score criteria for water depth in SI Recreation, which are based on the height of the average Dutch adult. Average height of the population in other countries is lower, ranging from less than 3 cm of difference with neighbouring countries, to more than 15 cm in many Asian and African countries (Roser et al., 2013). Therefore, scoring criteria for this parameter need to be adjusted to the population in the research area. Adjustments to the SIs are also needed because the definition of good suitability is context dependent. For example, the suitability classes of SI TEE are based on the heat extraction capacity of a water body in relation to typical heat demand of an average household. If the typical heat demand of a household is significantly lower in other regions or in the future, the heat extraction capacity that is needed for a 'good' classification is lower. This affects the scoring criteria of the SI parameters.

Ongoing scientific, technical and policy developments also influence the validity of the SIs in the future. For example, SI Transport scores reflect the suitability of urban waterways for common vessel types. As the development of specialized urban freight vessels continues (e.g. Citybarge.eu; urbanwaterwaylogistics.net), the criteria for the parameters water depth, width and air draft may need to be updated. Another example is the parameter selection and definition of scoring criteria for SI Recreation. The selected indicators for pathogens that limit suitability for swimming are based on national or European guidelines for bathing water (Chapter 3). As the European Bathing Water Directive is currently under revision (ec.europa.eu), new or other specific indicators, parameters of adjusted criteria may be applied in an updated version of SI Recreation.

5.5 Conclusions

In-depth studies in two urban contexts in Europe and Northern America reveal that urban surface waters are used for a wide variety of human use functions. Many use functions include in situ water uses, rather than the water extractions that are usually considered in urban water resources research. Water managers and spatial planners expect that demand for existing and new use functions will increase by 2040. This will lead to increasing pressure on urban surface water to be used for different use functions and underlines the importance of proactive function-oriented planning, design, and maintenance of these waters. It also motivates a broader perspective on urban water use in research and in water management, taking into account all desired use functions in the near decades. This research is focussed on TEE, transport, and recreation as increasing demand is most certain for these use functions.

In this thesis I propose to assess functional quality of urban surface water to support function-oriented urban water management. A new assessment framework for functional quality is presented in the form of Suitability Indices (SIs) for individual human use functions. The advantage of assessing suitability for single use functions is that the analysis can be targeted at those use functions that are relevant in a specific context. This thesis presents a generic protocol for SI development to guide parameter selection and definition of scoring criteria. The protocol considers parameters related to water quality, water quantity, and flora & fauna. The added value of this approach, compared to traditional water quality indices, is that the newly defined SIs enable assessment of the suitability for different human use functions in a consistent manner, including those that do not, or not only, depend on traditional water quality parameters.

The development of SIs for TEE, transport and recreation demonstrated that the protocol is applicable for developing SIs for different types of use functions. Despite limited data availability, the SIs were successfully applied to produce novel spatially explicit information about the suitability of urban canals and canalized rivers for TEE, transportation, and recreation for two European delta cities. The SI analysis also identified opportunities to improve the functional quality. Such insight into the functional quality of urban surface waters can support prioritization of use functions and optimization of their suitability for desired use functions. The assessment framework from this thesis can now be applied for existing urban surface waters and for designs for new or to be reopened urban waters. The framework enables researchers to assess the functional quality of urban surface water in studies on issues like the potential societal benefits of blue infrastructure or the impact of changes in urban water systems.

Future research is needed to further develop the assessment framework with SIs for more use functions and more urban contexts. Additional pilot studies will provide deeper insight into the added value of applying the assessment framework in different stages of planning, design and maintenance of urban surface water. New pilot studies can also be used to examine the potential of the functional quality concept, and SIs to review this, as a common language for water managers and spatial planners. To support practical water management, further research is needed on measures to improve functional quality of urban surface waters. The feasibility, effectiveness and efficiency of suggested measures to improve the suitability of urban surface water for TEE, transport and recreation should be studied in different cities. Lastly, additional research is required on trade-offs and synergies amongst use functions, between human use and ecological quality, and on the impact of current water use on functional quality at other locations or in the future. Such insights are needed to determine sustainable use potential of urban surface waters.

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Supplementary Information

Contents:

Supplementary Information 1

Table S1: Long list of potential use functions of urban surface water with explanation. Short notation refers to the short description of the use functions as applied in figures in this paper. '-'means no explanation is provided; use function is self-explanatory.

Category	Use function (short notation)	Explanation
Section 1: Provisioning use functions		
Nutrition	Fishing for consumption (Fishing)	Recreational fishing or commercial fisheries where at least part of the catch is intended for consumption. Including lobster, crab and shellfish. Either wild animals or aquaculture facilities in surface water.
	Catch of other surface water related animals for consumption (Other animals)	E.g. water birds.
	Harvest of aquatic plants or algae for consumption (Plants or algae)	Wild plants and algae or aquaculture facilities in surface water.
	Water extractions for drinking water production (Drinking water)	-
Water extraction for non-drinking purposes	For irrigation of crops (Irrigation agriculture)	E.g. in agriculture or allotment gardens.
	For irrigation of other vegetation (Irrigation other)	Irrigation of non-food vegetation. E.g. golf courses, gardens, public green space.
	For industrial processes (Industrial processes)	Not for cooling water (see thermal energy).
	For firefighting (Firefighting)	-
	For filling ponds (Filling ponds)	-
	For other non-drinking purposes (Other)	-
Other materials	Harvest of biomass for non-food purposes (Biomass)	E.g. plants or algae for non-food products.
	Extraction of abiotic materials (Abiotic materials)	Extraction with the aim to use the material. E.g. gravel, sand and clay for building or potting. Dredging for maintenance reasons is excluded.

Table S1 continued

Category	**Use function (short notation)**	**Explanation**
Energy	Thermal energy extraction (Thermal energy)	Using surface water for cooling and/or heating of buildings or infrastructure, as cooling water for industrial processes, or to balance aquifer thermal energy storage systems.
	Energy production using salinity gradient in water (Energy salinity)	Also known as reverse electro dialysis (RED), pressure retarded osmosis (PRO) or blue energy.
	Energy production using kinetic energy (Energy kinetic)	Producing energy from surface water movement E.g. Hydropower, tidal energy, wave energy extraction.
Section 2: Regulation & maintenance use functions		
Regulation & maintenance	Managing water quality (Managing water quality)	The intentional use of surface water to improve water quality elsewhere, by using processes like dilution, degradation, filtration, retention. For example: the use of an urban storm water pond or wetland to improve water quality of runoff water before it enters a river, or the use of urban river water to flush a canal to improve water quality.
	Managing water quantity (Managing water quantity)	The intentional use (as compared to e.g. an unmanaged free flowing river) of surface water bodies to manage retention, detention and drainage of water. This may be applied with the aim of e.g. flood protection, prevention of water shortage or (ground)water level management.
	Global climate regulation (Global climate regulation)	The intentional use of surface water to influence greenhouse gas emissions.
	Local climate regulation (Local climate regulation)	The intentional use of surface water to influence local temperature.
Section 3: Cultural use functions		
Recreation	Primary contact recreation (Primary contact)	Recreation in water with full body contact with the water. E.g. swimming/bathing, diving.
	Secondary contact recreation (Secondary contact)	Recreation on water with water-body contact limited to arms and legs. E.g. sailing, rowing canoeing, etc.

Table S1 continued

Category	Use function (short notation)	Explanation
Recreation	Recreational boating (Boating)	Recreational boating without body-water contact. E.g. excursion by boat, using a speed boat or motor boat for recreational purposes.
	Sport fishing (Sport fishing)	Recreational fishing in natural or stocked waters.
	Hunting aquatic animals (Hunting)	E.g. hunting water birds
	Enjoying a landscape characterized by surface water (Landscape)	E.g. walking/cycling/sitting by water, watching aquatic flora and fauna
	Ice-skating (Ice-skating)	-
Spiritual & symbolic interactions	Designation of cultural heritage value (Cultural heritage)	Formal acknowledgement of a surface water body as cultural heritage, protected cultural landscape.
	Religious use (Religious)	Using surface water for religious ceremonies.
Section 4: Space related use functions		
Space	Building on water (Building)	Using space on water for e.g. floating houses, solar panels, public facilities. May also relate to temporal buildings or facilities.
	Under water storage/infrastructure (Under water storage)	Storage of any materials in a surface water body, under the water surface. E.g. temporal sediment or coal depot.
	Transporting goods (Transporting goods)	Transport of goods by ship.
	Transporting persons (Transporting persons)	Transport of persons with the aim to transport them from one place to another, e.g. public transport ferry, river cruise or sea cruise harbouring in a city. When the aim is boating for recreation, it belongs to recreational boating (see section 3).
	Using water as a barrier (Physical barrier)	E.g. using water as a physical barrier, e.g. a moat to keep people or animals in or out.

Supplementary Information 2

Interview guide

I) Summary of the information provided to interviewees before the start of the interview
This survey is conducted in the context of the FUNqyWATER research project. FUNqyWATER is part of the Urban Pulse II program, a cooperation between Deltares institute for applied research, Wageningen University, the Amsterdam Institute for Advanced Metropolitan Solutions (AMS) and Ryerson University. The aim of the project is to assess the use potential of urban surface water.

As a first step in this research project we assess the use of surface water in two case study cities: Amsterdam (The Netherlands) and Toronto (Canada). We have composed an overview of surface water use by studying water management policy documents.
In addition to the information from these documents, expert information is needed is to complete and interpret this overview. For each city, we consult multiple key experts. Respondents are expected to have complementary knowledge.

The interview is focused on two topics:
1: Current use of surface water in Amsterdam/Toronto.
2: Future trends in the demand for use of surface water in Amsterdam/Toronto

The results of interviews will be published as such that individual respondents cannot be identified.

II) Interview questions
Interviewees were first asked with an open question how surface water in their city is being used during the last five years and what changes in demand they foresee towards 2040. Then the interviewer presented the results of the documents analysis for all use functions from the long list. Interviewees were invited to update or add information on current water use. Next interviewees were requested, for each use function, what trends in demand they expect towards 2040. Trends were formulated as no change/increase/decrease. Interviewees were asked how certain they are of the trends with the option to choose very certain/somewhat certain/somewhat uncertain/very uncertain. For each trend interviewees were asked with an open question what causes the trend. These are the drivers of change.

III) Data processing and analysis
Interviews have been recorded and transcribed; anonymized transcripts are used for analysis. Qualitative data analysis software ATLAS.ti is used to analyse the interview transcripts. Relevant information on current use, future demand, drivers and certainty of the trends is coded. Additional information on current water use is added to the table with results from the document analysis. Next a graph is produced to show use/no use

for each use functions from the long list. Information on future demand, certainty and drivers is collected in co-occurrence tables. Analysis of this table together with contextual information from the transcripts results in graphs that summarize information per use function.

IV) Respondents

Table S2 provides characteristics of the interviewees

Table S2: Characteristics of the interviewee population. Number of participants: 6 in Amsterdam, 5 in Toronto. Some interviewees fulfil multiple positions

Interviewee characteristics		**Study site**	
		Amsterdam	**Toronto**
Sector	Water management	5*	4
	Spatial planning and development	2*	1
Governance level	National	1	0
	Provincial	2	1
	Regional	2	2
	Municipal	1	2
Position	Policy maker	2	3
	Policy advisor	2	0
	Innovation manager	1	2
	Advisor operational water management/technical advisor	2	2
	Designer of public space	1	0
	Reviewer development applications	0	2
	Organisation manager	1	0

* One interviewees represents two sectors.

Supplementary Information 3

Current use of urban surface water in Amsterdam (Table S3) and Toronto (Table S4) based on documented examples and interviews with spatial planners and water managers in the two cities. Interviewees are identified by a respondent code consisting of a letter W or S and a number (e.g. W1).

Table S3: Current use of urban surface water in Amsterdam. Examples that were identified during and after the interviews based on interviewees input is indicated with ●*. ●: use; x: no use; n.e.: no examples found; - not applicable. References refer to documents and online sources

Use function	Use	Examples or motivation	References
Section 1: Provisioning use functions			
Nutrition			
Fishing	●	19% of interviewed anglers at canal Noordzeekanaal take home their catch at times, mainly Zander (also known as pike perch). Only one professional fisherman (www.vismetpiet.nl) at Amstel River and the harbour areas along Noordzeekanaal, main target is Zander.	Van Aalderen and Verspui (2013)
Other animals	n.e.	-	-
Plants or algae	n.e.	-	
Drinking water	x	Drinking water is produced by Waternet from sources outside Amsterdam. There are no extractions for human consumption in the WFD water bodies in Amsterdam.	Waternet (s.a.); Gemeente Amsterdam (2019c); (HHNK 2018); (Ministerie van Infrastructuur en Milieu, 2018); (AGV 2018)
Water extraction for non-drinking purposes			
Irrigation agriculture	●	In a questionnaire 118 participants state that they use surface water in Amsterdam to irrigate their vegetable garden.	(Van der Meulen et al., 2018)
Irrigation vegetation	●	In a questionnaire 122 participants state that they use surface water in Amsterdam for garden irrigation.	(Van der Meulen et al., 2018)
Industrial processes	●	Water from canal Noordzeekanaal is extracted for industrial use. The national water authority Rijkswaterstaat issued permits for extracting water from the canal and its arms to be used as process water for e.g. rinse water in an energy plant and for a fertilizer factory. The volume of surface water used as scrubber water is much larger than the volume used for rinsing (G. Jadoenathmisier of Rijkswaterstaat, personal communication, 6 May 2020)	(Ministerie van Infrastructuur en Milieu, 2018; Rijkswaterstaat, 2017, 2019b)

Table S3 continued

Use function	Use	Examples or motivation	References
Firefighting	●*	Water from the canal Noordzeekanaal is used for firefighting at the oil terminals in the harbour.	(Rijkswaterstaat, 2019a)
Filling ponds	n.e.	-	
Other	n.e.	-	
Other materials			
Biomass	●*	Regional water manager Waternet and company NPSP experiment with the production of nature based composite from biomass. Mowed reed and aquatic plants from Amsterdam's waterways are used for this purpose at a pilot scale (Interviewee W2).	(Fermont & Groot, 2018)
Abiotic materials	x	There are no extractions of building materials (sand, clay gravel) from the large water bodies in Amsterdam: Noordzeekanaal, lake IJmeer , IJ River or Amsterdam-Rijnkanaal. None of the interviewees have examples for other water bodies in Amsterdam either.	(Rijkswaterstaat, 2015)
Energy			
Thermal energy	●	Energy plants cooling with water from canal Noordzeekanaal. Lake IJmeer water is used for cooling an energy plant and a residential complex in the Centrumeiland IJburg neighbourhood (M. Van der Velde of Rijkswaterstaat, personal communication, 18 October 2019). Water from deep lakes Nieuwe Meer and Ouderkerkerplas is used for cooling buildings in business districts. Houses in the Schoonschip area, Houthaven residential district, are cooled by IJ River water with and without seasonal subsurface storage (ATES). IJ River water is also used to optimize the thermal balance of the ATES system. Cooling of bridges during summer to prevent expansion (Interviewee W4).	(Rijkswaterstaat, 2015); (NUON, s.a.-a); (NUON, s.a.-b); (Vattenval, s.a.-a); (Vattenval, s.a.-b); (Gemeente Amsterdam, 2016; Rijkswaterstaat, 2017, 2019a, 2019b; Van der Hoek, 2011)
Energy salinity	n.e.	-	-
Energy kinetic	n.e.	-	-
Section 2: Regulation & maintenance use functions			
Managing water quality	●*	Inflow of water from Lake IJmeer and canal Amsterdam-Rijnkanaal into the water system of Amsterdam is temporarily increased to reduce inflow of saline water from the coast. (Interviewees W2, WS3).	-
Managing water quantity	●	The entire surface water system has a water regulation function for the city and the region. Discharge and retention can be controlled.	(Gemeente Amsterdam, 2016)

Table S3 continued

Use function	Use	Examples or motivation	References
Global climate regulation	n.e.	-	-
Local climate regulation	n.e.	-	-
Section 3: Cultural use functions			
Recreation			
Primary contact	●	People swim 'everywhere', e.g. in smaller canals, while the only designated swimming locations within Amsterdam are in deep city lakes Sloterplas, Gaasperplas, Nieuwe Meer and at beach IJburg in shallow lake IJmeer and beach Diemerpark. Scuba diving takes place in the deep city lakes Noorder IJplas, Sloterplas and Gaasperplas.	(Gemeente Amsterdam, 2016)
Secondary contact	●	Amsterdam hosts 23 rowing associations, most rowing activities at Amstel river. Canoeing at deep city lake Sloterplas. Water bikes on the smaller canals. Wind surfing and sailing are concentrated at the deep city lakes and shallow lake IJmeer. Sailing is popular with children. SUP-ing and fly-boarding at the inner city canals, Amstel river, the deep city lakes and IJmeer. Wake boarding and water scooters are only allowed in a designated area at the border of IJ River and lake IJmeer. Yacht harbours for sail yachts concentrated at IJ River shores, lake Nieuwe Meer and lake Nieuwe Diep.	(Gemeente Amsterdam, 2016)
Boating	●	Canals in Amsterdam, IJ River and Amstel River are intensively used for excursion boats and pleasure boats. There are approximately 10,000 pleasure boats in Amsterdam. Excursion boats host 3 to 5 million passengers per year, mainly in the inner city canals but also in shallow lake IJmeer such as to the island Pampus. Yacht harbours for large motor boats are concentrated at IJ River shores, lake Nieuwe Meer and lake Nieuwe Diep. High speed motorized boating, is only allowed in a designated area at the border of IJ river and IJmeer, called Buiten IJ.	(Gemeente Amsterdam, 2016); (Gemeente Amsterdam, 2019a)
Fishing	●	The number of sport fishermen is approximately 11,000. Over 200 official competition events take place in Amsterdam. Fishing also takes place waters in Amsterdam West district.	(Gemeente Amsterdam, 2016); (AGV 2014b)
Hunting	n.e.	-	
Landscape	●	In a questionnaire 437 participants state that they recreate along the water shores in Amsterdam. Hiking and cycling along the shores of lake Noorder IJplas. Hiking and cycling are popular activities along the Amstel River, the large canals and in the rural wetland area in the north part of Amsterdam (Interviewee W4).	(Van der Meulen et al., 2018); (Gemeente Amsterdam, 2016)

Supplement

Table S3 continued

Use function	Use	Examples or motivation	References
Ice-skating	●	Ice-skating at deep city lake Sloterplas and smaller canals.	(AGV 2014a)
Spiritual and symbolic interactions			
Cultural heritage	●	The seventeenth-century inner city canal ring area of Amsterdam is designated as UNESCO World Heritage.	(Gemeente Amsterdam, 2016; UNESCO, 2010)
Religious	n.e.	-	
Section 4: Space related use functions			
Building	●	Approximately 2500 houseboats in Amsterdam. Floating houses in IJburg district, in an enclosed part of shallow lake IJmeer. Public events are taking place on water such as the nautical event Sail; the Canal Parade, Amsterdam City Swim and concerts on temporal stages in the canals. These events host thousands up to millions of visitors.	(Gemeente Amsterdam, 2016)
Under water storage	n.e.	-	
Transporting goods	●	The large canals Amsterdam-Rijnkanaal, Noorzeekanaal and IJ River are part of international shipping routes and the main national shipping network for cargo. The sea harbours along the Noordzeekanaal are exclusively designated for the harbour function. The sea harbour is the fourth in Europe in terms of tons of goods in transhipment. Shallow lake IJmeer is part of the shipping route between Amsterdam and the northeast of the country. Inland vessels also use the canals Kostverlorenvaart and Noordhollandsch-kanaal, and Amstel River. Transport of goods within the city accounts for less than 1% of all transports, and most of it concerns transport of building materials to building sites.	(Gemeente Amsterdam, 2016); (Rijkswaterstaat, 2015); (Gemeente Amsterdam, 2019b) ; (Ministerie van Infrastructuur en Milieu, 2018)
Transporting persons	●	The large canals Amsterdam-Rijnkanaal, Noorzeekanaal and IJ River are part of international shipping routes for river cruises and sea cruises. Sea cruise boats moor close to the city centre at the passengers terminal along the south shores of IJ river. In 2014, 126 sea cruise boats arrived with over 276.000 passengers. River cruise ships are mainly moored along the southeastern shores of IJ river close to the central train station. 1,685 ships and 420,800 passengers in 2014. Waterborne public transport is limited to the ferries crossing IJ River in the city centre and the Noordzeekanaal in the western harbour area.	(Gemeente Amsterdam, 2016)
Physical barrier	n.e.	-	

Table S4: Current use of urban surface water in Toronto. Examples that were identified during and after the interviews based on interviewees input is indicated with ●*. ●: use; x: no use; n.e.: no examples found; - not applicable. References refer to documents and online sources

Use function	**Use**	**Examples or motivation**	**References**
Section 1: Provisioning use functions			
Nutrition			
Fishing	●	Sport fishing in rivers, ponds and Lake Ontario nearshore, bay areas and offshore waters targeted at popular species for consumption like salmon and trout. Several studies reveal consumption of Great Lakes sport-caught fish. Commercial and aboriginal fisheries far outside Toronto, in north-eastern Lake Ontario.	(Turyk et al., 2012); (Government of Ontario, s.a.); (Stewart et al., 2017)
Other animals	n.e.	-	-
Plants or algae	n.e.	-	-
Drinking water	●	Drinking water for Toronto is primarily withdrawn from Lake Ontario with intake points close to the waterfront.	(CTC, 2015)
Water extraction for non-drinking purposes			
Irrigation agriculture	●	Humber water is mainly used for, 56% of extracted volume, and is the main source for agricultural water. Most of these extractions are located outside the city of Toronto (interviewees W8, W11, W12, S10).	(TRCA, 2008a)
Irrigation vegetation	●	In Humber watershed surface water is the predominant source for commercial use, which accounts for 33% of total extracted volume. 60% of commercial withdrawals relate to golf course irrigation. 50% of Don River surface water users, use the water for golf course irrigation. In Rouge watershed, 58% of extracted volume of surface water is for golf course irrigation. Lake Ontario water is used for irrigation of the 192 acre surrounding grounds of Beanfield conference centre (M. Goss of the Beanfield Centre, personal communication, 31 March 2019).	(TRCA, 2007b, 2008a, 2009a)
Industrial processes	n.e.	-	-
Fire-fighting	●*	Lake Ontario water is used by the Beanfield conference centre to augment seasonal shortages of storm water collected on the roof for the building sprinkler system for fire-fighting (M. Goss of the Beanfield Centre, personal communication, 31 March 2019).	-
Filling ponds	●	In Don watershed surface water is mainly, 62% of total extracted volume, used for and is the predominant source for filling aesthetic ponds or fish ponds. In Rouge watershed surface water is the predominant source for filling aesthetic ponds. <1% of total extracted volume of Humber water is used for filling small aesthetic ponds.	(TRCA, 2007b, 2008a, 2009a)

Supplement

Table S4 continued

Use function	**Use**	**Examples or motivation**	**References**
Other	●	Surface water in Humber, Don and Rouge watersheds is used for 'other uses' that are not documented as specific use functions. Water from the storm water pond in Earl Bales Park is used for snow making for the nearby ski hill.	(City of Toronto, 2020a; TRCA, 2007b, 2008a, 2009a)
Other materials			
Biomass	n.e.	-	-
Abiotic materials	n.e.	-	-
Energy			
Thermal energy	●	Dozens of buildings in downtown Toronto City use deep lake water from Lake Ontario for cooling. Water is first purified to drinking water quality. Next it goes to heat exchangers that facilitate energy transfer between the cold lake water and a closed chilled water supply loop. After the energy transfer process, the water is directed to the city's potable water system. The DLWC system has a capacity of 42,000 ton of cooling, can cool over 150 buildings and 30 million sq ft of space in downtown Toronto (J. Lee of Enwave, personal communication, 22 January 2019).	(City of Toronto, 2018; Enwave, 2018)
Energy salinity	n.e.	-	-
Energy kinetic	n.e	-	-
Section 2: Regulation & maintenance use functions			
Managing water quality	●	Hundreds of stormwater management ponds have been constructed or are proposed. Ponds constructed after the late 1980s are designed to provide both water quantity and quality control. Earl Bales pond in West Don River watershed is one of the largest in Canada.	(City of Toronto, 2020a; STEP 2019a; STEP 2019b; STEP 2019; SWAMP 2002; SWAMP 2003; TRCA, 2007b, 2009b)
Managing water quantity	●		
Global climate regulation	n.e.	-	-
Local climate regulation	n.e.	-	-

Table S4 continued

Use function	**Use**	**Examples or motivation**	**References**
Section 3: Cultural use functions			
Recreation			
Primary contact	●	Popular activities at Rouge Beach, where Rouge River joins Lake Ontario, are swimming, canoeing, bird-watching and fishing. Lake Ontario shores has 14 public beaches, 8 of these are blue flag beaches; a popular swimming site is at Rouge Beach, where Rouge River joins Lake Ontario	(TRCA, 2007a)
Secondary contact	●	Canoeing, kayaking and rowing are popular activities at Rouge Beach and the marshes and there are canoe routes in central Markham, on the Main Rouge River. In 2015, 325 boats paddled the Don River to raise money for watershed conservation projects and programs.	(TRCA, 2007a, 2015)
Boating	●	Lake Ontario shores has 5 public boat launches. Interviewees confirm observations of many sail boats at Lake Ontario (interviewee W9) and lower parts of the rivers (interviewee S10).	(TRCA, 2018)
Fishing	●	Recreational fishing at Lake Ontario takes place in nearshore and bay areas and in offshore waters. Seasonal sport fishing in tributaries. Many popular spots for recreational fishing in streams and ponds are located in Rouge Park and other major parks, such as Rouge Beach, Milne Park, Toogood Pond and Little Rouge River.	(Stewart et al., 2017; TRCA, 2007a)
Hunting	x	No documented examples found. Not allowed in the city (NRISC web reader of Ministry of Natural Resources and Forestry, personal communication, 15 May 2019).	(Government of Canada, 2018; TRCA, 2019)
Landscape	●	There is 87 km of Waterfront Trail along the shoreline of Lake Ontario and trails along rivers such as the Lower Don Trail. Interviewee S10 confirms popularity of cycling and hiking along the waterfront. Hiking or skiing on trails around Earl Bales pond, along Lake Ontario shores and Lower Don Trail confirmed by observation by the main author of this paper in January 2020. Bird watching is popular along Lake Ontario waterfront such as at Tommy Thompson Park and in Petticoat Creek Conservation Park.	(City of Toronto, 2020b; TRCA, 2018)
Ice-skating	●*	Interviewees explain that ice-skating mostly takes place on ice rinks but some ponds are popular for skating. One pond is located near the waterfront (interviewee W8) and the large Grenadier pond is popular for ice-skating although it is not allowed (interviewee W12).	-

Supplement

Table S4 continued

Use function	Use	Examples or motivation	References
Spiritual and symbolic interactions			
Designation of cultural heritage value	●	Humber River is designated as Canadian Heritage River. This is a recognition of its contribution to 'the development of the country, its importance in the history of First Nations peoples, the early Euro-Canadian explorers and settlers of Upper Canada'.	(TRCA, 2008b)
Religious use	●*	One interviewee (W8) observed religious or funeral ceremonies along the waterfront, on the water of Lake Ontario and throwing of ashes into the rivers.	-
Section 4: Space related use functions			
Building	●*	Interviewees (W8, W9) observed some house boats and mention that this is a rare phenomenon in Toronto.	-
Under water storage	n.e.	n.e.	-
Transporting goods	●	The international Port of Toronto is located on the shores of Lake Ontario, close to the city centre. In 2018, 178 ships visited the harbour, mainly with bulk products like sugar, road salt, aggregate and sand, cement, and steel.	(Ports Toronto, 2019)
Transporting persons	●	Public transport ferries to Toronto Island Park in Lake Ontario. Toronto Cruise Ship Terminal in the harbour along Lake Ontario was visited by 17 Great Lakes cruise ships in 2018 that host approximately 6,000 passengers.	(City of Toronto, 2019; Ports Toronto, 2019)
Physical barrier	n.e.	n.e.	-

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Supplementary Information 4

Quotations from the transcripts of the interviews are coded to identify and categorize drivers for changing demand of urban water use functions.

Table S5: 'D-' indicates driver for increased demand; in a few exceptions these are also used by the respondent in relation to a decrease or no change in demand. 'Db-' indicates drivers for decreased demand or reason for no change in demand. D0 indicates reason for no change. [...]: interviewer asks for clarification or summarizes what has been said before. (...): Irrelevant text. '...' Speaker breaks

Codes	**Quotation Content**
D-Wetland development	And the development of big new areas, like the Portlands. Where a number of big wetlands are going to be put in, for recreation-, for aesthetic purposes primarily. So, there would be, some of the old wetlands that used to be there in the past, they are going to be restored, you know, they will recreate those, and that will be part of the developments. So yes, the surface water system there would be very much a part of that development, it's being centred around that actually. The development is kind of being centred around the wetlands and so on, and the nature, that surface water provides.
D-Welfare increase	meer welvaart
D-Welfare increase	Meer geld
D-Welfare increase	steeds meer mensen die kunnen het betalen
D-Water use per capita increases	en mensen ook volgens mij steeds meer water gebruiken
D-Water use efficiency increase	[...but it may be diminished by increasing efforts in being efficient with water.] Absolutely. And I will say the ministry at the provincial level, we are promoting, like we want people also get into the habit of water re-use, so capturing water for the purpose of re-use, so toilet flushing and irrigation systems for gardens, that type of thing, we are encouraging that. Actually included in our Ontario Building Code now, there is something for that, so it's covered in each home to put in a water tank and you can actually do that.
D-Water use efficiency increase	Our water efficiency is getting better so we are decreasing the per capita consumption, but you can only go down so much,
D-Water quality improvement	Ik denk dat men er bewuster mee omgaat, dat het water niet vervuild wordt. [Dus eigenlijk, de waterkwaliteit verbetert en daardoor ontbreekt de behoefte om te spoelen..] Ja, en je mag niet meer afwentelen dus je mag niet het probleem zomaar wegspoelen.
D-Water quality improvement	Ik denk ook misschien wel omdat de waterkwaliteit beter wordt dat mensen ook op meer plekken gaan zwemmen.
D-Water quality improvement	we're trying to protect our river and water system to keep algae levels low. Algae means you have a eutrophic water system and that's not healthy

D-Water quality improvement	as we continue to start cleaning things up and we start improving by putting a wetland in at the bottom end of the Don we'll just continue to improve water quality. Over time, the contaminated sediments will get cleaner. That's my biggest concern with a fish like carp because they're bottom feeders.
D-Water quality improvement	I think as the city of Toronto continues to separate its combined sewers and continue to build capacity for improving on their ability to treat that combined sewage; they put in a big tunnel, they built a really big tunnel to capture some of this. (...) So the city of Toronto continues to find ways to improve the water quality I think that will contribute by 2040. I actually think you will see improved water quality near shore
D-Water quality improvement	Again, as the waterways get cleaner, as the water quality improves and as more people come in and they're doing rehabilitation, for instance, of the Don, I can see that because you're not in direct contact with the water, so I can see people definitely increase recreational use by boat definitely.
D-Water quality improvement	cleaner water, and improved water quality.
D-Water quality improvement	If we do clean up the lake as the goals of the city and other people around the province and around the lake, I think people will want and be willing to eat the fish more
D-Water quality improvement	As I said earlier, if our water quality does increase I can see a higher demand. [Do you expect this water quality increase to happen?] I think in the long run in 2040 there would be some increase. How much of an increase, I'm not certain. All new development that comes into the city are supposed to provide water quality controls. The city is being re-developed as we speak, it's a slow rate but it is getting re-developed. Even our road works; when we put in new roads we're looking at quality control, some type of improvements in water. [So you expect some improvement there?] Yes. That's why I'm somewhat confident there will be an increase in quality of the overall system in 20 years.
D-Water quality improvement	So, if the fish were more consumable, and the... If this was provable by looking at fish tissues over time and trending to... being more and more consumable, then I would imagine that that would definitely increase the amount of people interested in doing fishing for consumption purposes.
D-Water quality improvement	Because the quality of the fish will likely increase
D-Water quality improvement	and also because many of their actions over time are helping to improve the water quality, along the waterfront, specifically in those areas
D-Use and value of surface water increases	Ik kan me voorstellen dat het wel toe zou nemen omdat er gewoon ... de vraag naar gebruik op en rondom oppervlaktewater groter is dus het wordt ook meer gewaardeerd. Ik denk dat daardoor ook de vraag om het te behouden zoals het is ook groter is.
D-Use and value of surface water increases	I think so. People are more connected with water, so I think so.

D-Urbanization/land use change	Omdat ik hier... de ontwikkeling zie ik... ik zie minder landbouw en dat heeft ook met landbouw te maken, irrigatie en ik denk dat dat eerder af zal nemen dan toe zal nemen in de omgeving van Amsterdam.
D-Urbanization/land use change	new settlements and developments.
D-Urbanization/land use change	as the urban frontier expands and as urban areas continue to swallow up prime real estate for agriculture, agricultural land is disappearing in the greater Toronto area. I mean, as the urban development continues outward, you'll see less and less need for irrigation for farmlands because they won't exist anymore.
D-Urbanization/land use change	as the city expands, the golf clubs are going to disappear
D-Urbanization/land use change	because, again, it's very urban.
D-Urbanization/land use change	many golf courses are shutting down and they're developing them.
D-Urbanization/land use change	It will still be required. Right now, we have over a 1,000 storm water ponds in our jurisdiction and that number will go up as we continue to develop
D-Urbanization/land use change	because much of Toronto was developed without stormwater management. And now, whenever there is a major redevelopment, stormwater management is required by law, and by the City of Toronto standards. And therefore, there would be more of these kinds of facilities in place over time, as more and more of the city becomes redeveloped. And certain areas that are underdeveloped are developed. So, there are areas in Toronto that are underdeveloped and they will be developed, because there is big money in developing them. And when they develop them, they will be required to do water quality management. And the primary means by which water quality management is done in this city, is through stormwater ponds, and other small infrastructure, but for the most part stormwater ponds are usually required for flood control. So, yeah, I think, yeah, so I think it will increase because of that
D-Urban agriculture increase	There's a possibility it will increase due to urban agriculture.
D-Tourism growth	Toerisme neemt alleen maar toe
D-Tourism growth	meer toeristen
D-Tourism growth	met het oog op toename van de toeristen
D-Tourism growth	meer toeristen
D-Tourism growth	Deels door het toenemende toerisme, die willen ook het water op.
D-Temperature increase due to climate change	We hebben te maken met hogere temperaturen. Bruggen zijn daar minder op ontworpen en hebben daar last van, die kunnen dan niet meer open dus moeten gekoeld worden.
D-Temperature increase due to climate change	Omdat je ... net als grotere periode van droogte heb je ook grotere periode van hitte
D-Temperature increase due to climate change	ook omdat we grotere periodes van hogere temperaturen gaan krijgen. Dus dan is de behoefte aan verkoeling ook groter
D-Temperature increase due to climate change	en ook weer meer warmere dagen, of extreme warme dagen, dan is verkoeling op of in het water ... die vraag zal toenemen.

D-Temperature increase due to climate change	Ook omdat het door ons klimaat steeds minder voorkomt wordt het steeds unieker en steeds belangrijker denk ik. Misschien dat het minder voorkomt omdat het minder snel dichtvriest, maar als het het geval is wordt er denk ik meer gebruik van gemaakt.
D-Temperature increase due to climate change	Als je kijkt naar hittestress en dat soort dingen, dat zomers, als we nog een paar van zulke hittegolven hebben denk ik dat daar de vraag naar wel toe gaat nemen.
D-Temperature increase due to climate change	je hebt enorme heat islands in de steden, dus volgens mij kan je die tegengaan met water manipuleren.
D-Temperature increase due to climate change	Deels komt het natuurlijk ook door veel warme periodes, dus als het warm is; hier voor de deur ligt het helemaal vol hier, dit grasveldje.
D-Temperature increase due to climate change	warme omstandigheden, zomerse omstandigheden
D-Temperature increase due to climate change	Je zoekt verkoeling ergens, aan het water is dat beter te vinden. [En waarom denk je dat die behoefte toeneemt?] Ook weer klimaatverandering; die temperaturen van 30, 40 graden, dat leidt daar gewoon toe.
D-Temperature increase due to climate change	Het is te warm
D-Temperature increase due to climate change	Omdat de zomers warmer worden waardoor je met luchtkoeling gewoon niet genoeg kan koelen.
D-Temperature increase due to climate change	Ik denk dat de zomers warmer worden, dus dat je in principe meer zou moeten sproeien in je volkstuin bijvoorbeeld, wat ik dus doe.
D-Temperature increase due to climate change	want ik denk dat het warmer wordt, het klimaat wordt warmer 's zomers
D-Temperature increase due to climate change	Ook weer de hete zomers. [Dat dat vaker plaatsvindt?] Ja.
D-Temperature increase due to climate change	Als de mensen die veel hebben geschaatst te oud zijn om te schaatsen. De kinderen kunnen gewoon niet zo goed schaatsen nu. Die hebben nooit zo veel op oppervlaktewater geschaatst. Een paar keer. Omdat er minder ijs is.
D-Temperature increase due to climate change	Omdat het ook geassocieerd wordt met verkoeling.
D-Temperature increase due to climate change	en meer verkoeling zoeken en gebruik van het water. [En waarom zoeken mensen meer verkoeling dan nu?] Door de hetere zomers.
D-Temperature increase due to climate change	Ja, ik verwacht ook dat verkoeling zoeken op het water. [Dus vooral dat, het neemt toe omdat mensen meer verkoeling zoeken..] Ja.
D-Temperature increase due to climate change	Dat mensen ook als zij niet het water ingaan wel aan het water ook verkoeling gaan zoeken.

D-Temperature increase due to climate change	Om die hitte... hoe meer water en hoe meer groen, hoe minder je die opwarming hebt.
D-Temperature increase due to climate change	Meer warmte
D-Temperature increase due to climate change	meer warmte
D-Temperature increase due to climate change	I think it will because of heat increases. (...) I'll just say mainly because I think the temperature is changing in the city, and the extremes that we're getting so people need to have access to different types of cooling, such as swimming
D-Temperature increase due to climate change	From what we know on urban heat island, I can see experiencing it only near the water course so not much farther away, but that's a good point about another benefit of the green infrastructure idea in terms of urban heat island reduction. So that would be another reason that it probably will increase
D-Temperature increase due to climate change	The problem comes in that with climate change we could get warmer weather
D-Temperature increase due to climate change	And as the climate warms and Toronto gets warmer in the summer
D-Temperature increase due to climate change	because we don't know with climate change if these natural water bodies will be frozen in the winter.
D-Temperature increase due to climate change	because we are getting warmer temperatures, and so there is more melt events – and that is kind of proven, that there is more melt events happening in Toronto – so it's less likely that there is thick enough ice to skate on, and there will likely be more efforts put on by the city to keep people off of those areas, because of fears that, you know, the ice might crack, and there might be a problem. So, yeah, I think ice skating on surface waters is likely to decrease, because of change in climate.
D-Technological developments	En de technologie gaat vooruit, en ook de sensortechnologie, dus waarschijnlijk in de toekomst is het makkelijker om de kwaliteit van water te controleren. Dus ook de technologische ontwikkeling draagt eraan bij dat dit kan of zou kunnen.
D-Technological developments	Dus aan de ene kant zullen bedrijven meer moeten koelen, maar aan de andere kant verwacht ik dat het door innovaties...dat ze dat... [Dat ze minder water nodig hebben.] Ja.
D-Technological developments	Ik denk dat ze die bruggen gewoon, als ze ze nu opknappen dat ze technische maatregelen nemen waardoor je ze niet de hele tijd hoeft te koelen.
D-Technological developments	I suspect it will as they start developing more and more, let's say, grasses that are hardier and can survive on less water. I just think that development in terms of plants and their ability to live longer with less water and live through harsher winters, and that type of thing, I just think science is just going to continue to improve, so I think there will be a reduction
D-Technological developments	it may decrease a little with other technologies.

D-Sustainability ambitions	Met de energietransitie, dat zie ik nu ook heel erg in het project hier. In Amstelstad wordt er heel erg gezocht naar alternatieve vormen van koelen dan wel verwarmen van huizen. Ik denk dat oppervlaktewater daar een van de bronnen kan zijn, zowel voor koelen als wellicht voor verwarmen.
D-Sustainability ambitions	Nee, behalve dan dat ik denk dat met oog op duurzaamheid in de toekomst men meer gaat gebruiken.
D-Sustainability ambitions	Amsterdam heeft natuurlijk het beleid om gasvrij te worden, en aquathermie wordt gezien als één van de alternatieven voor gas.
D-Sustainability ambitions	Vliegen wil niemand meer uiteindelijk, en dan is vervoer over water, ook voor dat soort transport van bulkmateriaal of wat dan ook, is een goed alternatief
D-Sustainability ambitions	Provincies en gemeenten zijn heel erg bezig om te kijken van als heel Nederland aardgasvrij moet zijn, op welke manier dan in energiebehoefte kan worden voorzien en zijn aan het studeren waar zonnepanelen kunnen komen, waar windenergie. En de waterschappen benadrukken steeds, ook bij ons, let op, want misschien kunnen we ook wel warmte uit oppervlaktewater gebruiken.
D-Sustainability ambitions	Misschien dat er ook wel een trend is dat mensen gewoon ook meer om huis recreëren en minder straks gaan vliegen ofzo, maar misschien is dat wel wishful thinking, ik weet het niet.
D-Sustainability ambitions	Ik denk dat er een enorme behoefte komt aan zonnepanelen. Als energie.
D-Sustainability ambitions	Omdat ik denk dat je heel veel aan de energie infrastructuur moet doen als je energietransitie wil realiseren.
D-Sustainability ambitions	Omdat je in zo'n stad als, zo'n verdichtende stad, natuurlijk toch zo energiezuinig mogelijk wilt worden en wilt gebruiken wat er is.
D-Sustainability ambitions	Omdat we gewoon steeds meer minder afhankelijk willen worden van gas en al die andere fossiele brandstoffen
D-Sustainability ambitions	Because we're trying to find more carbon energy sources, and that's one of the easy ones we have nearby, a sustainable renewable resource of cold, particularly because the lake at the bottom is very cold.
D-Sustainability ambitions	I think there's an interest in wanting to get all of the old ports that we have along the waterfront being fully utilised again; also as a sustainable way, or even just another way to transport goods as opposed to by truck or rail, just to have that diversity
D-Sustainability ambitions	The Ontario building code over the next 10 years - and this is in the federal government's plans which is to get to net zero energy homes, I can see all of the residential buildings are all going to move towards a net zero energy consumption, and this would be in alignment with that kind of thinking.
D-Sustainability ambitions	It's actually driven by provincial policy that says you should be doing a treatment train approach as opposed to just conventional storm sewer and pipe facilities. We actually had an interpretation bulletin that was put out by our ministry that actually said: The ministry is actively seeking to move towards a treatment train approach and not just strictly end of pipe treatment. [And why do they prefer that?] Because we think we will be mimicking the hydrologic cycle better. We will actually be infiltrating more water into the ground and we will be able to actually end up with a cleaner water quality overall by going through a treatment train approach as opposed to an end of pipe facility.
D-Sustainability ambitions	It's just people are more aware of environmental issues, trying to grow local sources of goods.

Supplement

D-Sustainability ambitions	because there is a, well, Toronto has a climate plan, and in order to meet that climate plan, they need to find ways of reducing greenhouse gas emissions. And this is a very successful way of doing that, so it could be a potential… something that potentially expands over time
D-Stocking fish measures	Well, they've been stocking fish, so they specifically stock fish to increase it. So, I think, because there is a marketing campaign, because there are efforts on the way to stock the rivers with certain fish, recreational fish particularly, like salmon, that the fishing has to increase, yes.
D-Ship size and number of ship increases	Daar wordt wel rekening mee gehouden dat het aantal schepen en ook de omvang van de schepen dat dat toeneemt, dat het groter wordt.
D-Self-sufficiency ambitions	het is vooral de wens om zelf in behoefte voor energie en water voorzien
D-Saving drinking water ambitions	Ik weet niet waar die mee besproeid worden maar ik kan me voorstellen dat als dat nu drinkwater is dat dat op een gegeven moment oppervlaktewater … dat ze daar naar omschakelen. Omdat drinkwater is gewoon, dat is eigenlijk zonde en duur en niet circulair om dat te gaan sproeien over je planten.
D-Saving drinking water ambitions	de drinkwatersector zelf zegt wel steeds: wees zuinig met water. Er zijn zelfs bedrijven waar je niet meer je tuintje mag sproeien. Dus je ziet wel dingen in die richting ontwikkelen
D-Saving drinking water ambitions	omdat je er vanaf wil dat het drinkwaternet gedimensioneerd wordt op een bluswatercapaciteit. Dus moeten er alternatieven zijn, en oppervlaktewater is één van die alternatieven.
D-Redevelopment close to water	Zeeburgereiland wordt nu volgebouwd. [Meer woningen?] Ja. [Dus behoefte aan duurzame oplossingen, behoefte aan meer verkoeling..] Ja [En toename van het aantal gebruikers omdat de stad groeit] Ja (…) Er zijn volgens mij ook, hoewel het laatste volgens mij afgeschoten is, om hier toch ook woonwijken te gaan ontwikkelen. Men wil de cruiseschepen uit de stad zodat ook de havens meer ontwikkeld kunnen worden voor woningbouw. Dus ik verwacht, als dat aan het water ligt dat er wel duurzame, dat er gekeken wordt van kunnen we het water gebruiken om te koelen.
D-Redevelopment close to water	Ja, je hebt hier ook een aantal ontwikkelingen met tentjes langs het Noordzeekanaal, daar kun je met het pontje over, daar kun je aan het water op een terrasje zitten. [Dus de horeca neemt toe?] Ja en ik verwacht dat daarmee mensen ook wel zin hebben om daar te zwemmen op een warme zomerse dag.
D-Redevelopment close to water	Er is een draagvleugelboot geweest naar Velsen, maar daar werd zoveel verlies op geleden dat die weer eruit is gehaald door de provincie. Maar er zijn nu weer mensen aan het studeren of dat toch weer een openbaarvervoerroute over water, of die toch levensvatbaar is. En dan met name ook om 'm hier te laten stoppen, op het Hembrugterrein. Dat is een oud terrein aan het Noordzeekanaal van defensie en daar zijn plannen om daar een woonwijk van te maken en dan zou je hier een soort tussenstop kunnen maken en dan door kunnen varen richting Velsen.

D-Redevelopment close to water	Omdat Amsterdam-Noord steeds meer hierbij betrokken wordt dus ik denk dat dat... ja, dat die ontwikkeling wel doorgaat. [U bedoelt dat... dat gebied zich ontwikkelt?] Ja, ja. En hier ook, hier gaan ze ook bouwen dus ook hier en was ook een verbinding. [interviewee points to Het Westelijk Havengebied.]
D-Redevelopment close to water	growth in our city and closer to the waterfront as well
D-Redevelopment close to water	Then we have a lot of development, too. We have a lot of development on our waterfront right now under revitalisation, so even for direct distribution of whatever it is, construction materials, etc. it could be useful for that
D-Redevelopment close to water	Waterfront development. [Can you explain that a little more?] Yes, the whole what we call the Bad lands or the Don lands where there's currently like all industrial, contaminated sites, it's all going to get transformed, cleaned up and they're going to put a whack load of condominiums in there. There's going to be a lot of condominiums and building going on in there
D-Redevelopment close to water	I actually did approval for another system that’s going to be built downtown as part of the revitalisation, so I know there's another pond that’s going to be built down there. I think they’re looking to increase the recreational use for waterfront residents. [And this pond will be also be part-time skating, part-time summer recreation?] Yes, in the summer, my understanding is there will be a fountain. [So you think it will increase because you know there will be, at least, one other pond and there's a desire to increase the recreational use for the waterfront residents.] Absolutely. As you’re putting more and more people, the concentration of people increases per square metre, the city is also planning to put more and more spaces like parks and recreational areas for people to go to. That’s just smart planning.
D-Redevelopment close to water	I think as the waterfront gets revitalised with a mix of building and natural settings, you’ll see more pathways being put in and TRCA will be overseeing a lot of that.
D-Redevelopment close to water	I'm confident of that because I know the parklands are in discussion as we have new developments along the lake, they are in discussion on building more of this type of infrastructure.
D-Redevelopment close to water	because people are requesting more access to the lake and if we build up the systems along the stream up the rivers, more pathways and that, then there will be more demand. That’s one of the plans for the new developments in the mouth of the Don to have more access to that greenery. Also, as I said earlier, the ponds that are besides the city parks, we’re trying to make it as part integrated so they can enjoy the landscaping around the ponds more.
D-Redevelopment close to water	because we’re building more and more trails and giving more and more access for people to do that.
D-Redevelopment close to water	I think it might increase a little because they have the infrastructure there already. [And why would it increase?] Because of new developments joining that Enwave system.

D-Redevelopment close to water	And especially down at the waterfront, and there is a lot of development along the waterfront, I would expect that the recreational use of those waterways would increase. [Also in the rivers?] Yes, in the rivers too, yes. (...) It's really associated with population increase. There are specific areas where they targeted... they targeted growth areas. So, there is this area the Portlands, that used to be contaminated fill, all in the Portlands, and they have cleaned it all up, and they have changed it, and they have added flood berms, and they made a huge, huge efforts to try to create a huge development down there. And it's been successful, and that land will have huge number of people on it, and it's right down on the waterfront, and it's right next to those rivers.
D-Redevelopment close to water	A lot of the big, big developments and the condo developments are right down there on the waterfront, right. So, as these increase, there is gonna be increases in those recreational uses for sure.
D-Redevelopment close to water	because the trail system along the waterfront has become better and better over time, the bike trail, pedestrians' trails have become better and better over time. They used to, you know start and stop, and you'd have to get onto the road and so, but they have pretty much a bike trail all the way across the waterfront, right through the downtown section now. And there are various parks, like Tommy Thompson Park, which is managed by TRCA, that are... And there's a lot of work been done, a lot of money being invested to make that into a more usable area, from the perspective of birdwatching and habitat and so on. So, I think that... the surface water system along the waterfront will become more and more a destination. There will be more and more demand for it, for recreational, just for kind of aesthetic purposes, just for enjoying life you know. Just enjoying the view than it was in the past. Because there's a lot of efforts being put on by Toronto to improve various sections of the waterfront. The waterfront is its main resource, of all the things that Toronto has to offer, the waterfront is in their view the best, of everything, right everything, that is where all of the downtown area is centred, right. So, they want to make it more walkable, more liveable, more bikeable, everything. And they want to bring nature back to many areas along the waterfront as well. And there is big efforts and big money being put into that, not only by Toronto, but either private companies well investing. So yeah, I think definitely, very certain, that that will become a bigger
D-Redevelopment close to water	de toename van het aantal inwoners in Noord stijgt enorm
D-Rain storms more intense due to climate change	Meer extremen qua weer. [Dus klimaatverandering?] Ja.
D-Rain storms more intense due to climate change	misschien ook periodes van hevige neerslag
D-Rain storms more intense due to climate change	we verwachten eigenlijk dat er veel meer van die enorme buien ook zullen zijn. En we weten nu al dat als je alle pompen uit de polders aanzet die allemaal op het Noordzeekanaal, Amsterdam Rijnkanaal pompen, dat de pomp in IJmuiden niet genoeg capaciteit heeft om dat ook weer weg te pompen. De huidige pomp. Dan kan je of die pompcapaciteit vergroten, maar als de zeespiegel stijgt zou je 'm nog extra moeten vergroten. En we zijn nu aan het kijken van kan je geen andere maatregelen nemen. Kan je niet meer waterberging in die polders realiseren.

D-Rain storms more intense due to climate change	Door de piekbuien
D-Rain storms more intense due to climate change	Climate change.
D-Rain storms more intense due to climate change	In the future, in terms of climate change, there is discussion that climate change will result in more floods occurring or more intensive events so the need to provide flood protection is becoming more and more important due to climate change so we are looking at water quantity ponds again
D-Rain storms more intense due to climate change	De extremen van piekafvoeren en droogte zullen groter worden, dus de extremen komen verder uit elkaar te liggen. Dus wil je het nog beter kunnen sturen, eigenlijk langer vast kunnen houden en afvoeren wanneer jij dat wil.
D-Promotion campaign by authorities	It will increase because the city is really pushing that, I think there's a lot of marketing campaigns associated with that. And, because the city is attempting to try to provide areas that are cleaner. So, they are trying to improve the water quality, as are other areas north of Toronto, to... and for Toronto the main reason is to try to improve occupancy at the beaches. So, I guess it's kind of... Because they have a marketing campaign, because they want... They have a specific objective associated with that, with swim, swimmable beaches and also because many of their actions over time are helping to improve the water quality, along the waterfront, specifically in those areas.
D-Promotion campaign by authorities	because there is a marketing campaign, because there are efforts on the way to stock the rivers with certain fish, recreational fish particularly, like salmon, that the fishing has to increase, yes. I would be somewhat certain about that, although I am not a fish person, I would say somewhat certain about that. [Yeah, and this marketing campaign, where does it come from? Who is doing this marketing?] Toronto. Toronto does it. [The city?] Yeah, yeah. And I think the province also is helping, so the province is also helping to fund this kind of thing.
D-Population growth	de toename van het aantal inwoners in Noord stijgt enorm
D-Population growth	Met de groeiende bevolking binnen Amsterdam en metropool Amsterdam wil je denk je kansen gaan spreiden.
D-Population growth	A, simpelweg het aantal inwoners wat toeneemt
D-Population growth	Meer inwoners
D-Population growth	Ik denk dat het ook zal toenemen gewoon door het aantal inwoners dat toeneemt
D-Population growth	,met meer mensen is er meer vraag
D-Population growth	Er zijn meer inwoners
D-Population growth	Ja de groei van de stad.
D-Population growth	Bevolkingsgroei, meer mensen die in de stad wonen
D-Population growth	meer bewoners
D-Population growth	meer mensen
D-Population growth	Meer mensen
D-Population growth	Gewoon ook omdat de inwonersaantallen groter worden
D-Population growth	Steeds meer inwoners,
D-Population growth	door meer inwoners

D-Population growth	meer bewoners.
D-Population growth	Omdat er binnen Amsterdam natuurlijk steeds meer bewoners komen
D-Population growth	er wordt nu in Noord vrij veel ontwikkeld, veel gebouwd, dus daar komen meer bewoners.
D-Population growth	er komen meer mensen wonen
D-Population growth	Meer bewoners
D-Population growth	meer mensen
D-Population growth	meer mensen
D-Population growth	It will change based on the fact our population continues to rise so we continue to grow.
D-Population growth	with the increase in population that we have
D-Population growth	it's just the number of people, I think.
D-Population growth	because the city of Toronto brings in about 60,000 people a year. It continues to grow every single year. So on a per-capita basis, I expect it to either remain the same of modestly increase but on an overall basis I expect it to increase because there's just going to be a lot more people.
D-Population growth	The question will come in is - it's the same thing I said before that you've got 60,000 people a year coming into the city constantly, there's constantly an expansion to Toronto, so overall I expect there to be an increase in water consumption
D-Population growth	I think also the fact you're just getting more people, so there's always more and more people coming in. [The population is increasing, you mean?] Yes, 60,000 people come into Toronto every year. You're always getting an increase to Toronto. It's the fourth largest city in north America. It's a big city.
D-Population growth	we're going to see a very large influx of people in that area.
D-Population growth	Population growth
D-Population growth	Increased population
D-Population growth	More people
D-Population growth	Because of population growth.
D-Population growth	The demand will increase over time with population. Because of population growth. Our water efficiency is getting better so we are decreasing the per capita consumption, but you can only go down so much, and we do have a big population growth in the Toronto area. [So that will overrule that?] It will overrule that, yes. Our plants are not in bad shape in terms of the ability to do it but the overall demand will increase mainly for population
D-Population growth	Population growth.
D-Population growth	And just generally population growth. Even if you had the same percentage of people going to the beaches there will be an increase because we have a population growth.
D-Population growth	Once again, I would be very confident that would increase just as I said from an overall population standpoint, even if the percentage stays the same because of the growth in population we would have an increase in that demand.
D-Population growth	As I said, the population growth percentage

D-Population growth	and once again in population itself. Even if you had the same percentage, the population will drive that
D-Population growth	there is a population growth
D-Population growth	as the city grows
D-Population growth	The population is increasing so much.
D-Population growth	As the population increases there will be a need to have more
D-Population growth	So I think it again will be because of population increasing it will increase, but not substantially.
D-Population growth	I think all of these from fishing and all that is tied to population so if you have more population the demand will increase.
D-Population growth	Population. More population, more demand.
D-Population growth	One example I have is again population. [Population growth, do you mean?] Population growth, yes.
D-Population growth	it should increase as the population goes up
D-Population growth	because of population again.
D-Population growth	Because all of the populations around Toronto are using that source as their drinking water source. So, as the population expands, the urbanfringe expands, continuous to expand northward, up towards to the Oak Ridges Moraine, there will be a larger population that needs to be served. And so there will be more water being extracted to serve that population, so it is just a population growth issue. We get all of our drinking water from there, and so as the population expands, so too will the use.
D-Population growth	Population growth.
D-Population growth	sailing will increase, motorboating, boating of all kinds along the waterfront will increase with population growth.
D-Population growth	population growth.
D-Population growth	as population grows. But that is just a population thing. Same thing for transporting persons. More people will be transported and there will be more cruises along the waterfront. It's a kind of a common activity, you know, people book cruises along the waterfront and have big parties along the waterfront in these cruise boats. And that is likely to become more popular, more common, a bigger use over time as population grows.
D-Popularity of the activity	Een aantrekkelijke vorm van sport en die is toevallig op het water.
D-Popularity of the activity	Als ik weet niet hoeveel dagen vorst er moet zijn, dan moet het waterschap de gemalen stoppen zodat grachten kunnen dichtvriezen. Dat laat al zien dat er belang aan wordt gehecht en als er überhaupt ijs is dan gaan mensen allemaal de grachten op.
D-Popularity of the activity	Omdat de vraag naar wonen überhaupt toeneemt en wonen op water is aantrekkelijk
D-Popularity of the activity	Omdat mensen dat fijn vinden en ik verwacht niet dat mensen op een gegeven moment denken nou we vinden het niet fijn om te zwemmen.
D-Popularity of the activity	suppen is populair, ik verwacht dat dat nog wel, ik verwacht niet dat dat afneemt, en kanoën en dat soort dingen
D-Popularity of the activity	Ja, volgens mij zijn er altijd mensen die dat leuk blijven vinden.

D-Popularity of the activity	Omdat ik me niet kan voorstellen dat mensen schaatsen opeens niet meer leuk vinden. Het gebeurt niet zo heel vaak dus het is wel bijzonder. Dus mensen willen dat meemaken.
D-Popularity of the activity	Volgens mij is cruisen populair en is dat nog een groeiende business.
D-Popularity of the activity	Maar ik weet niet wat de drijfveer is, er is gewoon een wens om in de lokale water te kunnen zwemmen.
D-Popularity of the activity	en het wonen is natuurlijk.. wonen op water heeft gewoon een meerwaarde vinden veel mensen.
D-Popularity of the activity	[En die cruises, waarom denk je dat dat groeit?] Nou, volgens mij is dat een groeiende markt,
D-Popularity of the activity	Volgens mij neemt ook de behoefte trouwens toe om bijvoorbeeld in plaats van naar de sportschool gewoon zelf ergens langs hard te lopen. [Dus buiten sporten.] Buiten sporten in plaats van binnen sporten.
D-Popularity of the activity	Ja, en het ook leuk vinden.
D-Popularity of the activity	I think people are more aware of their natural surroundings today. I think it's a change in attitude
D-Popularity of the activity	There's a demand for waterfront usage, it's increasing all the time. People just want that place to go and as long as that water quality's there that population
D-Popularity of the activity	One example is some cultures cremate and they sprinkle ashes in the river. We're seeing more and more requests to do that.
D-Popularity of the activity	Because people love to fish, people love to fish. We do fishing, we are big on fishing in Canada, because we have all of these lakes, and we go long distances to go fish. So, if they could fish right in Toronto, they would do it more often.
D-Popularity of the activity	It's a kind of a common activity, you know, people book cruises along the waterfront and have big parties along the waterfront in these cruise boats. And that is likely to become more popular
D-Popularity of the activity	And I think that they... yeah, it is a good question, why they want to do that, I think they just... They know people like to fish, and they know people would want to fish, so it's really... And these are public agencies, and so they tried to meet public demand.
D-People live longer	mensen gaan langer... leven langer, maken langer gebruik van al die faciliteiten
D-People live longer	langer leven
D-People live longer	en die worden ouder, die vinden het makkelijk met zo'n boot te gaan, ik zie dat toch meer als een ouderenvervoer
D-People have more free time	Mensen hebben meer vrije tijd, dus dat de behoefte aan dat soort activiteiten toeneemt.
D-People have more free time	meer vrije tijd
D-People have more free time	Mensen hebben misschien meer vrije tijd
D-People have more free time	iedereen heeft meer vrije tijd

D-People have more free time	mensen hebben gewoon veel meer vrije tijd
D-People have more free time	Meer vrije tijd
D-People have more free time	meer vrije tijd
D-Opportunity to combine with increasing demand for water storage	Ik denk dat er bij nieuwe stedelijke ontwikkelingen meer aandacht is voor het bergen van water, dus als er verharding komt, dat dat gecompenseerd wordt, dat het niet sneller gaat afstromen. En dat er nu ook het besef is dat water verkoelend kan werken en goed is voor het klimaat dus dat dat nu misschien beter ingezet wordt dan vroeger, waarbij het bijvoorbeeld in bezinkbakken onder parkeerplaatsen opgeslagen wordt. [Ja, ja, dus dat er een voorkeur komt voor berging bovengronds...] Ja en dat het zichtbaar is
D-Opportunity to combine with increasing demand for water storage	Het is een combinatie... Ja, omdat het... Je ziet... Je hebt meer oppervlaktewater nodig, je hebt meer opslagruimte nodig, berging heb je nodig en ik denk dat dat... ik weet niet zeker of dat in de stad zou kunnen maar ik denk dat bouwen op water zoals bijvoorbeeld de IJmeer dat dat wel toe zal gaan nemen, juist door die combinatie omdat je gewoon berging nodig hebt. Je hebt gewoon meer oppervlak nodig. Je hebt én behoefte aan ruimte om te gaan bouwen en je hebt meer behoefte aan oppervlaktewater vanwege de bergingsmogelijkheden vanwege droogte en vanwege overlast en ik denk dat dat gewoon, ja, de behoefte om dat te gaan combineren dat die wel zal toenemen. [Ja en op welke manier kan dat gecombineerd worden, denkt u dat er dan meer oppervlaktewater komt en dat daar dan op gebouwd kan?] Nou, drijvend wonen, ja en oppervlak... Je kunt gaan denken aan een bodemdalingsgebied onder water zetten en daarop gaan bouwen bij wijze van spreken.
D-Opportunity becomes more rare	Dat is een exceptioneel iets als dat een keer kan, dus ik denk op het moment dat die grachten dicht liggen, dat het een hele grote toeloop zal hebben.
D-New, bigger sea locks	En de haven blijft denk ik ook heel belangrijk, want er wordt een grote zeesluis gebouwd waardoor er ook veel meer schepen weer doorheen kunnen. Dus dat zal ook groeien.
D-New, bigger sea locks	Maar daar gaan wel dingen in veranderen, want die zeesluis wordt veel groter. Dus daardoor kan er gewoon meer zout water naar binnen komen.
D-New, bigger sea locks	Omdat er een grotere zeesluis komt en dat er meer schepen komen, grotere schepen komen. [Dus er wordt meer zout aangevoerd.] Meer zout aangevoerd. En dat proberen we te voorkomen, maar ik ben bang dat het... dat het... de onzekerheid of... het is nog niet helemaal zeker of het lukt omdat om die hele verzilting die extra verzilting tegen te gaan met de maatregel die we nu hebben genomen en er bleek al sowieso dat zonder die zeesluis er ook al verzilting erg toenam dus afgelopen zomer, dus het zal ongetwijfeld nog wel wat problemen op gaan leveren.
D-New, bigger sea locks	Vanwege de hoge chloridegehaltes. Met de nieuwe zeesluis verwacht ik dat dat eerder zal toenemen dan zal afnemen.

D-Local products trend	Het enige wat we me dan te binnen schiet is dat mensen, dat zie je wel steeds meer, producten die ze zelf kunnen ... dus in moestuinen of ... In west heb je de Tuinen van West waar je voedsel kunt kopen wat biologisch is en waarvan je ziet waar het geteeld wordt. Dat wordt steeds interessanter. Misschien dat vissen daar ook een onderdeel van is maar.... [Het past in die trend om zelf je voedsel ...] Ja, om zelf je voedsel of van dichtbij.
D-Local products trend	Yes, because you know local sourcing, seeing the whole idea of not buying goods from far away, I think that's going to happen more.
D-Local products trend	It's just people are more aware of environmental issues, trying to grow local sources of goods.
D-Limits to transportation on land (rail, road)	de binnenstad slibt echt dicht. De wegen bedoel ik dan, niet de grachten maar de wegen. Toename van het pakketjesverkeer, van allerlei busjes, waardoor het vast komt te staan. Ik kan me voorstellen dat bevoorrading van diverse winkeliers, restaurant et cetera, dat ze gaan proberen dat via de gracht te doen.
D-Limits to transportation on land (rail, road)	Kijk, de grachten zijn ook verstopt, maar goed,de wegen in de stad zijn ook verstopt; je kan nergens door met de auto. Maar om dingen te bezorgen kan je de grachten handiger benutten.
D-Limits to transportation on land (rail, road)	Omdat ik denk dat wegen vol zitten, treinen vol zitten en dat dus meer transport over water gaat plaatsvinden. Gewoon omdat het verdrongen wordt op wegen en op spoorwegen.
D-Limits to transportation on land (rail, road)	Ook de groei van het vervoer van mensen over de trein en over bussen en dat deze dan dus ook weer in beeld komt. [Omdat er meer mensen met bussen gaan?] En treinen en dat die vol raken en dat je dan toch dus kijkt van wat is dan nog mogelijk over water.
D-Limits to transportation on land (rail, road)	Door het dichtslibben op het land, zeg maar, van transport van mensen en spullen.
D-Limits to transportation on land (rail, road)	Nou ja, als het qua files en in de metro's allemaal dichtslibt kan ik mij voorstellen dat daar wel naar gekeken gaat worden.
D-Limits to transportation on land (rail, road)	Ik denk dat het een snelle manier is om in Amsterdam te komen.
D-Limits to transportation on land (rail, road)	because Toronto is such a grid-locked city. I can see definitely trying to get from the east to the Westside of the city, it would be really beneficial to be able to get on a boat and bypass Toronto and go from the Westside to the east, or east to the Westside.
D-Land value increase	The farmers are getting older and their children don't want to farm the land and that land is now worth a fortune for development, so a farmer who probably doesn't have children that want to take it over, and he's not going to sell it to another farmer to take it over, he'll likely sell it and take that money and live on it quite comfortably for him/her and their family.
D-Land value increase	because land is so expensive
D-Land value increase	Because the value of the land in the Toronto area has gone up so much that many golf courses are shutting down and they're developing them.
D-Land value increase	I think in the future the land values are so high that maybe they'll start putting the ponds underground.

D-Lack of space on land	Water is gewoon in de beperkte ruimte die er is voor evenementen een van de belangrijke plekken.
D-Lack of space on land	Er is gewoon een enorme druk op het gebruiken van de openbare ruimte, je ziet dat er woningen op water zijn, drijvende fietsenstallingen op de Amsterdamse grachten. [Dus het gaat om een gebrek in ruimte aan land wat het...] Ja.
D-Lack of space on land	Ik zie dat er steeds meer discussies zijn over hoe we de ondergrond gebruiken, waar volgens mij, dat was jaren geleden was dat nooit een discussie. Je trok gewoon een nieuwe leiding van A naar B. En nu zie je dat het echt gewoon ingewikkeld is om nog de ruimte te vinden in de ondergrond om kabels en leidingen te trekken. Het is echt vol.
D-Lack of space on land	en er binnen de stadsgrenzen van Amsterdam gewoon bijna geen plek meer is om uit te breiden. Dus, ja. [Omdat er op land geen plek meer is] Nee. [wijkt men uit naar water.] Ja, ja.
D-Lack of space on land	Right now, we have over a 1,000 storm water ponds in our jurisdiction and that number will go up as we continue to develop, but the amount of land that's available for development is a lot less now near our waters. So we're not going to see as many new ponds being built because there's just not that much more land available to develop.
D-Lack of space on land	because there's less land for development so the demand will be higher.
D-Lack of space on land	but it is not going to increase by a lot, because there is not much land
D-Industrial use of drinking water increases	Dat is iets wat we ook nog willen uitzoeken. Maar we krijgen signalen dat het drinkwatergebruik door de industrie erg toeneemt ook.
D-In case that pilot application is successful	Afhankelijk van de onderzoeken, als dat uit gaat wijzen, zal de vernatting zeker op enkele plekken een oplossing bieden.
D-Hydrogen factories expected	We verwachten er worden heel veel windparken op zee gebouwd en die elektriciteit komt aan, maar die moet je eigenlijk op de een of andere manier zien op te slaan. En een van de manieren is dus om er waterstof van te maken, waterstofgas. Dat zou waarschijnlijk ook goed door de industrie gebruikt kunnen worden als energiebron. Dus wij verwachten dat er waterstoffabrieken worden gebouwd. En bij Tata is er een in voorbereiding, maar we verwachten dat in het Noordzeekanaal, ook omdat die kabels van die windparken komen waarschijnlijk in dit gebied aan.
D-Flood protection ambitions	I think water quantity management will increase to address our urban flooding and we're doing water quantity, or erosion control, within the river systems. [(...) Does the surface water system play a role in that or will it mainly be targeted at measures on the land?] It would be mainly in the land with some exceptions such as the change in the mouth of the Don River where we're expanding that, providing a new outlet. [So when you look at the role of the surface water systems, or the measures you take in this system, will that also increase?] I think so. We will look at quantity more. One of the plans is to re-urbanise some of our channels, rivers that have been channelized. That's a longer term goal we'll reach in 2040 hopefully. If we do that that will help with the flooding. As you know, channel water is always faster, it can cause more flooding much easier so we'd naturalise the quantity.

Supplement

D-Electricity demand increases	[Maar je zegt: die behoefte aan meer elektriciteitsproductie lijdt tot een toename in behoefte aan koelwater voor de energiecentrales.] Ik denk het wel, ja. Want ik zie nog niet dat in een periode van twintig jaar die elektriciteitsvoorziening via duurzame energie volledig tot stand gebracht kan worden.
D-Electricity demand increases	Maar ik denk dat er heel veel behoefte komt weer om kabels en leidingen te trekken. [Om daar die ruimte voor te gebruiken.] Om de ruimte te gebruiken in het water. [En waarom denk je dat dat toeneemt?] Omdat ik denk dat je heel veel aan de energie infrastructuur moet doen als je energietransitie wil realiseren. (...) Ook in Amsterdam moeten er veel nieuwe elektriciteitsleidingen worden getrokken. Als iedereen over moet op elektrisch koken en elektrisch verwarmen van huizen. [Dus een toename van de vraag.] Ja en dat zal heel veel vragen van het netwerk. En ik denk dat het netwerk dus deels vernieuwd moet worden en dat er extra kabels nodig zijn.
D-Electricity demand increases	There's an increase in demand of electricity for the city as the city grows, that's why I think there will be a demand for this type of energy.
D-Dry periods longer and/or more frequent due to climate change	Met van die droge zomers kan ik mij voorstellen dat, om die goed op peil te houden die gebieden, dat er meer water nodig gaat zijn in de zomer.
D-Dry periods longer and/or more frequent due to climate change	De extremen van piekafvoeren en droogte zullen groter worden, dus de extremen komen verder uit elkaar te liggen. Dus wil je het nog beter kunnen sturen, eigenlijk langer vast kunnen houden en afvoeren wanneer jij dat wil.
D-Dry periods longer and/or more frequent due to climate change	langere periodes van droogte zomer
D-Dry periods longer and/or more frequent due to climate change	Door de grotere periodes van droogte in de zomer, langere periodes, en hogere temperaturen waardoor elk jaar eigenlijk het grondwater ook steeds meer uitzakt en de onverzadigde zone meer uitdroogt.
D-Dry periods longer and/or more frequent due to climate change	door grote periodes van droogte
D-Dry periods longer and/or more frequent due to climate change	Vooral klimaatverandering speelt dan mee; van die lange droge periodes, hoge temperaturen, een grote behoefte aan je tuintje water geven of op landbouwgronden sproeien, dan zou je toch naar andere bronnen moeten uitwijken.
D-Dry periods longer and/or more frequent due to climate change	Ook gerelateerd aan klimaatverandering; er treedt veel meer verdamping op, weinig neerslag weer, ook al wil je iets nuttigs doen met die neerslag, als die er niet is kan je er niks mee doen, dus heb je wel een alternatief nodig. Dus zo kan ik me voorstellen: oké, dat oppervlaktewater zal ook gebruikt worden voor dat soort zaken.
D-Dry periods longer and/or more frequent due to climate change	Nou, met de klimaatverandering, dat er vaker periodes van droogte zijn, waarbij je actiever moet inspelen daarop, dus gerichter moet handelen.
D-Dry periods longer and/or more frequent due to climate change	Grote periodes van droogte, watertekorten

D-Dry periods longer and/or more frequent due to climate change	Doordat er veel minder tegendruk uit de Rijn komt, omdat de gletsjers zijn gesmolten en dus geen water meer in de zomer geven. En omdat de zomers droger worden.
D-Dry periods longer and/or more frequent due to climate change	Dus dat, maar wat je ook krijgt is dat er als de Rijn 's zomers minder water aanvoert richting Nederland, dan is er ook minder druk via het Amsterdam Rijnkanaal op die zoute, tegendruk, dus dat zoute water kan gewoon verder komen en dat zagen we vorig jaar zomer al en toen zijn er ook allerlei maatregelen genomen door Rijkswaterstaat en waternet met bellenschermen om ervoor te zorgen dat het Amsterdam Rijnkanaal niet zouter zou worden.
D-Dry periods longer and/or more frequent due to climate change	Nou, ik kan mij voorstellen dat door de klimaatverandering dat er meer behoefte is aan beregeningswater
D-Dry periods longer and/or more frequent due to climate change	because we won't be able to, I mean unless we come up with a sustainable way of doing it we wouldn't be able to irrigate as much because one of Toronto's big weather changes is heat, for example, in summers of periods drought, things like that so we may not be able to irrigate in the same way over time as our water levels decrease.
D-Dry periods longer and/or more frequent due to climate change	I think we're going to see decreasing, surface potable water sources globally in all parts of the world, so a greater pressure on cities like Toronto that have an abundance of freshwater at this time, to both serve our population here but being demanded upon elsewhere-, For example, the US who wants to have our potable water because they're in drought conditions, even as far down as Florida.
D-Densification	daarnaast verdicht Amsterdam. Het wordt steeds een verharder oppervlak dus de temperaturen buiten Amsterdam en binnen Amsterdam, dat verschil wordt steeds groter.
D-Densification	Het beperkte groen dat er nog is. Water kan deels daar ook een functie in overnemen dus denk ik dat in die zin er ook een grotere vraag naar is. [Bedoel je dat mensen in plaats van naar groen naar water gaan?] Ik denk een combinatie. Dat meer mensen dichter op elkaar wonen waar voorheen misschien het buiten, naar het bos of de polder, dichterbij was, nu eerder naar het water wat ook dichterbij is want dat ligt er nog steeds.
D-Densification	Door het verdichten van de stad komt er een grotere druk op de bestaande groene parken en andere groene delen van de stad. Daar heeft water, want dat is vaak onderdeel van die groenblauwe structuur, een heel groot aanbod in en heeft daar ook een belangrijke functie in. Dus de druk, meer inwoners, meer vraag naar op korte afstand kunnen ontspannen zijn denk ik … Er zit natuurlijk meer hoogbouw in dus mensen willen ook naar buiten om … als je zelf geen tuin hebt maar toch ergens in het groen of in het blauw kunnen ontspannen.
D-Densification	de stad verdicht dus de vraag naar openbare ruimte waar evenementen, hoe klein of hoe groot dan ook, die zal toenemen. Daar vormt het oppervlaktewater gewoon een onderdeel van, van dat systeem.
D-Densification	En het komt ook omdat, wat ik ook wel zie is een trend dat huizen toch weer kleiner worden. Meer mensen op elkaar wonen.
D-Densification	en steeds intensere bebouwing, steeds meer hoogbouw.
D-Densification	en verdichting van de stad
D-Densification	steeds meer verdichting
D-Densification	want de stad wordt dichter
D-Densification	meer stedelijke druk

D-Densification	Well, this is always going to be, like it says, the fourth largest city in North America, so I don't really see us converting our settlement areas to agriculture.
D-Densification	As you're putting more and more people, the concentration of people increases per square metre, the city is also planning to put more and more spaces like parks and recreational areas for people to go to. That's just smart planning.
D-Densification	as the density of population increases in Toronto.
D-Data centers increase	al die datacenters, die hebben water nodig voor koeling, en die schieten als paddenstoelen uit de grond.
D-Data centers increase	De datacenter. Die gebruiken veel water om te koelen als het heet is.
D-Cost saving ambitions	Want initiatiefnemers denken wel van: dat is hartstikke leuk, goedkoop
D-Cost saving ambitions	Just because of the cost of the municipal drinking water system and the cost of energy; I think they're going to be looking at ways of reducing it.
D-Cost saving ambitions	Energy costs
D-Cost saving ambitions	It was very cost effective and successful, so there was a very good business case associated with it, and it was very successful, so I think they might be looking for other options there.
D-Circular economy/re-use of waste streams ambitions	Ja, en je ziet naast die trend, dat heb ik bijvoorbeeld bij het waterschap wel gezien, dat ze steeds meer gaan kijken naar het optimaliseren. Dus wat kun je doen met afvalproducten? Daar horen ook bijvoorbeeld rivierkreeften bij, dat is een plaag. Of muskusratten, waterkonijnen in het Vlaams genoemd. Dus ik kan me ook voorstellen dat dat omslaat dat die dieren worden geconsumeerd. Dat je naar een soort meer circulaire aanpak kijkt van een bedrijfsvoering. Wat kan ik eigenlijk met al mijn producten binnen mijn keten?
D-Circular economy/re-use of waste streams ambitions	het wordt nu gemaaid uit beheerdoeleinden. Maar je zou nog eens kunnen denken: als het echt een goed materiaal is en er is een grote markt voor, gericht zoiets gaan kweken, maar dat is meer toekomstmuziek. Nu is het zo: dat maaisel heb je toch, kan je dat goede een bestemming geven?
D-Circular economy/re-use of waste streams ambitions	Het is toch gericht op hergebruik van grondstoffen, het is een alternatief voor meer milieubelastende grondstoffen, maar goed, dat zit in het idee van circulaire economie, het opwaarderen van stoffen. Dus dat is de belangrijkste drijfveer.

D-Circular economy/re-use of waste streams ambitions	Ik kan mij wel voorstellen dat wij nog iets met die kreeften moeten die wij steeds vaker in het water hebben en die nu niet gevangen mogen worden maar wel heel veel schade soms aan het ecosysteem en ook aan kunstwerken van water veroorzaken. Dus als daar nog een wijziging komt in de regelgeving dan. (...) Volgens mij zijn ze nog beschermd. (...) Nou ja, ik kan mij voorstellen want in sommige stukken van het watersysteem zijn zij zo bovenmatig aanwezig dat het gewoon heel dominant is in het ecosysteem, en ook echt schade oplevert bijvoorbeeld aan stuwen en dergelijke. Dus dat er op een gegeven moment wel een kentering komt. Of dat het misschien gedeeltelijk of een bepaald aangewezen water of zo, dat dat op een gegeven wel toegestaan gaat worden. (...) [En jij denkt, dat het misschien dan ook wel opgegeten gaat worden?] Ja, dan zijn zij volgens mij ook geschikt om te consumeren. Dan is het zonde om ze niet naar het restaurant te brengen.
D-Circular economy/re-use of waste streams ambitions	If we get increased algae blooms, I can see someone harvesting and then actually re-using it somewhere for something. [Like compost?] Compost, exactly. Or even something else that one hasn't considered yet. I was trying to think where it was, but in Venice, they actually collect the seaweed and they dry it and burn it and create electricity.
D-Circular economy/re-use of waste streams ambitions	I could see that type of thing maybe where the mouth of the Don is going to be cleaned up and all this contaminated soil, I know there was a potential opportunity there for that type of situation: How could we take that contaminated sediment and re-use it as opposed to land-filling it? How could it be re-used? So I could see that as a potential.
Db-Water quality not sufficient	dat is daar te zout voor
Db-Water quality not sufficient	Of er moeten echt heel andere gewassen geteeld worden die meer resistent zijn tegen zout. Maar er is een grote huivering voor water uit het Noordzeekanaal vanwege het hoge zoutgehalte.
Db-Water quality not sufficient	Omdat ik denk dat het water niet schoon genoeg is.
Db-Water quality not sufficient	En we hebben gekeken of we die kabel konden trekken door het Noordzeekanaal. Maar de bodem daarvan is zo vervuild en er liggen al zoveel andere dingen en er zaten zoveel onzekerheden dat het verder toen niet is onderzocht. Maar het was wel een optie. En toen gingen ze het onderzoeken en toen kwamen er zoveel onzekerheden over vervuilde bodem
Db-Water quality not sufficient	Omdat de Amstel natuurlijk gewoon een afvoerrivier is met alle effluenten en poldergemalen en zo erop. Dus dan moet je er wel heel veel uitzuiveren voordat het drinkwater is, denk ik.
Db-Water quality not sufficient	I think our public health would be very concerned about the quality of surface water and the bacteria, bacteria in terms of airborne, having disease and bacteria getting airborne.
Db-Water quality not sufficient	Given the quality of the water in the urban systems, I think a lot has to happen before we could utilise it for consumption of fish in our area.
Db-Water quality not sufficient	Again, a lot has to be done to clean up the water before you could utilise the waterways for consumption.
Db-Water quality not sufficient	The nearshore of Toronto to Lake Ontario, the water quality is very poor.
Db-Water quality not sufficient	but I don't think swimming in our natural systems like our lakes and rivers the water quality is good.

Db-Water quality not sufficient	Yeah, because, you know, process water also has to be of a certain quality as well, sometime, often, right. And no one wants to put salty water in their – well, most of the time salty water is the problem. So, I can't see it increasing in Toronto, outside of Toronto, further north, maybe. But not so much in Toronto
Db-Water quality detoriation/salinization	Vanwege de hoge chloridegehaltes. Met de nieuwe zeesluis verwacht ik dat dat eerder zal toenemen dan zal afnemen.
Db-Water quality detoriation/salinization	Ja, ik kan me voorstellen dat die zoute kwel toeneemt en dat ook de druk vanuit de Noordzee met zoutlast ook toeneemt
Db-Water quality detoriation/salinization	En een van de dingen die er gebeurt is dat het water aan het verzilten is. Nou is het water eigenlijk hier tot hier ongeveer is het al verzilt. [Dus tot het Buiten-IJ.] Ja. En hier tot het begin van het Amsterdam Rijnkanaal. Maar daar gaan wel dingen in veranderen, want die zeesluis wordt veel groter. Dus daardoor kan er gewoon meer zout water naar binnen komen. Er zijn ook wel allerlei technische maatregelen genomen. Ik weet niet of {name} dat heeft verteld. Dus dat, maar wat je ook krijgt is dat er als de Rijn 's zomers minder water aanvoert richting Nederland, dan is er ook minder druk via het Amsterdam Rijnkanaal op die zoute, tegendruk, dus dat zoute water kan gewoon verder komen en dat zagen we vorig jaar zomer al en toen zijn er ook allerlei maatregelen genomen door Rijkswaterstaat en waternet met bellenschermen om ervoor te zorgen dat het Amsterdam Rijnkanaal niet zouter zou worden. (...) We zijn heel benieuwd of als het zouter wordt, of dat van invloed is op het proceswater.
Db-Water quality detoriation/salinization	En dan gaat het vooral over verzilting, over die waterkwaliteit
Db-Water quality detoriation/salinization	omdat water alleen maar viezer wordt heb ik het idee
Db-Water quality detoriation/salinization	and the warmer weather could trigger algae blooms more frequently. So the question really comes down to which way that's going to go? The algae blooms happen because of a mix of nitrogen and phosphorous, so depending on what the nitrogen and the phosphorous and the temperature, those three factors play a big role in terms of algae blooms. So climate change could result in more algae blooms in the future
Db-Water quality detoriation/salinization	And as the urban area expands north, we get more and more salt in the rivers. It's likely to become more and more salty, even if it's cleaner from other perspectives, the salt is likely to increase or stay the same.(...) [Okay, so there you say (...) the golf courses are forced to move to another source. Who forces them?] Well they are forced just by the quality of the water, because it is no longer making the grass green, you know, it's actually hurting the grass. So, that's what forcing them, it's just the practicalities of it. So, and I don't expect that the salt, that the rivers will become less salty over time, because of the urban growth. So, I am saying that that is likely not going to change. We are not going to use more irrigation for vegetation because it is not becoming less salty, and salt is the main reason why we are not taking as much as maybe we used to take from the river, for irrigation and other vegetation like golf courses, park.
Db-Water quality detoriation/salinization	And the river is becoming more and more salty over time, and therefore it will become less and less suitable for many uses. So, that's why I think it's not going to become more, it's not gonna come more, it might stay the same, but it won't become more

Db-Unreliable source	Niet in het oppervlaktewater omdat de omstandigheden niet even constant zijn en dat is gewoon niet de plek. Dus nee. De omstandigheden zijn niet constant en ook niet controleerbaar
Db-Unreliable source	Als we naar resource recovery kijken; nutriënten terugwinnen, andere grondstoffen die je kan hergebruiken, is het veel meer op het gebied van drinkwater en afvalwaterzuivering. [Ja. En waarom zijn die interessanter?] Is een veel geconcentreerdere… nou, geconcentreerdere… beter gedefinieerde stroom. (…) Ja, en je kan het op een goede locatie inzetten, het is makkelijker hanteerbaar ja.
Db-Unreliable source	en onvoorspelbaar van kwaliteit
Db-Unreliable source	Omdat er gewoon heel veel water mee gemoeid is en het water uiteindelijk… het is… ja, dit is zo lastig te beheren met ups en downs, daar heb je gewoon… je hebt daar een vrij zekere factor voor nodig en in Andijk heb je gewoon een enorm reservoir in het IJsselmeer waar je gewoon altijd je productie kunt halen, dus het voegt niks toe.
Db-Unreliable source	No, I don’t think they could count on it
Db-Perception about water quality	it’s also having the residents being confident the water’s clean. It's not so much just cleaning it, they have to be confident that it is clean
Db-Perception about water quality	And I think the thing preventing them from doing that, is that there is a perception – whether right or wrong – that all fish caught in those rivers is too contaminated for consumption.
Db-Other functions prevail/conflict between users/lack of space	doordat er al zoveel botenverkeer is op het water, dat het elkaar gaat bijten. Dat ze toch, dat het aantal boten, dat is misschien lastiger in te perken dan het uitgeven van vergunningen voor woonboten. [Ja ja, dus de vraag neemt wel toe maar het gaat niet toegestaan worden.] Nee, dus het is echt het reguleren, wat past er nog op het water? De woonbootbewoners hebben erg veel last van verkeer op de grachten; golfwerking en gewoon overlast door mensen die dronken zijn of wat dan ook. In die zin wordt er gezocht naar een soort van evenwicht en dat kun je vinden door het reguleren van bijvoorbeeld woonbootvergunningen, en natuurlijk ook het beperken van ligvergunningen voor bootjes.
Db-Other functions prevail/conflict between users/lack of space	Omdat het eerder een andere bestemming zou krijgen. Nou ben ik geen planoloog, maar als ik daar zie in Amsterdam, Rotterdam, noem maar elke havenstad op, daar krijgen oude havens een woonbestemming; daar wordt nieuwbouw neergezet. En dat is niet zozeer om het water… nou ja, het waterfront wordt wel een beetje bewaard, maar… [Dus begrijp ik het goed dat je zegt: het cultureel historische zit vooral in de havens, maar die gaan we niet erkennen als cultureel erfgoed, die gaan we ombouwen naar woonwijken.] Krijgt een hele andere functie ja.
Db-Other functions prevail/conflict between users/lack of space	Dan krijg je problemen met de scheepvaart, als je het peil ophoogt kunnen boten niet meer de brug onderdoor.
Db-Other functions prevail/conflict between users/lack of space	Of er plekken zijn waar dat mogelijk is. Maar ik denk dat het water in Amsterdam al zo erg benut wordt dat je dat dus niet gaat doen
Db-Other functions prevail/conflict between users/lack of space	en er liggen al zoveel andere dingen

Supplement

Db-Other functions prevail/conflict between users/lack of space	Om de inlaatbehoefte in ieder geval niet heel veel groter te laten worden, want dan kom je gewoon in de knel in droge zomers, Want dan gaat natuurlijk gewoon die pikorde spelen van waar dan nog wel water voor beschikbaar wordt gesteld, en waar niet. En daar wil je natuurlijk niet afhankelijk van worden.
Db-Other functions prevail/conflict between users/lack of space	Nou ja, je merkt toch wel de druk op het water, het wonen aan het water, het wonen op het water, zonnepanelen op het water, wat ik net allemaal noemde. Dus of wij dat vast kunnen houden, ja, dat wordt nog wel lastig denk ik met die verdichtende stad. [Dus het kan zijn dat door de plannen om op water te bouwen er water verdwijnt, zeg maar, oppervlaktewater verdwijnt.] Ja, of zo overkluist wordt dat het natuurlijk gewoon niet meer zo functioneert
Db-Other functions prevail/conflict between users/lack of space	So, for things that are not essential, like we might need to be focusing on the use of water for priorities like drinking water as opposed to irrigation
Db-Other functions prevail/conflict between users/lack of space	The main reason for this is because it's a very densely populated area and it should be maximised for public use, and I just don't see that the city, the province or the federal government would want to encourage individuals living in boathouses.
Db-High costs	maar je loopt er toch tegenaan dat je die waterkwaliteit moet controleren. Hoe klein je waterhoeveelheid ook is, dan moet je toch die analyses erop loslaten, dus dat wordt gigantisch duur dat water.
Db-High costs	Because it would require an investment in infrastructure to change our system,
Db-High costs	there's a lot of cost involved to do that.
Db-High costs	The reason I say 'somewhat' is boating is not cheap. (...) I think, as I said, there is a population growth so there could be an increase in population but with the cost I'm not sure whether that percentage will keep pace.
Db-High costs	This material's usually extracted from land; it would be more costly and expensive to try finding it from water.
D-Awareness of animal welfare increases	Misschien ook een maatschappelijke trend, met meer aandacht voor dierenwelzijn.
D-Awareness of animal welfare increases	misschien ook een maatschappelijke trend, want hoe wreed vinden mensen dat, zo'n vis uit het water hengelen met een haak in zijn bek, om het plat te zeggen?
D-Awareness about heat stress increases	omdat gewoon de afgelopen jaren zie je meer bewustzijn over hittestress en de gevolgen in de zomer, bewoonbaarheid van de stad. Dus ik denk dat dat, je ziet al een tendens dat daar meer aandacht voor is en ik verwacht dat dat de komende jaren groter wordt, dat er ook met plannen meer rekening mee gehouden wordt, met leefbaarheid.
D-Awareness about heat stress increases	Bij al het klimaatadaptatiebeleid wordt wel de verkoelende werking van die wateroppervlakken steeds genoemd als belangrijke maatregel ook om hittestress te voorkomen. Dus groen en water in woonwijken wordt heel erg gewaardeerd. [En wordt het daar ook bewust voor ingezet?] Ja. En we discussiëren nu ook bijvoorbeeld of je in ruimtelijke ordeningsregels zou moeten zetten dat bewoners recht hebben op verkoelende plekken op 300 meter afstand of 500 meter afstand. En die verkoelende plekken kan groen zijn, maar kan ook heel goed water zijn.

D-Awareness about First Nations heritage increases	I think just greater awareness of First Nations' heritage. We have the First Nations reconciliation that was done by the federal government. I think just there's a greater and greater awareness of the injustices towards First Nations and the need to be more inclusive and bring them into the fold more.
D-Awareness about First Nations heritage increases	Given the current landscape of recognising indigenous rights more, it's more prominent now. I think that will increase.
D-Awareness about First Nations heritage increases	But there is always an attempt to try to better document where indigenous communities used to have their villages and where they used to live and what the historical use of this area was. And that is always increasing over time, it is always increasing over time, as we do more and more research on it and find those areas through different archaeological programmes. It's only likely to increase, but I am somewhat uncertain about that. [Yeah, and the reason is that there is more and more knowledge about it, because of the research?] Yeah, yes. Yeah, knowledge is the driving factor there, yeah. And I think I'd say there is more and more emphasis and more and more concern put on… or more and more awareness of indigenous issues and more and more concern and awareness about indigenous issues. And that, I think, more and more people appreciate the value of that activity, so that is another driver. So, even in the schools, they regularly talk about it to kids in the school, you know, they make mention of the original… the original in habitats of different areas. So yeah, I think it's something that will increase as the result of that too.
DO-Water is no longer a physical barrier	dat water is geen barrière meer. Dat is op alle manieren is daar overheen te komen
DO-This is not a habit or lack of knowledge	We gaan niet in Nederland volgens mij van die gated communities met een grote gracht er omheen. Ik denk niet dat het in onze cultuur zit om het zo te bouwen.
DO-This is not a habit or lack of knowledge	dat doen gewoon heel veel mensen niet
DO-This is not a habit or lack of knowledge	Because in cities it's not something people do. Also what are they using for hunting? You don't want people walking around with rifles for hunting animals in the city, really
DO-This is not a habit or lack of knowledge	I think it's just that people are not aware of it or how to do it.
DO-This is not a habit or lack of knowledge	It's just not a practical use that we have right now.
DO-This is not a habit or lack of knowledge	I think that there is just not that much interest in catching animals and cleaning them for consumption, you know. It would be… The knowledge just isn't there and the interest isn't there. And I don't meet anyone – put it that way – or I don't talk to anyone or I don't see anything in the literature that suggests that that is indeed something that would be a trend.
DO-This is not a habit or lack of knowledge	Uhm. Well, it is minor because there are not very many groups that know anything about aquatic plants, or how to harvest them for consumption purposes. And so… I mean, your regularly person in Toronto is gonna know nothing about that. And the same with algae,
DO-This is not a habit or lack of knowledge	I don't think it will change, because there is no awareness of it as it being a management option. And I don't know that there are any demands for it, like I don't know where we would benefit from such a thing.

DO-This is not a habit or lack of knowledge	But the ponds are not generally thought to do that. They actually probably do do that, to some extent – ha-ha – but they are not generally thought to be a heat island mitigation measure. They aren't talked about in that sense, they never talked about in that sense. So, while they might actually be having that effect, they are not encouraged for that reason ever.
DO-Regulations don't allow the use	I just don't think that would be something people would be allowing.
DO-Regulations don't allow the use	No. Again, we have strong regulations against it.
DO-Regulations don't allow the use	And also... there tends to be more and more restrictions related to water takings. And so... To take water like that requires a permit, and it takes a long time to get the permit and so and so. I think they are trying to reduce the numbers of illegal water takings, and legal water takings. Not increase them. So, I think that is... I think the city would prefer if they just got the water from their sources, and pay them for it – ha-ha – rather than taking it from the river.
DO-Regulations don't allow the use	Well, I think there is regulations, and the regulations aren't becoming less stringent over time, they are becoming more stringent if anything.
DO-Potential capacity is too small to be relevant	Niet in Amsterdam volgens mij omdat de verschillen gewoon ... Er is wel een zout gradiënt door de invloed van het Noordzeekanaal maar het verschil is niet heel erg groot.
DO-Potential capacity is too small to be relevant	Dat is denk ik ook lastig hier omdat er vrij weinig verval is.
DO-Potential capacity is too small to be relevant	Daar is het veel te klein voor. (...) ik denk dat het weinig zin heeft.
DO-Potential capacity is too small to be relevant	Omdat er denk ik weinig te winnen valt.
DO-Potential capacity is too small to be relevant	En we hebben een aantal jaar terug een onderzoek gedaan naar alternatieve drinkwaterbronnen, dan zijn ze hier toch redelijk klein om heel je drinkwatervoorziening daarop te richten
DO-Potential capacity is too small to be relevant	Ik denk niet dat je daarmee in het voedselvraagstuk ofzo kan voorzien ook. Het zal heel klein zijn, het zal heel klein blijven. Ik denk niet dat je daar je brood mee kan verdienen.
DO-Potential capacity is too small to be relevant	Ik denk dat niet iemand er zijn brood mee kan verdienen
DO-Potential capacity is too small to be relevant	Omdat ik denk dat als mensen echt algen gaan eten, dat er iemand opstaat die maakt ergens een algenkwekerij, maar dat gebeurt dan gewoon op een industrieterrein professioneel in grote tanks. Of ergens in een bassin in het IJsselmeer ofzo. Dat lukt je volgens mij niet in de stad. (...) Omdat de stad te vol is. [Het moet groter?] Ja, het moet groter.
DO-Potential capacity is too small to be relevant	want volgens mij stroomt er niet zo, er stroomt volgens mij minder
DO-Potential capacity is too small to be relevant	dat is toch meer iets wat ergens op zee speelt. Dat is niet, die gaat hier niet werken.

DO-Potential capacity is too small to be relevant	Because there's very low kinetic energy there.
DO-Potential capacity is too small to be relevant	because I don't think that there's enough, I think there's a better economic plan for the wastewater re-use for creating electricity or reducing your electrical cost than I do see for the surface water.
DO-Potential capacity is too small to be relevant	because our rivers are not big enough and the grades are not big enough to generate power. If the new technology comes along, maybe, but right now we have a couple of dams that we looked at the possibility of generating power and it didn't work.
DO-Potential capacity is too small to be relevant	I don't think we have so many species so I don't think it's going to increase that much.
DO-Potential capacity already fully used	maar echt de frequentie vanuit Centraal Station, dat kan eigenlijk niet hoger.
DO-Potential capacity already fully used	Ik bedoel het heeft al een bepaalde status dus het is belangrijk dus het is hun visitekaartje van de stad, dus volgens mij kan het niet veel groter worden dan het nu is en ik verwacht ook niet Amsterdam zich anders gaat presenteren.
DO-Potential capacity already fully used	Nou, ik denk dat dat voor de binnenstad van Amsterdam het zo erg verweven is met het visitekaartje van Amsterdam, hoe het eruit ziet, dat dat, ja, dat is nu al heel groot. Dat dat belang en die waardering van het water in de binnenstad, ik denk niet dat daar snel nog iets verandert.
DO-Potential capacity already fully used	I'd say it's already probably high.
DO-Popularity declines	Maar ik zie ook wel dat het sproeien gebeurt vooral door de oudere tuinders. Die willen hun tuin heel mooi groen houden. Terwijl de jongere tuinders denken: nou ja weet je, dan verdort het en volgend jaar komt het wel weer op. Die zijn minder perfectionistisch zeg maar. Die gaan meer mee met de natuur.
DO-Popularity declines	Because apparently golfing isn't as popular as it used to be.
DO-No reason for change/don't know	Ik weet niet zo goed waarom.
DO-No reason for change/don't know	ik zou niet zo goed weten wát je dan in het water zou willen doen
DO-No reason for change/don't know	Omdat ik niet verwacht dat de populatie heel erg gaat toenemen. Misschien dat het eerder afneemt. [Je bedoelt de populatie van vissers?] Van vissen en vissers, beiden.
DO-No reason for change/don't know	Dit is meer een onderbuikgevoel van: ik zie geen ontwikkeling.
DO-No reason for change/don't know	Ik zie het nu niet, en ik zie het in de toekomst ook niet optreden
DO-No reason for change/don't know	Je hebt al de lightrail, busverbinding, tram… dat zie ik veel eerder gebeuren.
DO-No reason for change/don't know	Maar dat is ook weer een onderbuikgevoel. Ik ken het niet, dus, omdat ik geen idee heb.
DO-No reason for change/don't know	Nee, ik denk wel dat het veel meer gewaardeerd wordt dat water, dus dat je er graag bij wil wonen en of je er dan op woont of erbij woont, dat maakt denk ik voor bewoners niet zo heel veel uit.
DO-No reason for change/don't know	Ik verwacht niet dat wij dat meer gaan doen dus minder kan eigenlijk haast niet dus.

DO-No reason for change/don't know	Omdat ik niks kan verzinnen
DO-No reason for change/don't know	Dat is voor Amsterdam zo herkenbaar en zo belangrijk, dat blijft gewoon gelijk.
DO-No reason for change/don't know	We don’t have as much industry anymore. We’re still trying to keep the industry, and industry will want to decrease water use, where possible. So, we’re not a growing industry. We’re not having increases in industry in the city, let's say, so we’re just trying to keep what we have
DO-No reason for change/don't know	Canada still does export a lot of raw material so I think there's still some raw material coming up to through the lakes. Goods are still coming through. There's still shipping coming through and moving goods even into Canada.
DO-No reason for change/don't know	There's not so many. It's very minor. You have storm water plants; there are many storm water plants. The water is collected from the watershed before it goes into the river. It's not extracted from the river; it's collected before.
DO-No reason for change/don't know	Uhm, I don’t hear any talk about it, you know. But again, this is not my area, so I’d have to ask someone in the energy sector. But I don’t hear any talk about that.
DO-No reason for change/don't know	I don’t hear any talk about that, anyways.
DO-Local water system not suitable	We wouldn’t have any salinity. It's freshwater
DO-Local water system not suitable	There's nothing to eat, it's not the kind of species we have
DO-Local water system not suitable	The amount of water, quite frankly. I just don’t think the rivers are big enough to support that type of activity. I don’t think people will want motorboats in there. Sailing? Maybe, but even sailing, most people sailing on a river is not really-, most people sail on the lake. They might sail at the mouth of the river or a little bit up the river from the mouth but that would be about it.
DO-Local water system not suitable	We don’t have that much of a change in salinity unless somebody figures a way to take the salty road water to do it, runoff, and that would not be consistent, too, so I don’t think it would work.
DO-Local water system not suitable	Our temperature’s not consistently cold enough to have ice-skating on those ponds. In actual fact, we discourage that because we don’t know how thick the ice is so I don’t see an increase in ice-skating in these bodies of water just because of temperature. We don’t have that consistent, cold temperature. I'm going 50 years ago, the harbour of Toronto used to freeze over and people would drive cars on into the harbour. That has not happened for many, many years, or decades. We just don’t have the consistent temperature that will produce the ice that’s safe enough for ice-skating or any of that type of recreation.
DO-Local water system not suitable	It's just the depth and the facilities are not there.
DO-Local water system not suitable	because our river systems we don’t have that much water in them so the volume doesn’t allow for so much boats
DO-Local water system not suitable	The temperature fluctuates in the winter so you can't count on these natural water bodies to maintain the ice so in some cases, even in the winter time, you could have a warm front come in and melt and make it

	unsafe so we prefer to have people skate on outdoor ice rinks but manmade ice rinks.
DO-Local water system not suitable	I can't imagine that we would. If you look at our harbour-front where Lake Ontario is, it's all urban. There's very little opportunity to harvest for fish or anything.
DO-Ecological protection ambitions or policies	En omdat waarschijnlijk het aantal vergunningen beperkt wordt. Ik bedoel het is onwenselijk als het Noordzeekanaal leeggevist gaat worden.
DO-Ecological protection ambitions or policies	And it's very damaging to habitats; it disturbs the floras of the river systems like that. We have a very strong habitat protection framework here. I think you'll find when you talk to the TRCA, those kinds of things would, again, be frowned upon at provincial levels, municipal levels and conservation authorities. [But is there a clear demand?] You get all sorts of aquatic life in those sediments so you don't want to be digging them out. [Apart from the fact you think it's not a very good idea because it's degrading the ecology, do you think that there's a change in demand of parties who want to do this?] No, because the policy's already strict about it. The federal fisheries act as well.
DO-Ecological protection ambitions or policies	We don't want to extract those because that's interfering with the natural system and it would be degrading the system
DO-Ecological protection ambitions or policies	People want natural areas, right? They want to protect the rivers and systems so I see it as the public at large want to protect it
DO-Ecological protection ambitions or policies	Plus, we have very strong regulations in our water systems. In terms of our fisheries, it would be very difficult and costly to do that.
DO-Ecological protection ambitions or policies	Regulations don't allow for that because of the disruption to aquatic habitat
DO-Ecological protection ambitions or policies	No, you're not allowed. This is again something that they are trying to, from a regulatory point of view, they are trying to ensure it doesn't happen. They don't want to disturb the creeks, any work in the creek, any sort of takings from the creek, any sort of small change to the creek requires extensive permits, to do. So, I would say that is not happening very much right now, and is likely to happen less and less over time. As... as the regulations start to become more stringent.
DO-Ecological protection ambitions or policies	Well, any sort of religious use that might in any way contaminate the water, no not gonna happen, not allowed and not encouraged
DO-Ecological protection ambitions or policies	There is definitely not any desire to put in dams specifically for energy production. That's just something that is out of fashion, it used to be in fashion, and now it is completely out of fashion because of the other by-products of that, of those dams
DO-Alternatives are better	Omdat de verbinding die er nu zijn, metro, tram, bus, trein, dat die dat veel beter kunnen verbinden dan over water. Dat gaat veel sneller, de eerste die ik noemde.

DO-Alternatives are better	Because the province is pushing for a new way of thinking and actually targeting 90 percent of the total annual volume of rainwater which is the minor storm event, and that that 90 percent total volume will be done by low impact development, where possible, and therefore we're looking at reducing, getting away from wet ponds and going to more of a dry pond so you will get, at least, the quantity control from the dry pond but the quality control will come from the treatment train system that will include low impact development and others like separators and other types of systems.
DO-Alternatives are better	Runoff will be harvested to irrigate the parks.
DO-Alternatives are better	because we have good access to nuclear power.
DO-Alternatives are better	I think likely what is gonna happen, is they are just going use more main supply water
DO-Alternatives are better	Because there are many, many sources for a lot of those abiotic materials, gravels and sands, and those kinds of things are... There's many other sources, they can buy them.
DO-Access to surface water is unpractical	maar de twijfel die daar in is, je moet er iets meer voor doen. Kijk je tuinslang sluit je heel makkelijk aan op je buitenkraan, en naar een sloot lopen of daar een verbinding aanleggen is veel lastiger.
DO-Access to surface water is unpractical	Heel praktisch, omdat de mensen meestal hun tuin aan de achterkant van het huis hebben, terwijl het water aan de voorkant in de gracht zit of in de Amstel of weet ik het wat. Dan moet je een pijp door het huis leggen. Dat doet niemand.
DO-Access to surface water is unpractical	Plus, because you have to understand in our area, so we've protected our rivers and next to our rivers we've protected the ravine and the valley, so development is very far from the river system. We've protected all that's natural so in order to get the water from there would require a whole new infrastructure
DO-Access to surface water is unpractical	but outside of downtown, outside of Lake Ontario where you have that access, it's very difficult.
DO-Access to surface water is unpractical	Because, in order to fight a fire effectively, you need to respond quickly, and if... And the quickest response is to connect to a hydrant. That's what all their equipment is geared towards. The slowest response is to go running down to the river, and putting an intake in the river, and then connecting it to a pump and then turning the pump on, and then, that's just not gonna happen,
DO-Acceptance of salinization	of zeggen we op een gegeven moment verzilting is ook goed ofzo

Supplementary Information 5

Co-occurrence table based on coding of interview transcripts in ATLAS.ti for research project FUNqyWATER. Dataset shows trends in demand for specific use functions of urban surface water as expected by interviewed water managers and spatial planners in Amsterdam (Sheet AMSTERDAM) and Toronto (Sheet TORONTO).

- Numbers indicate frequency of specific codes per use function.
- Codes refer to trends in demand (row 2-5) and drivers of change in demand (row 6-66).
- Db refers to drivers that are mostly mentioned by interviewees in the context of decreasing demand or demand remaining absent.
- D0 refers to drivers that are mostly mentioned by interviewees in the context of demand remaining absent.
- D refers to drivers that are mostly mentioned by interviewees in the context of increasing demand. Use functions are given in short notation.

The table below shows the longer notation for clarification.

Short notation	**Long notation**
Fishing	Fishing for consumption
Other animals	Catch of other surface water related animals for consumption
Plants or algae	Harvest of aquatic plants or algae for consumption
Drinking water	Water extractions for drinking water production
Irrigation agriculture	Water extraction for irrigation of crops
Irrigation other	Water extraction for irrigation of other vegetation
Industrial processes	Water extraction for industrial processes
Firefighting	Water extraction for firefighting
Filling ponds	Water extraction for filling ponds
Other	Water extraction for other non-drinking purposes
Biomass	Harvest of biomass for non-food purposes
Abiotic materials	Extraction of abiotic materials
Thermal energy	Thermal energy extraction
Energy salinity	Energy production using salinity gradient in water
Energy kinetic	Energy production using kinetic energy
Managing water quality	Managing water quality
Managing water quantity	Managing water quantity
Global climate regulation	Global climate regulation
Local climate regulation	Local climate regulation
Primary contact	Primary contact recreation
Secondary contact	Secondary contact recreation
Boating	Recreational boating
Sport fishing	Sport fishing
Hunting	Hunting aquatic animals
Landscape	Enjoying a landscape characterized by surface water
Ice-skating	Ice-skating
Cultural heritage	Designation of cultural heritage value
Religious	Religious use
Building	Building on water
Under water storage	Under water storage/infrastructure
Transporting goods	Transporting goods
Transporting persons	Transporting persons
Physical barrier	Using water as a barrier

AMSTERDAM																																	
Code	Fish-ing	Other animals	Plants or algae	Drinking water	Irrigation agriculture	Irrigation other	Industrial processes	Fire-fighting	Filling ponds	Other	Bio-mas s	Abiotic materials	Thermal energy	Energy salinity	Energy kinetic	Managing water quality	Managing water quantity	Global climate regulation	Local climate regulation	Primary contact	Secon-dary contact	Boating	Sport fishing	Hunting	Land-scape	Ice-skating	Cultural heritage	Religious	Building	Under water stoarge	Transpor ting goods	Transpor ting persons	Physical barrier
Decrease	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Increase	1	2	0	3	3	3	1	1	2	0	1	0	6	1	1	4	6	1	6	6	5	5	2	0	5	3	1	0	5	1	5	6	0
No change	2	1	2	4	3	2	0	0	0	1	0	2	0	1	3	2	1	1	0	1	1	1	2	1	0	1	4	2	1	1	0	2	3
No information	2	3	4	0	0	1	5	5	4	5	5	4	0	5	3	0	0	4	0	0	1	1	2	5	1	1	1	4	1	4	1	0	3
D0-Acceptance of salinization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Access to surface water is unpractical	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Alternatives are better	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
D0-Ecological protection ambitions or policies	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Local water system not suitable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-No reason for change/don't know	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	2	1	1	0	1	1
D0-Popularity declines	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Potential capacity already fully used	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	0
D0-Potential capacity is too small to be relev	1	1	1	1	0	0	0	0	0	0	0	1	0	1	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Regulations don't allow the use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-This is not a habit or lack of knowledge	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
D0-Water is no longer a physical barrier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
D-Awareness about First Nations heritage inc	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Awareness about heat stress increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Awareness of animal welfare increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Db-High costs	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Land value increase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Other functions prevail/conflict between u	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	1	0	2	1	0	0	0
Db-Perception about water quality	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Unreliable source	0	0	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Water quality detoriation/salinization	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Water quality not sufficient	0	1	0	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
D-Circular economy/re-use of waste streams	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Cost saving ambitions	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Data centers increase	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Densification	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	1	0	0	0	3	1	0	0	2	0	0	0	0
D-Dry periods longer and/or more frequent d	0	0	0	0	3	3	1	0	2	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Electricity demand increases	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
D-Flood protection ambitions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Hydrogen factories expected	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-In case that pilot application is successful	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Industrial use of drinking water increases	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Lack of space on land	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0
D-Limits to transportation on land (rail, road)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	0
D-Local products trend	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-New, bigger sea locks	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
D-Opportunity becomes more rare	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
D-Opportunity to combine with increasing der	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
D-People have more free time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	2	1	0	1	1	0	0	0	0	0	0	0
D-People live longer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	1	0
D-Popularity of the activity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	1	1	0	1	2	0	0	2	0	0	2	0
D-Population growth	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	4	4	3	2	0	2	2	0	0	2	0	0	3	0
D-Promotion campaign by authorities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Rain storms more intense due to climate cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Redevelopment close to water	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0
D-Saving drinking water ambitions	0	0	0	0	1	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Self-sufficiency ambitions	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Ship size and number of ship increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
D-Stocking fish measures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Sustainability ambitions	0	0	0	0	0	0	0	0	0	0	0	0	6	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0
D-Technological developments	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Temperature increase due to climate chan	0	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0	0	0	4	4	4	3	1	0	2	3	0	0	0	0	0	0	0
D-Tourism growth	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	0	0	0	1	0
D-Urban agriculture increase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Urbanization/land use change	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Use and value of surface water increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
D-Water quality improvement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Water use efficiency increase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Water use per capita increases	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Welfare increase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	2	0
D-Wetland development	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Supplement

TORONTO Code	Fish-ing	Other animals	Plants or algae	Drinking water	Irrigation agriculture	Irrigation other	Industrial processes	Fire-fighting	Filling ponds	Other	Bio-mass	Abiotic materials	Thermal energy	Energy salinity	Energy kinetic	Managing water quality	Managing water quantity	Global climate regulation	Local climate regulation	Primary contact	Secon-dary contact	Boat-ing	Sport fishing	Hunting	Land-scape	Ice-skating	Cultural heritage	Religious	Building	Under water stoarge	Transport ing goods	Transport ing persons	Physical barrier
Decrease	0	0	0	0	1	4	0	1	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Increase	2	1	0	5	1	0	0	0	0	0	2	1	5	0	1	2	3	0	1	5	5	4	4	0	5	1	4	2	1	0	4	4	0
No change	2	3	3	0	3	2	2	2	1	1	1	3	0	4	4	0	1	0	2	1	0	2	1	3	0	2	1	1	1	1	1	0	2
No information	2	1	2	0	0	0	3	2	4	4	2	1	0	1	0	0	0	5	2	0	0	0	1	1	0	1	0	2	3	4	0	1	3
D0-Acceptance of salinization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Access to surface water is unpractical	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Alternatives are better	0	0	0	0	1	1	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Ecological protection ambitions or policies	0	0	0	0	0	0	0	0	0	0	1	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
D0-Local water system not suitable	0	1	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	2	0	0	0	2	0	0	0	0	1	0	0
D0-No reason for change/don't know	0	0	0	0	0	0	2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
D0-Popularity declines	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D0-Potential capacity already fully used	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
D0-Potential capacity is too small to be relev	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
D0-Regulations don't allow the use	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0
D0-This is not a habit or lack of knowledge	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	2
D0-Water is no longer a physical barrier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Awareness about First Nations heritage inc	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0
D-Awareness about heat stress increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Awareness of animal welfare increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-High costs	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Db-Land value increase	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Other functions prevail/conflict between u	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Db-Perception about water quality	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Unreliable source	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Water quality detoriation/salinization	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db-Water quality not sufficient	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Circular economy/re-use of waste streams	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Cost saving ambitions	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Data centers increase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Densification	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
D-Dry periods longer and/or more frequent d	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Electricity demand increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Flood protection ambitions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Hydrogen factories expected	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-In case that pilot application is successful	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Industrial use of drinking water increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Lack of space on land	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
D-Limits to transportation on land (rail, road)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
D-Local products trend	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-New, bigger sea locks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Opportunity becomes more rare	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Opportunity to combine with increasing der	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-People have more free time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-People live longer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Popularity of the activity	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	0
D-Population growth	0	1	0	5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	4	4	5	3	0	5	0	1	1	0	0	3	3	0
D-Promotion campaign by authorities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
D-Rain storms more intense due to climate cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Redevelopment close to water	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	1	3	0	0	4	1	0	0	0	0	1	1	0
D-Saving drinking water ambitions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Self-sufficiency ambitions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Ship size and number of ship increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Stocking fish measures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
D-Sustainability ambitions	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
D-Technological developments	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Temperature increase due to climate chan	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	2	0	0	0	0	0	2	0	0	0	0	0	0	0
D-Tourism growth	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Urban agriculture increase	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Urbanization/land use change	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
D-Use and value of surface water increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
D-Water quality improvement	2	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	1	0	2	0	0	0	0	0	0	0	0	0	0
D-Water use efficiency increase	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Water use per capita increases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Welfare increase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D-Wetland development	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

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Text S1. Additional explanation on the definition of criteria for sub-index scores for SI TEE

Width and discharge

Scoring criteria for width and discharge are derived by a rough estimation of the required surface area to reach the heat extraction capacity that is related to SI-class 4. For the calculations the following formula from Kruit et al. (2018) was used: $HEC=Q*dT*\rho w*cp + (Z*A*dT)/10^6$ (following Kruit et al., 2018). Q=discharge [m^3s^{-1}], dT = temperature range for heat extraction [°C], ρw = density of the water [kg m^{-3}], cp= heat capacity of water [J $kg^{-1}°C^{-1}$], Z=heat transfer coefficient [W/$m^2°C^{-1}$], A = water surface area [m^2]. We assume 2,184 days of extraction (3 months), dT between 5°C and 10°C and Z between 20 and 40 W/$m^2°C^{-1}$.

For a 100 to 150 m trajectory, a common hydro unit length, a width of approximately ≥100 m is required. A reduction of width with factor 10 results in a reduction of the extraction capacity that relates to one suitability class lower. Therefore, width is considered as excellent (score=4) if ≥100 m, good (score=3) if 10 to 99 m, fair (score=2) if 1-9 m, low (score=1) if < 1 m.

We assume that discharge of the extraction cannot exceed discharge of the water body. A discharge of approximately 0.3 m^3 s^{-1} results in a heat extraction capacity that covers the heat demand related to class 4. 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}.

Text S2. Additional explanation on the definition of criteria for sub-index scores for SI Transport

Precondition

The precondition for depth is based on the minimal draft of the vessel 'CityBarge' that is operational in Leiden, The Netherlands. The vessel is especially designed for urban freight transport (https://citybarge.eu/).

Depth, width and air draft

Excellent suitability (score=4) is assigned to waterways that can accommodate for the largest vessels that are expected to be used for urban freight transportation. We assume that this is a vessel comparable to a large Rhine vessel with maximum beam of 11.4 m, draft 4.5 m and air draft 9.1 m (ECA, 2015). Required depth is calculated by multiplying ship draft with a factor 1.4; for width, the ship beam is multiplied by 4. This relates to the dimensions for a normal profile as defined in the guidelines for waterways by the Dutch national water authority Rijkswaterstaat (2017). Good suitability (score =3) relates to the smallest inland vessel type mentioned in the Classification of European Inland Waterways (CEMT) (ECA, 2015). This vessel is a barge with maximum beam of 5.05 m,

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draft 2.2 m and air draft 4 m. Required depth for this type of ship is calculated by multiplying ship draft with a factor 1.4; for width, the ship beam is multiplied by 4. This relates to the dimensions for a normal profile as defined by Rijkswaterstaat (2017). Fair suitability (score = 2) relates to the dimensions required for the smallest operational vessels for urban freight transport that are described in literature (Janjevic & Ndiaye, 2014; Maes et al., 2012). The vessel 'bierboot' in Utrecht, The Netherland has a beam of 4.2 m, draft 1.1 m and air draft 1.65 m. The City Supplier in Amsterdam has comparable dimensions. Required waterway dimensions are based on the guidelines for single lane or tight profile in Rijkswaterstaat (2017). Required depth 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.

Text S3. Additional explanation on the definition of criteria for sub-index scores for SI Recreation

E. coli

Sub-scores for *E. coli* relate to target values for inland waters in the European Bathing Directive (EC, 2006). In this directive <500 cfu/100 ml is considered 'excellent' and <1000 cfu/100 ml is considered 'good' water quality based on a 95-percentile. Values <900 cfu/100 ml are rated as 'sufficient', based on a 90-percentile. The Dutch Steering Committee for bathing water issued a signal value for high risk for individual measurements of 1800 cfu/100 ml (Stuurgroep Water, 2013).
In SI Recreation, criteria for sub-scores 4 (excellent) and 3 (good) are equal to the values for the classes 'excellent' and 'good' in the directive. Criteria for sub-score 2 (fair) is related to the signal value and higher values result in sub-score 1 (low).

Cyanobacteria

The most common potentially toxic species in the Netherlands are *Microcystis*, *Anabaena*, *Aphanizomenon*, *Planktothrix* en *Woronichinia* but the national protocol for cyanobacteria inspection is based on the assumption that all cyanobacteria are potentially toxic RIVM (2020). In the national protocol for cyanobacteria at designated swimming sites (RIVM, 2020), values <12.5 ug/l are related to 'risk level 0'. Since monitoring is only initiated at sites where a risk of cyanobacteria blooms is expected, we consider that even with values below 12.5 ug/l, some level of risk exists. Therefore, values below detection limit are related to excellent suitability (score=4). Values between detection limit and 12.5 ug/l are associated with good suitability (score=3). When values are between 12.5 and 75 ug/l, low risk is expected (RIVM, 2020)(RIVM (Rijksinstituut voor Volksgezondheid en Milieu), 2020) and swimmers need to be warned about this. We relate this to fair suitability (score=2). If concentrations exceed 75 ug/l, a negative swimming advice or prohibition is issued (RIVM, 2020); we therefore assign a score of 1 in this case (low suitability). Quantitative analysis of cyanobacteria presence is performed by fluoroprobe measurement of chlorofyl-a associated with cyanobacteria.

pH

Scores for pH are derived from the WQI for primary contact recreation by Nagels et al. (2001). They found a relative high degree of consensus for scoring of pH amongst panel members and between the panel's scores and the scoring from another study. A pH of 7–8 is considered ideal as it is close to the pH of the human eye. We consider this range as excellent (score=4). Beyond the optimal pH range, suitability declines abrupt. For fair (score=2) and good (score=3) suitability, we use the pH values that Nagels et al. (2001) label as respectively 'marginally suitable' and 'suitable'. Nagels et al. (2001) consider the water unsuitable at a pH of <5 or > 9.5 pH, which is close to Azevedo Lopes et al. (2016) and to the Canadian guidelines (Health Canada, 2012) that determine water suitable at pH 6-9 and5-9 respectively. For the SI, pH values <5 or > 9.5 are related to low suitability (score=1).

Clarity

The Canadian guideline for recreational waters prescribes at least 1.2 m Secchi disk visibility (Health Canada, 2012). We use this value as lowest value for fair suitability (score=2). Lower values are scored 1. This is comparable to the black disk visibility criteria in Nagels et al. (2001). They report marginal suitability at approximately 1.1 to 1.2 m black disk visibility; lower values are considered unsuitable. Nagels et al. (2001) report a relatively high consensus amongst the consulted experts and other studies. For good (score=3) and excellent (score=4) suitability we follow their visibility ranges for respectively 'suitable' and 'eminently suitable'. In case of water depth < 1.2 m, visibility is also considered excellent if visibility equals water depth (bottom is visible).

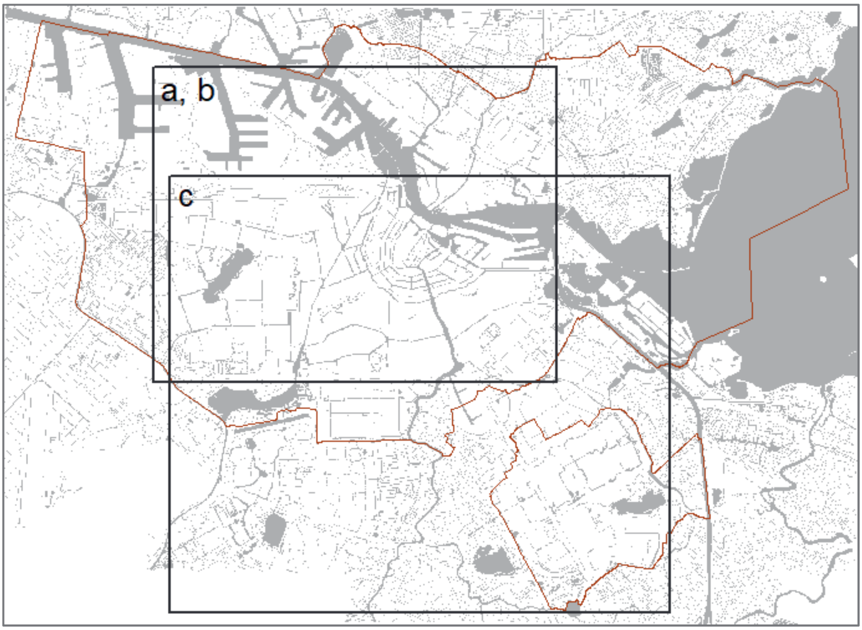
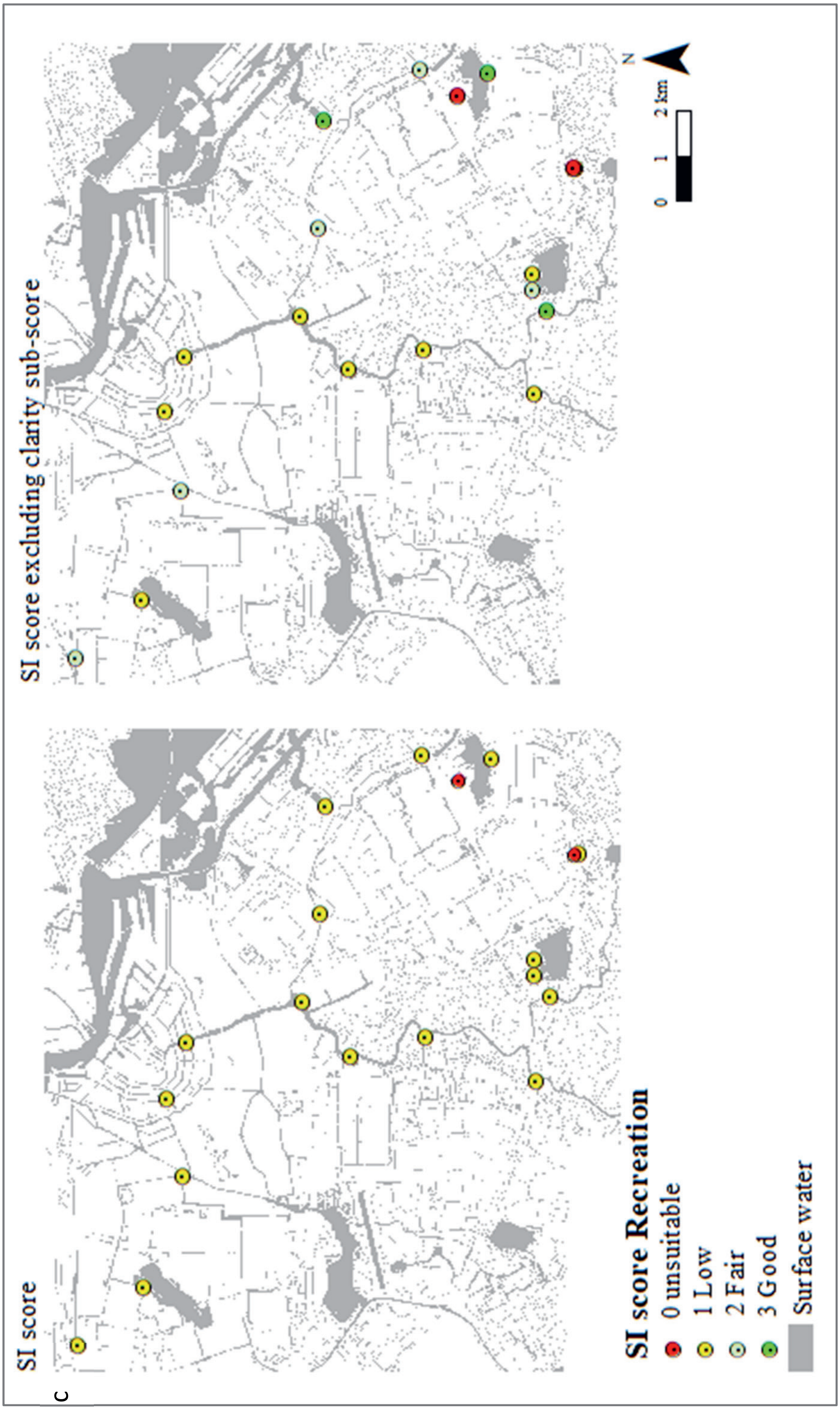


Figure S1a-c. SI scores for SI TEE (a), SI Transport (b) and SI Recreation (c). The maps have different extends (see overview map above) because the extend of the datasets differ per SI.


SI score TEE
2 Fair
3 Good
4 Excellent
No data
N
0
1
2 km
a


SI score Transport
1 Low
2 Fair
3 Good
No data
N
0
1
2 km
b


c
SI score
SI score excluding clarity sub-score
SI score Recreation
0 unsuitable
1 Low
2 Fair
3 Good
Surface water
N
0 1 2 km

Supplement

Dataset DS01

Dataset DS01 contains parameter values, sub-scores and SI scores per HU. The dataset is accessible at: https://doi.org/10.1016/j.cacint.2022.100079 (Supplementary data 2).

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Supplementary Information 7

Appendix S1: Suitability Indices

Suitability Index for Thermal Energy Extraction (TEE)

The SI score is related to indicative heat extraction capacity, assuming heat extraction during the three warmest months (Van der Meulen et al., 2022). During summer months, when water temperatures are the highest, heat is extracted from surface water with a heat exchanger. Warm water is stored for later use, for example in an Aquifer Thermal Energy Storage in the subsurface. When the heat is needed for heating of buildings during colder months, warm water is pumped up from the storage. Heat is extracted from the water through a heat exchanger and a heat pump further heats the water to the desired temperature for the building's hot water network. Data from the three warmest months are used for calculating the SI score. If the precondition for water depth is met, the SI score is determined by integrating the sub-scores for width, discharge and temperature (Table S6). Because a low value for one parameter can be counteracted by a high value for another parameter to some extent the integration method is the geometric mean of the sub-scores.

Table S6: SI TEE. Criteria for the boundary condition, sub-scores and integration method. n.a.: not applicable. (Table based on Van der Meulen et al., 2022)

Suitability	Sub-score	Parameters			
		Depth [m]	Width [m]	Discharge [$m^3 s^{-1}$]	Temperature [°C]
Excellent	4		≥100	≥0.3	≥15
Good	3	n.a.	10-<100	0.03-<0.3	10-<15
Fair	2		1-<10	0.003-<0.03	5-<10
Low	1		<1	<0.003	<5
Boundary condition:		≥ 0.5[a]	n.a.	n.a.	n.a.
Integration of sub-scores into SI score: geometric mean[b]					

[a] Maximum depth

[b] $SI = (\prod_{i=1}^{n} Si)^{1/n}$ where S_i is the sub-index score of the i-th parameter

Suitability Index for urban freight transportation

The SI score is related to the vessel types that can use the waterway (Van der Meulen et al, 2022). If the precondition for water depth is met, the SI score is determined by integrating the sub-scores for width, depth and air draft (Table S7). Since unsuitable conditions for one parameter cannot be counteracted by another, the minimum operator approach is used for integration of the sub-scores.

Table S7: SI Transport. Criteria for the boundary condition, sub-scores and integration method. n.a.: not applicable. (Table based on Van der Meulen et al., 2022)

Suitability	Sub-Score	Parameters		
		Depth[a] [m]	**Width [m]**	**Air draft [m]**
Excellent	4	≥6.3	≥45.6	≥9.1[b]
Good	3	3.1-<6.3	20.2-<45.6	4.0-<9.1
Fair	2	1.4-<3.1	8.4-<20.2	1.7-<4.0
Low	1	0.35-<1.4	<8.4	<1.7
Boundary condition:		≥ 0.35	n.a.	n.a
Integration of sub-scores into SI score: minimum operator[c]				

[a] Minimum depth in fairway

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

[c] SI=$Min(S_{i=1}^{n})$, where S_i is the sub-index score of the i-th parameter

SI Recreation

The SI score is related to the level of risk for adult swimmers (Van der Meulen et al, 2022). If the precondition for water depth is met, the SI score is determined by integrating the sub-scores for *E. coli* bacteria (indicator of faecal pollution), Cyanobacteria, pH, clarity and depth (Table S8). Data from the period April-September, the swimming season, are used for calculating the SI score. Since unsuitable conditions for one parameter cannot be counteracted by another, the minimum operator approach is used for integration of the sub-scores.

Table S8: SI Recreation. Criteria for the boundary condition, sub-scores and integration method. n.a.: not applicable. (Table based on Van der Meulen et al., 2022)

Suitability	Sub-Score	Parameters				
		Depth [m]	**E. coli [cfu 100 ml^{-1}]**	**Cyano-bacteria [ug L^{-1}]**	**pH**	**Clarity [m]c**
Excellent	4	Designated bathing zone	<500	<0.5	7-8	>4 or bottom visible
Good	3	≤1.40[a]	500-<1,000	0.5-<12.5	6-<7 or >8-9	2-4
Fair	2	>1.40[a]	1,000-<1,800	12.5-≤75	5-<6 or >9-9.5	1.2-<2
Low	1	n.a.	≥1,800	>75	>9.5 or <5	<1.2
Boundary condition		≥ 0.75[b]	n.a.	n.a.	n.a.	n.a.
Integration of sub-scores into SI score: minimum operator[d]						

[a] 1 m from shore; [b] At deepest point; [c] Secchi-disk transparency depth; [d] SI=$Min(S_{i=1}^{n})$, where S_i is the sub-index score of the i-th parameter

Appendix S2: Used data

The dataset for analyse with all data used for calculating the original sub-scores, SI scores and the impact of raising sub-scores on the SI values per HU or point location is provided in the separate file **Supplementaryfile1.xlsx** (available online at: https://doi.org/10.1007/s13280-022-01759-3). Table S9 contains an overview of all used data sources to create the dataset for calculation of SI scores for TEE, transport and recreation. Where applicable, additional remarks or motivations are provided below.

TEE Amsterdam

- Minimum depth in the fairway: This is an underestimation of the minimum depth in the waterway, but all values are above the precondition of 0.5 m.
- Temperature: data from point locations, at least one measurement per month. At all locations, average temperature and the 95th percentile of decreasing values is above 15°C during the three warmest months, even when taking into account that night-time temperatures are ≤1 °C lower (see Van der Meulen et al., 2022) than daytime values. Therefore, a sub-score of 4 is applied to all HUs.
- Discharge: values generated for line segments in the centre axis of waterways are assigned to the HUs that they cross. The 75th instead of the 95th percentile of decreasing values is used because flow direction variations otherwise result in (near-) zero discharge.
- Width: maximum width is the navigation database is the best available value but will give some overestimation.

TEE Ghent

- Depth: value is derived from allowed ship draft (see section on Transportation). This is an underestimation of maximum depth, but this is no problem because the precondition of 0.5 m is met everywhere.
- Temperature: The dataset includes temperature figures for 42 locations covering many waterways around the city of Gent. Values during the three warmest months are all ≥ 17.3 °C and therefore a sub-score of 4 is applied to all HUs.
- Width: Average width per polygon is determined in ArcGIS by measuring width at several points, the number of points depending on the length and shape of the polygon, and calculating the average.

Transport Amsterdam

- Minimum depth in the fairway: This is an underestimation of the minimum depth in the waterway but all values are above the precondition of 0.35 m.

Transport Ghent

- Depth: value is derived by multiplying allowed ship draft by 1.2 as best estimate of depth. This factor is based on applied keel clearance targets in several local sources

(Arcadis, 2007; De Rijck, 2011; Rijkswaterstaat, 2017); https://emis.vito.be/en/node/12231).

- Minimum width: measured by means of Google maps, taking into account jetties and other large permanent structures visible on the satellite image. Like in Amsterdam, some bridges (may) have piers. This seems less frequent than in Amsterdam. Their influence on width is not taken into account unless guidance jetties are dividing the fairway.

Recreation Amsterdam

- Water quality data at point locations based on field and laboratory measurements in samples from 0.3 m depth. Except for cyanobacteria, samples are taken at least monthly during summer months.
- We include all locations with at least 3 years of data.

Recreation Ghent

- We include locations with at least 3 days of E. coli- and pH data. At three locations (Houtdok and two locations in Watersportbaan), dozens of datapoints are available for *E. coli* and pH; for the other locations a maximum of 4 (pH) or 5 (E. coli) days of data are available. Apart from the three frequently monitored locations, there are less than 3 days of clarity data available.

Table S9: Datasets used for calculating the SI scores. The datasets are not publicly published unless a link to the dataset is provided in this table.

Parameter	Amsterdam		Ghent	
	Data used	**Source**	**Data used**	**Source**
Air draft	Minimum air draft [m]	Navigation database from municipality Amsterdam[1]	Air draft [m]	Navigation database from VWW (visuris.be). For the recently opened canal Reep: own field measurements[2] and port manager.
Bridge type	[fixed/ movable]	National navigation map (vaarweginformatie.nl)	[fixed/ movable]	Navigation database from VWW (visuris.be)
Clarity	Secchi disk depth [m]	Water quality dataset from AGV	Secchi disk depth [m]	Water quality dataset from Stad Gent, Geoloket by VMM
Cyano-bacteria	Cyano-bacteria [$\mu g\ L^{-1}$]	Water quality dataset from AGV	Cyano-bacteria blooms notifications	Cyanobacteria blooms notifications register VMM (Blauwalgen — Vlaamse Milieumaatschappij (vmm.be)
Depth (maximum)	Depth [m]	Own field measurements[2]	Depth [m]	Greatest value from these sources: VWW (visuris.be), Stad Gent, Geoloket by VMM (http://geoloket.vmm.be/Geoviews/), own field measurements[2]

Table S9 continued

Parameter	**Amsterdam**		**Ghent**	
	Data used	**Source**	**Data used**	**Source**
Depth (minimum)	Minimum depth in the fairway [m] for TEE and Transport	Navigation database from municipality Amsterdam[1]	Derived from allowed draft [m]	Navigation database from VWW (visuris.be)
Depth at 1 m from shore	Depth [m]	Own field measurements[2]	Depth [m]	Own field measurements2
Designated bathing area status (yes/no)	[Yes/no]	National bathing water quality register (www.zwemwater.nl)	[Yes/no]	National bathing water quality register (kwaliteitzwemwater.be)
Discharge	Values generated for each 15 minutes	Generated by a hydraulic SOBEK model (https://download.deltares.nl/en/download/sobek/) by AGV	Not available	No data available
E. coli	E. coli [cfu 100 ml^{-1}]	Water quality dataset from AGV	E. coli [cfu 100 ml^{-1}]	Water quality dataset from Stad Gent, Geoloket by VMM (http://geoloket.vmm.be/Geoviews/), Big Jump
Open water (infinite air draft)	-	Google Maps Satellite images (maps.google.nl)	-	Google Maps Satellite images (maps.google.nl)
pH	pH	Water quality dataset from AGV	pH	Water quality dataset from Stad Gent, Geoloket by VMM (http://geoloket.vmm.be/Geoviews/), Big Jump
Temper-ature	Daytime temperature [°C]	Water quality dataset from AGV	Daytime temperature [°C]	Water quality dataset from Stad Gent, Geoloket by VMM (http://geoloket.vmm.be/Geoviews/)
Width (for TEE)	Maximum width [m] for TEE	Navigation database from municipality Amsterdam[1]	Average width [m]	Measured on base map of the surface water system from Grootschalig Referentie Bestand Vlaanderen, (www.geopunt.be)
Width (for Transport)	Minimum width [m]	Navigation database from municipality Amsterdam[1]	Minimum width [m]	Google maps (https://www.google.com/maps)

[1] Dataset with data from field measurements between 2004 and 2016, data are still valid. Depth and air draft are expressed in a unit that requires correction for water level, which is done with water level data from AGV.

[2] By means of a lead line. For Amsterdam field campaign in January 2021, for Ghent August 2021.

Supplement

Appendix S3: Extra figures

Figures S2-4 illustrate notable geographic differences with respect to the parameters that need to be altered for improving SI scores.

(Figures start at next page)

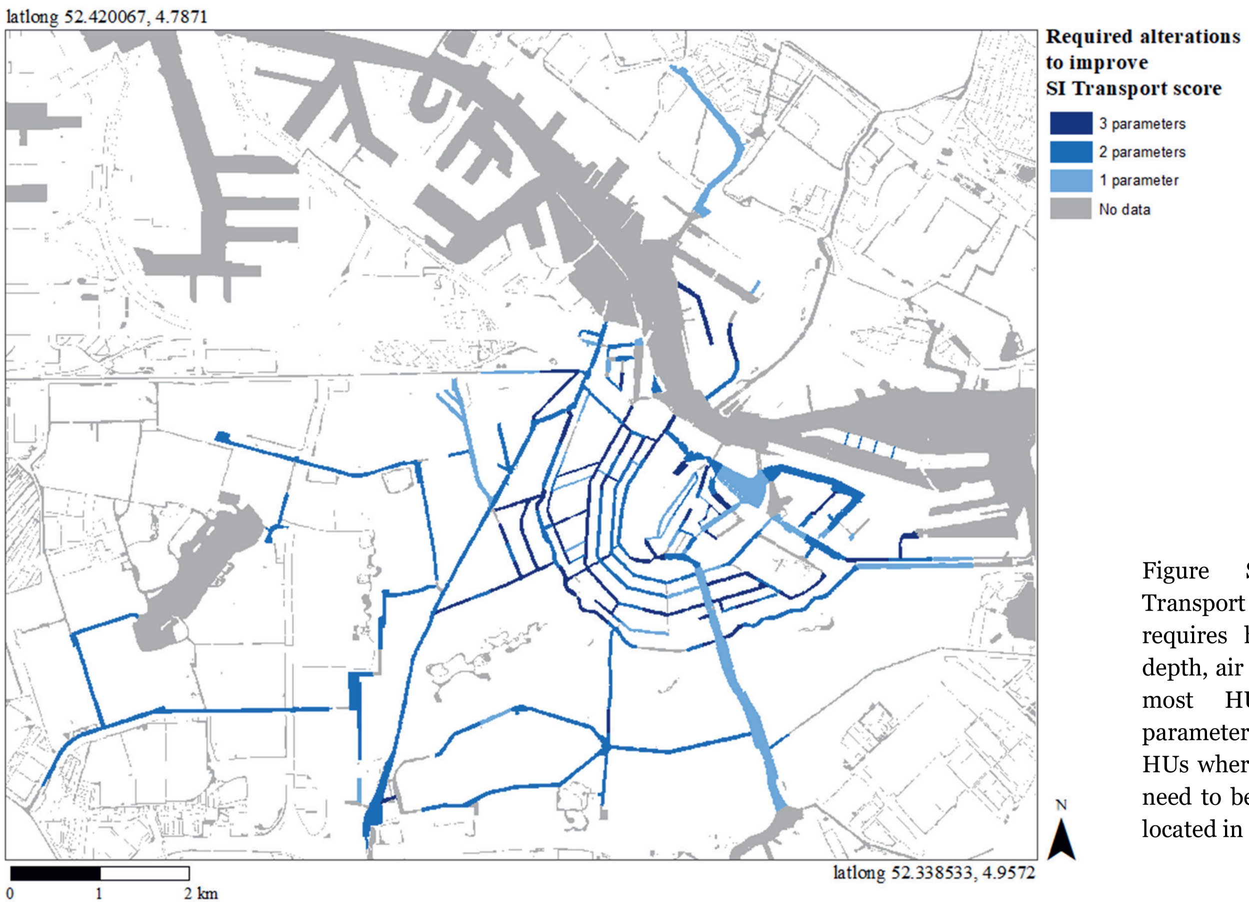

Figure S2: Improving SI Transport scores in Amsterdam requires higher sub-scores for depth, air draft and/or width. In most HUs, two of these parameters need to be altered. HUs where all three parameters need to be improved are mostly located in the city centre.

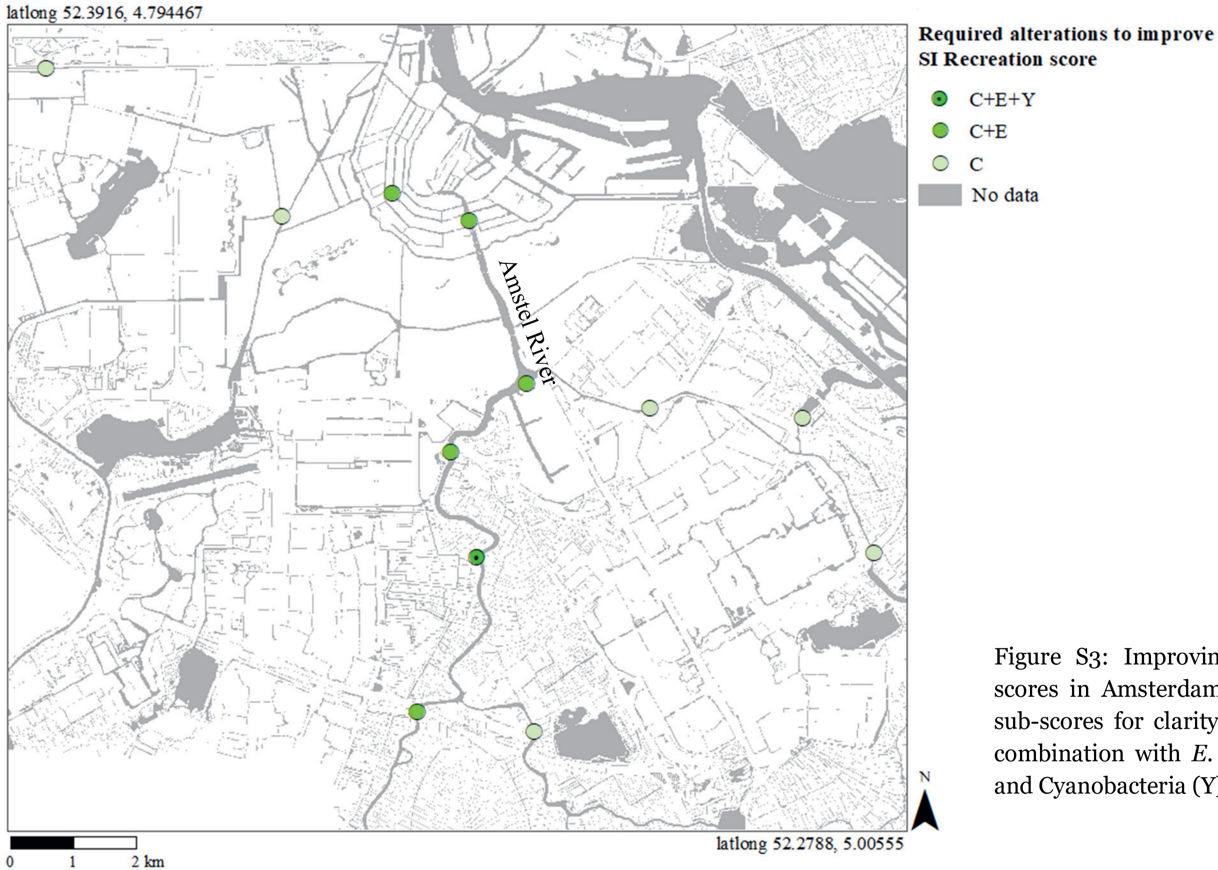

Figure S3: Improving SI Recreation scores in Amsterdam requires higher sub-scores for clarity (C) alone, or in combination with *E. coli* bacteria (E) and Cyanobacteria (Y).

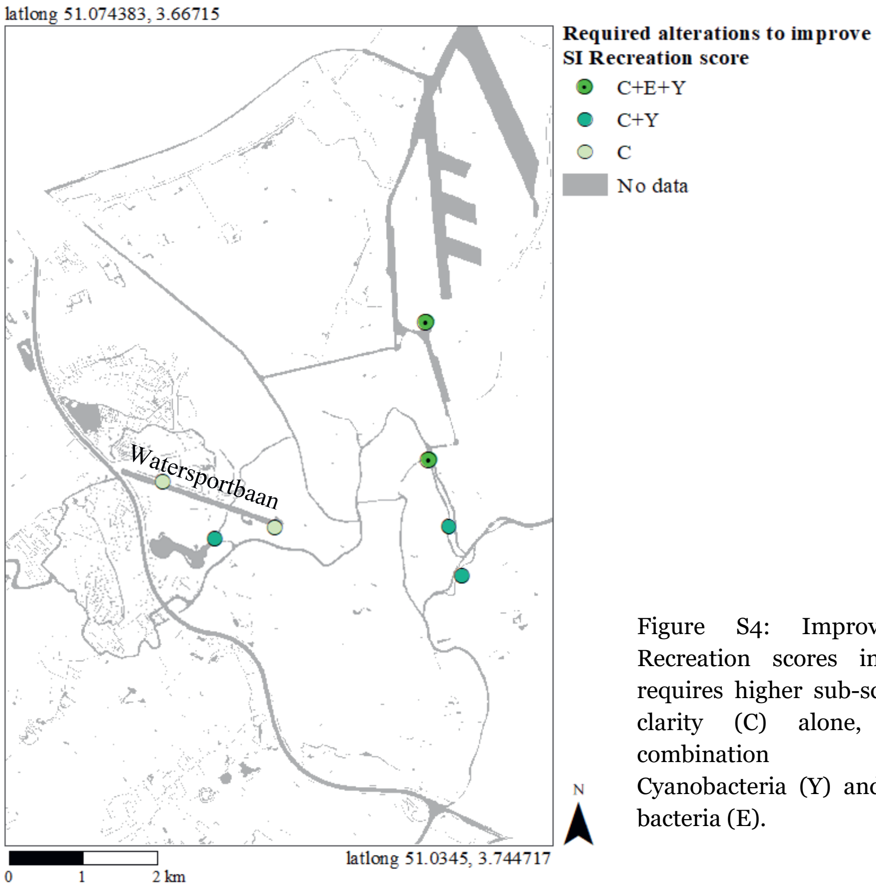

Figure S4: Improving SI Recreation scores in Ghent requires higher sub-scores for clarity (C) alone, or in combination with Cyanobacteria (Y) and *E. coli* bacteria (E).

Supplement

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Summary

Society's interest to use urban surface water for different human use functions is growing. To manage all uses of urban surface water, and to ensure that these waters are fit for purpose, it is important to consider the desired functionality during planning, design, and maintenance of surface waters. Such function-oriented water management requires insight into the *functional quality* of urban surface waters. Functional quality refers to the suitability of a water body for specific human use functions. To date, no scientifically underpinned framework is available to assess this functional quality (Chapter 1). Research on the functional quality of urban surface water is also hampered by a lack of insight into the actual use of these waters and future demand for use functions.

The aim of this research is to develop an assessment framework for functional quality of urban surface water that is applicable for all kinds of use functions. To reach this aim, research has been performed in three subsequent phases. Firstly, to determine which use functions are relevant to be included into the framework, the current use of urban surface water and the expected demand by 2040 were assessed for two urban contexts (Chapter 2). The actual use of urban surface water has been determined by analysis of water-related policy documents and technical reports for the cities of Amsterdam (The Netherlands) and Toronto (Canada). In-depth interviews with local water managers and spatial planners in both cities were performed to gain additional information on undocumented use of urban surface water, on future demand, an on drivers of trends in demand. Secondly, the assessment framework has been developed by combining scientific knowledge from two scientific fields (Chapter 3). The basic model for the assessment framework was established based on the common model for Water Quality Indices (WQIs); ecosystem services literature was used to identify relevant parameter groups for the assessment framework. Thirdly, the applicability and added value of the assessment framework have been tested for two European delta cities (Chapter 4). The framework was used in Amsterdam and Ghent (Belgium) to assess suitability of urban canals and canalized rivers for thermal energy extraction (TEE), transport of goods, and recreation in the form of swimming. The framework was also applied in these cities to identify opportunities for improving the functional quality of the surface water system.

The in-depth analyses for Amsterdam and Toronto provide evidence for actual use of urban surface water for 30 use functions related to nutrition, extractions of water or other materials for non-nutrition purposes, water regulation, recreation, symbolic use, transportation, and for floating buildings (Chapter 2). This study shows that the actual urban water use is much broader than the water extractions that are commonly considered in urban water management research as many use functions involve in situ use of urban surface water rather than water extractions. Water managers and spatial planners in both cities expect three major trends in demand for urban surface water use functions by 2040: 1) the demand for many use functions will increase; 2) an increasing demand is most certain for TEE, different types of recreation and transportation; 3) demand for new use functions will emerge. Major drivers for the increase in demand relate to urban growth and redevelopment, climate change, and sustainability ambitions. The trends in demand show that urban water use becomes broader and more intensive in the next decades.

The novel assessment framework that is presented in this thesis includes Suitability Indices (SIs) that classify the suitability of a water body for single human use functions, based on the water bodies' characteristics (Chapter 3). The SI parameters are each rated by a sub-score, and the sub-scores are integrated into the SI score. This thesis provides a generic protocol for SI development that guides parameter selection, definition of scoring criteria, and selecting the method for integrating sub-scores into the SI score. The assessment framework, unlike traditional WQIs, enables assessing the suitability of a water body for a wide variety of use functions in a consistent manner. Since the framework includes parameters for water quality, -quantity, and flora & fauna, it is also applicable to use functions that do not, or do not only, depend on traditional water quality parameters. Another advantage is that by assessing suitability for single use functions, the analysis can be targeted at those use functions that are relevant in a specific context. Applicability of the protocol is demonstrated by developing SIs for three important use functions for the context of The Netherlands: SI Thermal Energy Extraction (TEE, targeted at heat extraction), SI Transport (targeted at local freight transport) and SI Recreation (targeted at swimming by adults). The three SIs are shown to be applicable to medium sized, locally managed urban water bodies in the cities of Amsterdam and Ghent, using existing datasets and limited additional field measurements (Chapters 3 and 4). The SI analyses result in spatially explicit information about current suitability for the assessed use functions, and about opportunities to improve suitability by at least one SI class.

Application of the SIs in Amsterdam and Ghent provide novel insights on the functional quality of canals and canalized rivers that are likely to be also relevant for other European delta cities (Chapter 4). The 'fair' to 'excellent' SI scores for TEE show that even relatively small and medium sized urban waters are relevant as an alternative heat source for heating of buildings. Improving the suitability for TEE generally requires increasing either discharge or width of the water body considered. SI Transport scores show that in both cities, the entire canal and river system can become suitable for specialized urban freight vessels by increasing water depth, width of the waterway and/or air draft at short bottlenecks in the waterway network. The suitability for swimming in urban canals and canalized rivers is 'low' at all assessed sites. Improving the suitability requires improving clarity of the water at all sites. Other major parameters that limit SI Recreation scores at multiple locations are *E. coli* bacteria (indicating faecal pollution) and cyanobacteria. These insights contribute to the yet limited available knowledge on the functional quality of manmade and highly modified urban surface waters.

Researchers can now use the novel assessment framework from this thesis to assess functional quality of urban surface water (Chapter 5). *Functional quality* provides an additional perspective next to ecological or generic water quality classification, which can be applied for example in studies on the impact of climate change or water management interventions on the 'quality' of urban surface waters. Researchers are advised to apply a broader perspective on urban surface water use than mere water extractions, which has been the common focus in urban water management research. The protocol for SI development is now available and ready to be used for developing SIs for additional use functions and for other application contexts than the ones in this thesis. To support practical water management and spatial planning, future research on trade-offs between use functions and between use functions and ecological status is recommended. Insight in these trade-offs is needed to determine sustainable use practices of urban water. Future research is also needed to develop feasible strategies and measures for dealing with temporal variation in the suitability for certain use functions.

Water managers are advised to proactively manage the functional quality of urban surface waters to prevent future conflicts and functional water quality not being fit for purpose (Chapter 5). The assessment framework from this thesis is applicable to identify opportunities for using the water and for finding ways to improve suitability for desired use functions. Such analyses are applicable for existing waters, or for designs for new to be created water bodies. To improve the insight into functional quality of urban surface water, water managers are advised to extend surface water monitoring schemes with parameters that are relevant for the functional quality of these waters. This research has also shown that more monitoring sites within urban areas are needed to improve insight into the functional quality of urban water.

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- Research in context activity: 'Organising a workshop with water managers and planners of climate adaptation measures from regional water authorities and municipalities in the Netherlands' (2020)

Other PhD and Advanced MSc Courses

- Data visualisation, Amsterdam Institute for Advanced Metropolitan Solutions (2017)
- Supervising master students, Wageningen Graduate Schools (2019)
- Scientific publishing, Wageningen Graduate Schools (2019)
- Reviewing a scientific manuscript, Wageningen Graduate Schools (2020)
- Ethics in Plant and Environmental Sciences, Wageningen Graduate Schools (2020)
- Statistics in water management, Deltares (2021)

Management and Didactic Skills Training

- Organizing a session on ecosystem services based urban surface water management at the international ESP Conference (2017)
- Organising a stakeholder workshop with water managers in Toronto (2020)
- Co-developing content for MOOC on 'Citizens co-creating sustainable cities' (2017)
- Supervising internship of MSc student (2019-2020)
- Supervising thesis research of MSc student (2020-2021)
- Assessor in the BSc course 'Soil and water quality' (2022)
- Teaching in the MSc course 'MADE Living lab' (2021-2022)

Selection of Oral Presentations

- *Urban surface water: Future demand in Toronto and Amsterdam*. Urban Water Symposium, 20 January 2020, Toronto, Canada
- *Changing demands for urban surface water extractions and in situ use functions*. ESP Europe Conference, 7-10 June 2021 Tartu, Estonia (Online)
- **Keynote** speaker: *FUNqyWATER: Functional quality of urban surface water*. AquaConSoil, 14 June 2021, The Netherlands, Online
- *How to support increasing ambitions to use urban canals for thermal energy extraction, transportation, recreation*. Reinventing the City, 17 February 2022, Amsterdam, The Netherlands (Online)

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Photos

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Page 86	Artist impression of Promontory Park and River Valley Park in Toronto, Canada. Copyright: Waterfront Toronto

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