MCDA for NBS
A transdisciplinary approach combining multicriteria decision analysis and nature-based solution planning

Thesis

Morgane Bousquet

Sous la direction de :

Peter A. Vanrolleghem, directeur de recherche
Lavoie Roxane, codirectrice de recherche
Françoise Bichai, codirectrice de recherche

Résumé

Les solutions fondées sur la nature (SFN) sont des systèmes d'ingénierie inspirés de la nature, tels que les zones humides, les cellules de biorétention, les toits verts, les sols poreux ou les jardins de pluie, qui peuvent offrir de nombreux avantages dans un environnement urbain. Elles sont de plus en plus étudiées par la communauté scientifique et considérées par les décideurs comme des actions durables permettant de relever de nombreux défis urbains liés au changement climatique et au développement socio-économique des villes. En effet, elles ont le potentiel de réduire les effets des îlots de chaleur urbains, d'améliorer l'esthétique, d'accroître la biodiversité, d'apporter une gestion de l'eau pluviale à la source, etc. Cette diversité de bénéfices rend l'utilisation de méthodes d'aide multicritère à la décision (AMCD) pertinente pour aider à la prise de décision pour la planification des NBS et ainsi maximiser les bénéfices qu'elles pourraient apporter à l'environnement urbain.

Dans cette thèse, nous présentons un état des lieux de la pratique actuelle de la planification des NBS en nous intéressant de près à l'approche par scénarios et aux outils de conception et de planification pour la gestion des eaux pluviales les plus couramment utilisés. Nous présentons également un état des lieux des méthodes et outils AMCD et des processus participatifs qui permettent l'application de ces méthodes. De plus, nous effectuons une revue de littérature des outils et pratiques AMCD-SFN en examinant où ces pratiques sont appliquées, pourquoi et comment ce processus est mené, et qui y est impliqué. Les études sur la planification des SFN utilisant des méthodes AMCD impliquent rarement les parties prenantes au cours du processus et sont généralement menées sur la base d'une étude de cas unique, en utilisant des méthodes AMCD simplifiées et des outils SIG développés pour un contexte spécifique et qui ne sont pas partagés d'une façon ouverte et en ligne par leurs développeurs.

Au regard de ces constats, cette thèse a développé i) une approche participative et collaborative impliquant les décideurs, les chercheurs et les parties prenantes pertinentes pour la planification des SFN en suivant la méthode AMCD MACBETH, ii) une méthode qui combine l'outil d'ingénierie de l'eau UrbanBEATS et la méthode MACBETH pour l'évaluation des alternatives d'implantation des SFN, iii) des lignes directrices pour les décideurs concernant l'utilisation des résultats, des méthodes et des outils afin de faciliter le transfert de connaissances et l'utilisation des résultats, et iv) une démonstration de la flexibilité et de l'adaptabilité de la méthode AMCD-SFN dans différents contextes géographiques, socio-politiques et urbains. Cette nouvelle méthode AMCD-SFN comporte cinq étapes : (1) identification des parties prenantes, (2) développement du modèle multicritère, (3) génération d'alternatives d'implantation des SFN, (4) évaluation des alternatives d'implantation des SFN, et (5) présentation et discussion des résultats avec les parties prenantes. Nous présentons trois études de cas avec des municipalités situées dans différents pays et continents : Trois-Rivières au Canada, Toulouse en France et

Melbourne en Australie pour démontrer la pertinence et l'adaptabilité de la planification basée sur le AMCD-SFN pour soutenir le processus de prise de décision.

Abstract

Nature-Based Solutions (NBS) are engineered nature-inspired systems such as wetlands, bioretention cells, green roofs, porous pavement or rain gardens that can provide many benefits in an urban environment. They are increasingly being studied by the scientific community and considered by decision-makers as sustainable actions to address many of the urban challenges associated with climate change and the socio-economic development of cities. Indeed, they have the potential to reduce urban heat island effects, improve aesthetics, increase biodiversity, manage stormwater at source, etc. This diversity of benefits makes the use of multicriteria decision analysis (MCDA) relevant to help decision making for NBS planning and then maximise the benefits they could bring to the urban environment.

In this thesis, we present a state-of-the-art of the current practice of NBS planning with a close look at the scenario planning approach, and the different design and planning tools commonly used for stormwater management. We also present a state-of-the-art of the MCDA methods and tools and the participative processes that allow the application of these methods. Moreover, we carry out a critical literature review on MCDA-NBS tools and practices by looking where these practices are applied, why and how this process is conducted, and who is involved in it. We found that studies for NBS planning using MCDA rarely involve stakeholders during the process and are usually conducted on a single case study basis, using simple MCDA methods and GIS tools developed for a specific context and not shared online and open source by their developers.

Therefore, this thesis developed i) a participatory and collaborative approach involving decision-makers, researchers, and relevant stakeholders for NBS planning following the MACBETH MCDA method, ii) a method that combines the UrbanBEATS water engineering tool and the MACBETH MCDA method for evaluating NBS alternatives, iii) guidelines for decision-makers in the use of results, methods, and tools to facilitate knowledge transfer and the usability of results, and iv) a demonstration of the flexibility and adaptability of the MCDA-NBS method to different geographical, socio-political, and urban contexts. This new MCDA-NBS method has five steps: (1) identifying stakeholders, (2) developing the multicriteria model, (3) generating NBS alternatives, (4) evaluating NBS alternatives, and (5) presenting and discussing results with stakeholders. We present three municipality case studies located in different countries and continents: Trois-Rivières in Canada, Toulouse in France and Melbourne in Australia, to demonstrate the relevance and adaptability of MCDA-NBS-based planning to support the decision-making process.

Table of contents

List of figures, tables and illustrations

Liste des abréviations, sigles, acronymes

<u>Technologies</u>

BGI: Blue-Green Infrastructures

BMP: Best Management Practices

ES: Ecosystem Services

GI: Green Infrastructure

LID: Low Impact Development

NBS: Nature-Based Solutions

SUDS: Sustainable Urban Drainage Systems

WSUD: Water Sensitive Urban Drainage

Organizations

EPA: Environmental Protection Agency

INSA: Institut National des Sciences Appliquées

IWA: International Water Association

OTM: Observatoire Toulouse Metropole

Methods and analysis

CBA: Cost-Benefit Analysis

DPSIR: Drivers-Pressures-State-Impacts-Response

EIA: Environmental Impact Assessment

GMB: Group Model Building

MCDA: MultiCriteria Decision Analysis

PM: Participative Modelling

PSM: Problem Structuring Methods

SAW: Simple Additive Weight

SCA: Strategic Choice Approach

SIA: Societal Impact Assessment

SODA: Strategic Options Development and Analysis

SSM: Soft Systems Methodology

SWOT: Strengths-Weaknesses-Opportunities-Threats

Indicators and measures

EDD: Extended Retention Depth

FD: Filter media Depth

HC: Hydraulic Conductivity

SDGs: Sustainable Development Goals

SS: System Surface area

SZ: Saturated Zone depth

TN: Total Nitrogen

TP: Total Phosphorus

TSS: Total Suspended Solids

Tools, models, software

AHP: Analytic Hierarchy Process

ELECTRE: Elimination And Choice Translating Reality

FCM: Fuzzy Cognitive Map

GCS: Geographic Coordinate System

GIS: Geographical Information System

GSS: Group Support Systems

IUWSMs: Urban Water System Models

MACBETH: Measuring-Attractiveness by a Category-Based Evaluation TecHnique

MUSIC: Model for Urban Stormwater Improvement and Conceptualisation

OWA: Ordered Weighted Averaging

PAPRIKA: Potentially All Pairwise Rankings of all possible alternatives

PCS: Projected Coordinate System

PROMETHEE: Preference Ranking Organization Method for Enrichment and Evaluation

PSS: Planning Support Systems

SMART: Simple Multi-Attribute Rating Technique

SWMM: StormWater Management Model

TOPSIS: Technique for order preferences by similarity to ideal solutions

UrbanBEATS: Urban Biophysical Environment And Technologies Simulator

VIBe: Virtual Infrastructure Benchmarking

Documents

PDZA : Plan de Développement de la Zone Agricole

PU: Plan d’Urbanisme

SAD : Schéma d'aménagement et de Développement

Remerciements

Morgane Bousquet a obtenu une bourse ESSOR du fonds Marthe-et-Robert-Ménard, et le projet multi-universitaire a obtenu une bourse de démarrage du pôle de recherche FRQNT CentrEau et une bourse de projet de l'Institut EDS de l'Université Laval.

Je remercie tout d'abord mon directeur de recherche, Peter Vanrolleghem, et mes co-directrices, Roxane Lavoie et Françoise Bichai, pour m'avoir accompagnée tout au long de cette recherche. Je remercie Peter M. Bach qui a collaboré avec moi tout au long du projet sur le développement du modèle UrbanBEATS. Je remercie également Sandrine Lacroix, Martijn Kuller et Irène Abi-Zeid qui ont participé à l'écriture de certains articles scientifiques du projet.

Je remercie nos partenaires municipaux de Trois-Rivières, Toulouse et Melbourne ainsi que nos partenaires académiques, notamment l'équipe d'Etienne Paul de l'INSA Toulouse et l'équipe de Rhys Coleman de WERG (Melbourne, Australie) qui ont permis de réaliser les études de cas dans ces trois municipalités. Je remercie également les participants aux différentes sessions d'atelier pour leur implication et leur fiabilité.

Acknowledgements

Morgane Bousquet obtained an ESSOR scholarship from the Marthe and Robert Ménard fund, and the multi-university project obtained a starting grant from the FRQNT CentrEau research cluster and a project grant from Université Laval's EDS Institute.

First, I would like to thank my research supervisor, Peter Vanrolleghem, and my co-supervisors, Roxane Lavoie and Françoise Bichai, for accompanying me throughout this research. I would also like to thank Peter M. Bach, who worked with me on the development of the UrbanBEATS model during the project. I would also like to thank Sandrine Lacroix, Martijn Kuller and Irène Abi-Zeid, who took part in the writing of some of the project's scientific articles.

I would like to thank our municipal partners in Trois-Rivières, Toulouse and Melbourne, as well as our academic partners, in particular Etienne Paul's team at INSA Toulouse and Rhys Coleman's team at WERG (Melbourne, Australia) which enabled the case studies to be conducted in these three municipalities. I would also like to thank the participants in the different workshop sessions for their involvement and reliability.

Avant-propos

La recherche poursuivie durant cette thèse a conduit à l'écriture de 4 articles scientifiques. Le tableau suivant récapitule les titres des articles, le statut des articles (soumis, accepté, publié), le journal visé, les références sur les auteurs et co-auteurs ainsi que le chapitre d'insertion dans la thèse.

Titre	Statut	Journal	Auteurs	Chapitre thèse
A critical review of MCDA practices in planning of urban green spaces and NBS	Soumis le 10.06.2023; Accepté le 10.08.2023 Publié le 04.01.2024	Blue-Green Systems (IWA)	Morgane Bousquet (premier auteur); Martin Kuller, Sandrine Lacroix, Peter Vanrolleghem (co-auteurs)	Chapitre 1.3
MCDA-NBS: combining rigorous multi-criteria decision analysis and engineering tools for nature-based solutions planning	Soumis le 30.10.2023 En évaluation par les pairs depuis le 18.11.2023	Sustainable Cities & Society (Elsevier)	Morgane Bousquet (premier auteur); Peter Bach, Françoise Bichai, Roxane Lavoie, Peter Vanrolleghem (co-auteurs)	Chapitre 4.1
La planification des solutions fondées sur la nature : un travail collaboratif entre chercheurs et décideurs	Soumis le 2.06.2023	Techniques Sciences Méthodes (Astee)	Morgane Bousquet (premier auteur); Peter Vanrolleghem (co-auteur)	Chapitre 4.2
Applying multi-criteria decision analysis for nature-based solutions planning: findings from three different countries and continents	Soumis le 19.01.2024 En évaluation par les pairs depuis le 13.02.2024	Land Use Policy (Elsevier)	Morgane Bousquet (premier auteur); Irène Abi-Zeid, Françoise Bichai, Roxane Lavoie, Peter Vanrolleghem (co-auteurs)	Chapitre 4.3

Le premier article "A critical review of MCDA practices in planning of urban green spaces and NBS" est une revue de littérature qui dresse l'état de l'art des pratiques en aide à la décision multicritère pour la planification des espaces verts et des solutions basées sur la nature. Il a été préparé par Morgane Bousquet (premier auteur) et Martijn Kuller, Sandrine Lacroix et Peter Vanrolleghem (co-auteurs). Il a été soumis à la revue Blue-Green Systems, éditée par l'International Water Association (IWA), le 10 juin 2023 et a été accepté le 10 août 2023. Il est encore en cours de publication. Il s'inscrit comme étant le dernier chapitre de la section de revue de littérature (section 1.3).

Le deuxième article "MCDA-NBS: combining rigorous multi-criteria decision analysis and engineering tools for nature-based solutions planning" présente la nouvelle méthode MCDA-NBS développée pendant cette recherche. Il a été préparé par Morgane Bousquet (premier auteur) et Peter Bach, Roxane Lavoie, Françoise Bichai et Peter Vanrolleghem (co-auteurs). Il a été soumis à la revue Landscape & Urban Planning, éditée par Elsevier, le 30 octobre 2023. Il s’inscrit comme étant le premier chapitre de la section des résultats (section 4.1).

Le troisième article "La planification des solutions fondées sur la nature : un travail collaboratif entre chercheurs et décideurs" présente la mise en place d’un processus participatif et collaboratifs pour la planification des solutions fondées sur la nature. Il a été préparé par Morgane Bousquet (premier auteur) et Peter Vanrolleghem (co-auteur). Il a été soumis à la revue Techniques Sciences Méthodes, éditée par l’Astee, le 2 juin 2023. Il s’inscrit comme étant le deuxième chapitre de la section des résultats (section 4.2) et a été traduit en anglais pour des questions d’harmonisation linguistique de la thèse.

Le quatrième article " Applying multi-criteria decision analysis for nature-based solutions planning: findings from three different countries and continents" présente les résultats de l’application de la méthodes MCDA-NBS à trois études de cas. Il a été préparé par Morgane Bousquet (premier auteur) et Irène Abi-Zeid, Roxane Lavoie, Françoise Bichai et Peter Vanrolleghem (co-auteurs). Il a été soumis à la revue Landscape & Urban Planning, éditée par Elsevier, le 31 octobre 2023. Il s’inscrit comme étant le dernier chapitre de la section des résultats (section 4.3).

Les fichiers « matériels supplémentaires » liés à ces articles ont été mis en annexe de la thèse en indiquant l’article auquel ils sont liés.

Preface

The research carried out during this thesis led to the writing of 4 scientific articles. The following table summarises the titles of the articles, the status of the articles (submitted, accepted, published), the journal concerned, the references of the authors and co-authors and the chapter in the thesis.

Title	Statut	Journal	Authors	Thesis chapter
A critical review of MCDA practices in planning of urban green spaces and NBS	Submitted on the 10.06.2023; Accepted on the 10.08.2023 Published the 04.01.2024	Blue-Green Systems (IWA)	Morgane Bousquet (first author); Martin Kuller, Sandrine Lacroix, Peter Vanrolleghem (co-authors)	Chapter 1.3
MCDA-NBS: combining rigorous multi-criteria decision analysis and engineering tools for nature-based solutions planning	Submitted on the 30.10.2023 Under peer-review since the 18.11.2023	Sustainable Cities & Society (Elsevier)	Morgane Bousquet (first author); Peter Bach, Françoise Bichai, Roxane Lavoie, Peter Vanrolleghem (co-authors)	Chapter 4.1
La planification des solutions fondées sur la nature : un travail collaboratif entre chercheurs et décideurs	Submitted on the 02.06.2023	Techniques Sciences Méthodes (Astee)	Morgane Bousquet (first author); Peter Vanrolleghem (co-author)	Chapter 4.2
Applying multi-criteria decision analysis for nature-based solutions planning: findings from three different countries and continents	Submitted on the 19.01.2024 Under-peer review since the 13.02.2024	Land Use Policy (Elsevier)	Morgane Bousquet (first author); Irène Abi-Zeid, Françoise Bichai, Roxane Lavoie, Peter Vanrolleghem (co-authors)	Chapter 4.3

The first article "A critical review of MCDA practices in planning of urban green spaces and NBS" is a literature review that reviews the state of the art of multi-criteria decision support practices for the planning of green spaces and nature-based solutions. It was prepared by Morgane Bousquet (first author) and Martijn Kuller, Sandrine Lacroix and Peter Vanrolleghem (co-authors). It was submitted to the journal Blue-Green Systems, published by IWA, on 10 June 2023 and was accepted on 10 August 2023. It is still in the process of publication. It is included as the final chapter of the literature review section (section 1.3).

The second article "MCDA-NBS: combining rigorous multi-criteria decision analysis and engineering tools for nature-based solutions planning" presents the new MCDA-NBS method developed during this research. It was prepared by Morgane Bousquet (first author) and Peter Bach, Roxane Lavoie, Françoise Bichai and Peter Vanrolleghem (co-authors). It was submitted to the journal Landscape & Urban Planning, published by Elsevier, on 30 October 2023. It is the first chapter of the results section (section 4.1).

The third article "Nature-based solutions planning: a collaborative work between researchers and decision-makers" presents the implementation of a participatory and collaborative process for planning nature-based solutions. It was prepared by Morgane Bousquet (first author) and Peter Vanrolleghem (co-author). It was submitted to the journal Techniques Sciences Méthodes, published by Astee, on 2 June 2023. It is included as the second chapter of the results section (section 4.2) and is translated into English to align with the language of the thesis.

The fourth article, "Applying multi-criteria decision analysis for nature-based solutions planning: findings from three different countries and continents", presents the results of applying the MCDA-NBS method to three case studies. It was prepared by Morgane Bousquet (first author) and Irène Abi-Zeid, Roxane Lavoie, Françoise Bichai and Peter Vanrolleghem (co-authors). It was submitted to the journal Landscape & Urban Planning, published by Elsevier, on 31 October 2023. It is the final chapter of the results section (section 4.3).

Additional material files linked to these articles are annexed to the thesis, indicating the article to which they are linked.

Introduction

The growth of the world's population accelerated during the 20th century due to the technological development of our society during the industrial era. According to United Nations predictions (2019), it could reach almost 10 billion by the end of the 21st century. This phenomenon is accompanied by a concentration of populations in major urban areas, which are becoming denser. This trend should accelerate, with more than half of the world's population living in urban areas by the end of the 21st century, in order to have better access to water, energy and services such as health and education (United Nations - Department of Economic and Social Affairs, 2015). The impact of this development is significant, as it leads to the impermeabilization of land to the detriment of vegetation and natural areas. Decision-makers are concerned about the loss of urban biodiversity, the rise in temperature and the risk of flooding. Indeed, materials such as concrete, asphalt and stone have a much lower albedo (capacity to reflect the sun's radiation) than plant cover, which leads to a significant increase in the surface temperatures of these materials and consequently in air temperatures, causing urban heat island effects. Moreover, a considerable proportion (50%) of rainwater naturally infiltrates into the ground and helps recharge the water table, while the other part (10%) runs off into lakes and rivers or evaporates (40%) (Oral *et al.*, 2020). In an urban environment, this proportion is around 55% for runoff, 30% for evapotranspiration and only 15% for infiltration (Oral *et al.*, 2020), which increases peak flow significantly, potentially causing flooding. Climate change is amplifying these problems. For example, the Intergovernmental Panel on Climate Change (Masson-Delmotte *et al.*, 2018) has studied four scenarios (Representative Concentration Pathways) based on assumptions about global demographic and society changes in the year 2300. The main findings of these simulations show a general increase in temperature and major disruptions to the water cycle (e.g., melting glaciers, oceans acidification, intense rainfall, droughts).

On a global scale, the Sustainable Development Goals (SDGs) were adopted by all United Nations members in 2015 as a universal call to action to address global challenges. There are 17 goals, with reference to water management (Goals 6, 12), as well as adapting cities and communities to climate change (Goals 9, 11, 13). The concept of sustainable cities aims to make cities more resilient in the face of current and future major events, i.e., to increase their ability to overcome these events. For example, the concept of Urban Flood Resilience (O'Donnell *et al.*, 2020) refers to a city's ability to keep future flood risks to tolerable levels. The costs associated with these risks could reach 110 billion dollars per year by the end of the 21st century, and 75% of the damage would be in urban areas (Da Cunha & Thomas, 2017). Current resources and technologies are not sufficient to meet these challenges. In the case of rainwater management, the infrastructures put in place are retention basins and trenches, pipe networks and management infrastructures (e.g., gutters), also called grey infrastructures. Rainwater is conveyed through combined sewer systems, where it is mixed with wastewater, to the treatment plant, or through separate sewer systems to the receiving watercourse. In the case of combined sewers, the water is discharged into the receiving watercourse after treatment but, in the event of major rainfall events, there is a risk of overflow with part of the water discharged directly into the receiving environment, without treatment. Retention basins are installed in these networks to regulate flows and avoid overflow problems. However, retention basins simply create a time lag in runoff and are becoming less effective in the face of urban development and climate change, leading to increasingly frequent overflows and direct discharges into natural environments. The surfaces on which rainwater runs off are often loaded with pollutants (e.g., motor oils, treatment of natural and agricultural areas, household waste), which further impacts the environment.

Nature Based Solutions (NBS) are seen as an innovative and more sustainable urban alternative to current water management using grey infrastructures (Hamouz *et al.*, 2020; Steis *et al.*, 2020). They are engineered green systems such as rain gardens, green roofs and walls, ponds, swales, constructed wetlands and urban forests which allow storm water control at the source by enhancing functions of infiltration, evapotranspiration, retention, conveyance, and water quality treatment (Kuller *et al.*, 2017). Some of the primary benefits include surface water quality protection, flood reduction and resource recovery (e.g., water harvesting). NBS bring many co-benefits such as improving aesthetics, reducing the urban heat islands effect, and increasing biodiversity (Dagenais *et al.*, 2017; Qiu *et al.*, 2022; Skrydstrup *et al.*, 2020). A recent literature review listed all the existing types of NBS, the functions they could perform and the benefits they could bring to the environment (Anderson *et al.*, 2023). Limitations of NBS to be considered include maintenance and implementation costs, the high land pressure on vacant spaces such as natural green spaces, or the increased demand for water to irrigate these new spaces. Moreover, a recent literature review highlighted the lack of case studies of NBS implementation that could provide data on the cost, installation, maintenance and performance of NBS (Wang *et al.*, 2023). The multifunctional potential of NBS highlights the need for careful spatial planning, considering the three pillars of sustainable development: environmental, social, and economic sustainability (Brasil *et al.*, 2021; Dorst *et al.*, 2019; Goodspeed *et al.*, 2022; Monteiro *et al.*, 2020). However, most studies focus on environmental aspects (e.g., biodiversity, soil recovery) and stormwater management (Meerow, 2020; Monteiro *et al.*, 2020), and only consider a single benefit such as water quantity control (Meerow, 2019; Meerow & Newell, 2017). Moreover, opportunistic NBS planning leads to unintended results that do not maximize the potential of the multiple benefits of NBS *(Kuller et al., 2018; Li et al.*, 2019; Meerow, 2020). Multicriteria decision analysis (MCDA) is well suited to counter this issue by evaluating multiple objectives simultaneously, involving multiple stakeholders and preferences, as well as technical information.

The United Nations conference on Sustainable Development in Rio de Janeiro (Brazil) on 20-22 June 2013 showed global interest in NBS and led to numerous studies about strategic urban planning attempting to frame this new practice (Hanna & Comín, 2021; Meerow, 2020). Nature-Based Solutions in urban climate adaptation plans are also referred to as Green Infrastructure (GI) or Blue-Green Infrastructure (BGI) planning, Low Impact

Development (LID), Best Management Practices (BMP), Sustainable Urban Drainage Systems (SUDS), Water Sensitive Urban Drainage (WSUD), or Sponge City, depending on the study location (Fletcher *et al.*, 2015). The term Ecosystem Services (ES) is also widely used and refers more broadly to environmental and socio-economic benefits that any type of green space (e.g., natural forests, wetlands, grassland or engineered systems like the ones mentioned above) can provide to the urban environment (Billaud *et al.*, 2020; Dagenais *et al.*, 2017). In this thesis, the term NBS will be used, as it is the term used by the United Nations since the Convention on Biological Diversity COP15 in Montreal in 2022. Decision-makers express the need for more guidelines, methods, and tools for NBS planning (Ferreira *et al.*, 2021; Voskamp *et al.*, 2021), which are absent in the existing literature (Hanna & Comín, 2021; Mendonça *et al.*, 2021; Voskamp *et al.*, 2021). In addition, the use of MCDA methods to support NBS planning has gaps because it rarely involves stakeholders, uses simple methods (e.g., direct ranking) or methods with a high risk of bias (e.g., AHP), and uses GIS tools specifically developed for a specific context and case study.

The thesis objective is to develop a new MCDA-NBS method, combining social sciences with MCDA and applied sciences with water engineering tools for NBS planning, and to demonstrate that it helps the decision-making process for NBS planning. The method is based on stakeholder participation and collaboration between decision-makers, researchers, and stakeholders. It combines the MACBETH method (Costa, 2012; Costa *et al.*, 1999, 2003, 2019) and the UrbanBEATS tool (Bach, 2014; Bach *et al.*, 2015; Bach *et al.*, 2018; Bach *et al.*, 2020; Bach *et al.*, 2020; Bach *et al.*, 2015), and has been tested in three different geographical, socio-political, and urban contexts (Canada, France and Australia).

In the first part we will present the literature review on current NBS planning practices, including the basic scenario approach, and engineering tools for NBS design and planning, as well as MCDA tools, methods and participatory approaches, and finally a literature review on MCDA practices for NBS and green space planning. In the second part, we will identify the issues surrounding NBS planning and present the objectives of the thesis, the questions, and the answers proposed. In the third part, we present the methods (i.e., MACBETH and UrbanBEATS) and case studies on which we have based the development of the MCDA-NBS method. Finally, in the last part, we will present the results of the development of the MCDA-NBS method and its steps, a guide for setting up a collaborative and participatory process and an analysis of the results on the three case studies.

This thesis provides a systematic literature review on MCDA and NBS planning practices and presents a new MCDA-NBS method which aims to improve the decision-making process, demonstrated through three case studies. Those case studies present an application of the MCDA-NBS method in three different countries and continents: Trois-Rivières (Canada), Toulouse (France) and Melbourne (Australia). Partnerships with municipalities, decision-makers and stakeholders have been an essential part of the project as well as the partnerships with researchers and model developers. An important task was to manage the dialog between those partners, facilitate the participative MCDA process with the stakeholders and analyse the results produced. The research team was composed of experts in MCDA processes, NBS techniques, GIS modelling, urban planning for NBS and water management. As this research project is transdisciplinary, it was crucial to have experts in different domains to ensure the robustness of the proposed MCDA-NBS method. During this research, a literature review (Bousquet *et al.***,** 2023a) has been accepted to the Blue-Green Systems journal (i.e., IWA publishing), a scientific publication (Bousquet & Vanrolleghem, 2023) has been accepted to the journal Techniques Sciences Méthodes (i.e., Astee publishing), and two other scientific publications (Bousquet *et al.*, 2023b, 2023c) have been submitted to Landscape & Urban Planning journal (i.e., Elsevier publishing). The literature review presents a state-of-the-art for MCDA practices for NBS and green spaces planning and the three other publications present the MCDA-NBS method illustrated by the case study of Toulouse, a road map for applying a collaborative process, and the analysed results we obtained in the three case studies.

Chapter 1: Literature review

Nutt (1999) analysed over 400 decisions made by senior managers in private, public, and not-for-profit organisations in the US, Canada and Europe. Half of the decisions examined ended in failure, i.e., they were not fully implemented after two years. According to the author, these decisions failed for three main reasons:

1) The decision-makers identified a problem and adopted the first solution they encountered;
2) Decision-makers spent time and money, making decisions on the wrong issues;
3) The decision-makers applied methods that were prone to failure, including the lack of stakeholder involvement in the process.

In this literature review we will look specifically at the situation of NBS planning by focusing at current practice in NBS planning, good practice in the use of MCDA methods and tools and a review of MCDA approaches to NBS planning.

1.1 The current practices for NBS planning

Spatial planning is a principal element of green space policy in cities which integrate NBS planning (Zwierzchowska & Stępniewska, 2022). Water engineering is an important part of strategic planning for NBS, focusing on the issue of stormwater management, with a focus in runoff and water quality issues (Monteiro *et al.*, 2020; Wang *et al.*, 2023). This aspect of decision-making is supported by many government institutions, such as the Environmental Protection Agency (EPA) in the United States, because it provides a solution to the growing risks of flooding and urban runoff and, more generally, to the quantitative and qualitative management of water resources (Monteiro *et al.*, 2020). The first section of this chapter will present the scenario approach which is the basic planning approach for NBS. Then, the second and third sections will present two categories of water engineering tools that can be used to analyse the flow dynamics of an area: design tools for stormwater management and planning tools for stormwater management.

1.1.1 The scenario approach

The basic NBS planning approach focuses on building scenarios (Gielczewski *et al.*, 2011; Urich & Rauch, 2014) that consider short and long reference periods and global and local scales. These considerations are an important feature of assessing the sustainability of urban policy and governance (Boggia *et al.*, 2018). However, the studies in the literature are often carried out on a site scale and remain very limited on a global scale and also rarely consider a long-term vision, despite the need for territorial planning from municipalities (Anderson *et al.*, 2023). The scenario approach comprises four steps (Cortinovis *et al.*, 2021; Gielczewski *et al.*, 2011):

1) Characterisation of the present and near future, including the diagnosis, issues and objectives regarding an area;

2) Definition of a long-term vision (20-50 years), involving several possible scenarios, based on possible actions;
3) Critical review of the scenarios proposed at the previous stage, comparing them;
4) Assessment of the scenarios and their short-term actions, commonly known as impact assessment in relation to a baseline.

In the first step of diagnosis, the two most used methods in spatial planning are SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) and DPSIR (Drivers, Pressures, State, Impacts, Response) (Mustajoki & Marttunen, 2017). For the second and third step, maps are frequently used for spatial decision-making to identify the geographical sites that maximise benefits (Arciniegas & Janssen, 2012; Langemeyer *et al.*, 2016), which then become options, supporting different scenarios (Gray *et al.*, 2019). GIS (Geographical Information System) tools such as ArcGIS and QGIS are frequently used to identify these geographical sites and aim to store, manage, analyse and visualise geospatial data (Ferretti & Montibeller, 2016; Gonzalez & Enríquez-de-Salamanca, 2018; Mubeen *et al.*, 2021; Qiu *et al.*, 2022). However, the use of GIS software requires a certain amount of expertise, as it gathers a large amount of information (Arciniegas & Janssen, 2012). For the last step, the focus is on either benefits/performance or impacts/costs (Engström *et al.*, 2018). The most frequently used methods are Environmental Impact Assessment (EIA) and Cost-Benefit Analysis (CBA) (Gonzalez & Enríquez-de-Salamanca, 2018; Langemeyer *et al.*, 2016). EIA focuses on impacts with ecological value which can provide positive impacts on water, climate, habitats, and protected species but do not integrate social impacts of NBS. CBA, on the other hand, focuses on the monetary evaluation and has a limited capacity to integrate ecological, social and cultural values. These methods can be combined with the SIA (Societal Impact Assessment) method and complement the previous economic assessments with social values (Heathcote, 2009). Most economic studies use hedonic pricing methods that measure the implicit value of NBS by observing exchanges on existing markets, such as property markets (Badura *et al.*, 2021). One of the major shortcomings of this last step is that it performs a short-term valuation and therefore does not consider long-term life cycle impacts (Engström *et al.*, 2018). Furthermore, it does not incorporate spatial scales of NBS performance as some NBS might be effective on a small scale and in the short term but might not have the same effectiveness on a larger scale and in the long term (Albert *et al.*, 2021). Moreover, they do not study the combination of NBS with existing grey infrastructures, which is advocated by ecologists, engineers, and scientists as the best way of ensuring reliability in the face of extreme events in many urban contexts (Alves *et al.*, 2018; Sarabi *et al.*, 2019; Seddon *et al.*, 2020). Research is still ongoing to measure the actual performance of NBS and to establish comparisons with the relative value of the benefits provided by NBS (Albert *et al.*, 2021; Dick *et al.*, 2019; Meerow, 2020; Voskamp *et al.*, 2021; Wang *et al.*, 2023), which often tend to be underestimated (Dorst *et al.*, 2019; Seddon *et al.*, 2020).

Most of the studies use more than one tool and method simultaneously for NBS planning (Qiu *et al.*, 2022; Yeo *et al.*, 2022). The most popular tools are presented in the following sections, differentiating between design tools for stormwater management and planning tools for water management.

1.1.2 The design tools for stormwater management

There are several hydraulic modelling tools, of varying degrees of complexity, that are commonly used in engineering for stormwater management. Among the simplest, water balance tools (e.g., UWOT from the European SWARD project in 2004, and Urban Developer or UrbanCycle, in 2005) simulate total water inflows and outflows for an analytical unit of measurement (Kuller *et al.*, 2017). Hydraulic modelling tools assess and predict water flows in piped drainage and sewerage systems and help with system design. They are widely applied in urban water management, particularly for flood forecasting and urban drainage. The hydraulic modelling tool developed in the United States is SWMM (StormWater Management Model) (Simon & Tryby, 2018) and, on a smaller scale, MUSIC (Model for Urban Stormwater Improvement and Conceptualisation) developed in Australia. MUSIC is a tool for designing and sizing NBS, while SWMM was initially designed for conventional stormwater management networks and infrastructure (retention basins). Now, it also incorporates a module for management by NBS.

SWMM (EPA, 2018) is an American tool developed by the US Environmental Protection Agency (EPA) to simulate rainfall-runoff-infiltration. The tool is used to simulate a single event, or over the long term, the quantity and quality of surface or groundwater hydrology in urban or suburban areas. It can simulate precipitation runoff, evapotranspiration, infiltration and groundwater connection through sewer pipes, roots, streets, grassed areas and some NBS. SWMM uses two indicators to measure the performance of a new system: PI_{CSO} (Combined Sewer Overflow) and PI_{FLOOD} (Surface Flooding) (Urich *et al.*, 2013). PI_{CSO} indicates the efficiency of the system. It is used to calculate the ratio between the volume of surface runoff V_R (caused by rainfall without considering stormwater) and the volume of treated surface runoff, after the wastewater treatment plant, V_{WWTP}. The corresponding equation is: $PI_{CSO} = V_{WWTP}/V_R$. PI_{FLOOD} indicates the performance of the system for surface flooding. The corresponding equation is: $PI_{FLOOD} = 1 - V_P/V_R$; where Vp is the volume of stormwater surface runoff. The use of this tool is free and very well documented, with free exhaustive guides and an online platform for discussion between users, making it a tool used in 46% of the studies on stormwater management and NBS found in literature (Ferrans *et al.*, 2022).

MUSIC (eWater, 2020) is a conceptual software package, created by the eWater agency, and developed for the Australian urban water industry to assess pollutant loads and concentrations. However, experienced users increasingly use it to assess hydrological objectives, such as the treatment performance of NBS. MUSIC offers several configurations and parameters to suit the study context. It is based on four indicators: runoff reduction, reductions in total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN). The main variables for designing NBS are system surface area (SS), extended retention depth (EDD), hydraulic conductivity (HC), filter media depth (FD) and saturated zone depth (SZ). MUSIC helps to improve the design of technologies by constructing Design Curves. These Design Curves analyse the relationship between the surface area of the NBS and its performance in managing water over the total surface area to be treated. MUSIC is a commercial tool that requires an annual licence.

1.1.3 The planning tools for stormwater management

More complex water management tools include planning on a metropolitan scale using scenario analysis. They are called Integrated Urban Water System Models (IUWSMs) (Bach, 2014) and combine water infrastructure and disciplines (climate, economics, stakeholder behaviour, etc.) across the urban water cycle and are likened to Planning Support Systems (PSS) which concern systems that facilitate the process of planning using multiple technologies and common interfaces (Silva, 2010). They use local site conditions, and it has been found that many tools use similar inputs, such as DEM (topography), land use, soil type, imperviousness, groundwater depth and stream characteristics (Mubeen *et al.*, 2021; Yeo *et al.*, 2022). A literature review by Kuller *et al.* (2017) identified several tools, which are listed below.

The first attempts to model socio-technical systems were undertaken as part of the European MATISSE project in 2008 with the Multi-Level Perspective initially developed by Rip and Kemp in 1998 and refined by Geels in 2002. Most tools for urban water management focus on the simulation of demand and supply models, such as the Societal Transition Workbench in 2011 by De Haan *et al.*, which uses households, property owners, local government, and developers to simulate the spatial adoption of NBS in different scenarios. We can also mention the Water Sensitive City Continuum developed by Brown *et al.* in 2009, and its indexing tool recently developed in 2016 by Beck to measure the current state of transition of a city's water management and sustainability.

Scenario analysis is a concept widely applied in planning processes for urban water management. There are several tools that consider the interactions between the urban water system and societal, climatic, biophysical, environmental, and other factors, making it possible to establish several scenarios. These include DAnCE4Water, developed by Rauch *et al.* in 2015, VIBe (Virtual Infrastructure Benchmarking) developed by Sitzenfrei *et al.* in 2013 and ReVISIONS developed by Ward *et al.* in 2012.

In addition, there is a need for planning and spatial suitability assessment of NBS on a large scale *(*Mubeen *et al.*, 2021). Thus, many tools in the literature combine the use of GIS software with the assessment of spatial planning for NBS (Gonzalez & Enríquez-de-Salamanca, 2018; Mubeen *et al.*, 2021; Puchol-Salort *et al.*, 2020). These tools are often used as the main platform with simulation modules integrated or separate from the platform

(Yeo *et al.*, 2022). Among the tools equipped with planning algorithms for NBS, UrbanBEATS (Bach, 2014; Bach *et al.*, 2015a; 2015b; 2018; 2020a; 2020b), SSANTO (Kuller *et al.*, 2018; 2019), SUSTAIN-EPA (Lee *et al.*, 2012), AST (Voskamp *et al.*, 2021) and GISP (Meerow & Newell, 2017) are the tools frequently documented in the literature and sufficiently advanced in their development to produce reliable mapping results of NBS planning strategies. They rely on a technology selection process to evaluate and rank NBS according to their ability to provide the required services in certain locations or contexts (Mubeen *et al.*, 2021). They use optimisation algorithms that calculate what is optimal at each iteration by considering the targets already reached, unlike other approaches that apply static weights based on the relative importance of the targets in the initial conditions (Cortinovis *et al.*, 2021). The final map obtained is commonly referred to as the Suitability Map (Kuller *et al.*, 2017; 2018; 2019; Liu *et al.*, 2014) representing potential locations for NBS. UrbanBEATS stands out from the other tools in that it develops its own interface with independent model enabling data and results to be visualised, although GIS software is still required for data preparation. It is also the only tool to propose NBS planning alternatives considering all technologies simultaneously while the other tools conduct an analysis of the territory by technology individually (Meerow & Newell, 2017). This tool will be described more specifically in chapter 3.1.

In addition to these tools, Kuller *et al.* (2017) also cite SUDSLOC developed by Viavattene and Ellis in 2014, the DayWater multicriteria comparator developed by Ellis *et al.*, in 2008 and the Scholz matrix in 2006 and retrofit-SuDS developed by Stovin and Swan in 2007. Moreover, a literature review (Van Oijstaeijen *et al.*, 2020) listed the main tools for evaluating NBS as NVE, i-Tree eco, Gi-Val, CNT, TESSA, InVEST, EcoPLAN-SE, GI Benefits valuation tool, CAVAT, B£ST. However, despite the tools found in the literature, Padró *et al.* (2020) state that there is a lack of a multicriteria and multi-scale tool for evaluating the strategic planning of NBS.

1.2 The growing interest for MCDA

Operations research is a discipline that emerged in the 1940s and the first MCDA methods appeared in the 1970s (Belton & Stewart, 2002; Mingers, 2011). MCDA is a systematic approach to incorporate multiple objectives and combine subjective preferences with objective information in order to reach a rational decision. MCDA can help decision-makers analyze a complex decision problem that involves different stakeholders. These methods are used in various sectors such as education, human resource management, finance, real estate, construction, medical, multimedia, electronics, and IT sectors (Razmak & Aouni, 2015). MCDA methods and tools are presented in the next sections, followed by a special focus on the participatory processes behind the MCDA and the concept of facilitation.

1.2.1 The MCDA methods and tools

MCDA offers a rich collection of methodologies to structure planning problems with conflicting objectives, allowing the design, evaluation, and prioritization of decision alternatives from a multicriteria model representing stakeholder preferences (Ferretti & Montibeller, 2016; Marttunen *et al.*, 2017). Obtaining subjective preferences on a problematic situation, including objective weightings, is one of the main parts of MCDA (Aubert *et al.*, 2020).

MCDA methods and models use preference functions, which can be of several types. De Toro and Iodice (2017) have identified six types of functions:

i. The null preference function is the simplest case with no threshold;
ii. The U-shaped preference function is always used for qualitative criteria and uses a single indifference threshold that must be fixed;
iii. The linear preference function is used in the case of a criterion with a linear preference up to a preference threshold that is determined;
iv. The preference level function is used in the case of an indifference and preference threshold which must be fixed;
v. The V preference function is a special case of the linear preference function where the indifference threshold is equal to 0;
vi. The Gaussian preference function is an alternative to the linear version with a smoother form (preference increases and follows a normal distribution and the standard deviation must be fixed).

Belton & Stewart (2002) classified MCDA methods into three categories based on the type of model used. This review, however, relies on the work of Mustajoki & Marttunen (2017) to give method examples for each category (Table 1). Some methods are at the intersection of these models (e.g., MACBETH method) (Lavoie *et al.*, 2016). Although these methods are various and may look similar (Keeney, 2004), they are never strictly the same, as the domain and context in which the decision is made have a strong impact (Karacapilidis & Tzagarakis, 2007). Németh *et al.* (2019) evaluated some of the methods classified by Belton & Stewart (2002) and Mustajoki & Marttunen (2017) according to the need for resources, computer assistance, chances of bias, their complexitý and robustness. Thus, the first category methods are simple methods as they require little data and no software. However, the chances of bias are high. The AHP method remains simple, but it is less transparent than the first category methods which increases the chances of bias (Alves *et al.*, 2018). The third category methods are more complex and abstract and require the use of computer tools to conduct the calculations.

Table 1 - MCDA categories by type of model (value measurement, aspiration, outranking) based on Belton and Stewart (2002).

Type of model	Characteristics	Method examples
Value measurement models	Numerical preference scores are synthesized to perform aggregation into preference models.	Simple Multi-Attribute Rating Technique (SMART), Swing, Technique for order preferences by similarity to ideal solutions (TOPSIS), Ordered Weighted Averaging (OWA)
Aspiration models	Criterion weights are obtained from pairwise comparisons between criteria, using an eigenvector technique. Weights are aggregated to obtain the global relative weights of the alternatives describing their global preference compared to the other alternatives.	Analytic Hierarchy Process (AHP)
Outranking models	Preferences are obtained by asking whether the advantages of one alternative over another are sufficient to overcome its disadvantages. The degree of dominance is calculated between the alternatives, describing whether an alternative is at least as good as another.	Preference Ranking Organization Method for Enrichment and Evaluation (PROMETHEE), Potentially All Pairwise Rankings of all possible alternatives (PAPRIKA), Elimination And Choice Translating Reality (ELECTRE)

MCDA methods incorporate data that can be quantitative and qualitative at the same time which can lead to more bias, and the use of specific IT tools is highly recommended (Németh *et al.*, 2019). Mustajoki & Marttunen (2017) identified dozens of different tools and softwares supporting MCDA for spatial planning situations (e.g., M-MACBETH, 1000Minds, D-Sight, Expert Choice, Web-HIPRE, CoPe_it!, Web-Delphi, Decerns, Transparent Choice, VISA Decisions), but the general list is more exhaustive. Most of these tools provide a matrix-type table to capture the data per criterion relative to the alternatives in the model. In addition to the matrix representation of results, MCDA tools can also display results in the form of diagrams or curves. For example, the Analytica and DecideIT tools incorporate causal loop diagrams, representing the causes and effects of an action on a criterion (Mustajoki & Marttunen, 2017). Other tools (e.g., Decerns, Pure2, mDSS, Visual PROMETHEE, Diviz) aims to visualise the impacts of criteria on maps (Mustajoki & Marttunen, 2017). This option is often complementary to a classic software interface with data display. For example, in the case of Visual PROMETHEE, the alternatives are located on Google Map and some tools (e.g., GeoUmbriaSUIT, Diviz) are linked to GIS software (Boggia *et al.*, 2018; Mustajoki & Marttunen, 2017). Similar to these tools, the Fuzzy Cognitive Map (FCM) (Voinov & Bousquet, 2010) is another form of conceptual representation where the connections between criteria represent the impacts of one criterion and another. It is used in health, transport, education, natural resource management, project management, information systems, strategy development, inter-organisational collaboration and more (Franco & Montibeller, 2010). A free tool, FCMapper, can be used when systems are too complex to be built manually.

MCDA-GIS tools (Gonzalez & Enríquez-de-Salamanca, 2018; Sanches & Mesquita Pellegrino, 2016; Yeo *et al.*, 2022) have developed considerably over the last twenty years because they have the ability to produce rapid, effective and reliable assessments by considering multiple aspects in different geographical contexts and at different scales while remaining easy to understand for decision-makers (Gonzalez & Enríquez-de-Salamanca, 2018). Indeed, MCDA-GIS tools can combine objective data (i.e. environmental spatial data) and subjective values (i.e., the relative importance translated in weights) to emphasise priority areas or decision-makers concerns (Gonzalez & Enríquez-de-Salamanca, 2018). These tools can be used for diagnosis and analysis, design strategies and master planning (Dall'Ara *et al.*, 2019). The main recommendation is to rely on open and free access data so that local authorities can input their own GIS data and adapt methods if necessary (Van Oijstaeijen *et al.*, 2020).

1.2.2 A participative process

MCDA were developed as participative methods. Indeed, a participatory (Schein, 2017) and constructivist (Landry, 1995) approach involving stakeholders is recommended by the scientific community (Belton & Stewart, 2002), because it is expected to lead to the implementation of 80% of the decisions (Nutt, 1999). By "participatory", we refer to a collaborative process in which relevant stakeholders are involved in all steps of decision-making from objective definition to alternative development and preference elicitation. By "constructivist", we refer to a process that consists of several steps that build towards a result. However, at the beginning of an MCDA process, the group is often convinced that it will not be able to reach an agreement that benefits all parties given their differences of opinion (Kaner, 2014). Moreover, most of the MCDA methods and tools have been deemed inaccessible to a user with no prior experience (Mustajoki & Marttunen, 2017). In this sense, group facilitation has been identified as a potentially key element in improving group effectiveness (dialogue, analysis, decision-making, planning, divergence, and convergence of opinions) as well as improving the outcomes and satisfaction of the group of participants (Mittleman *et al.*, 2000; Pauleen & Yoong, 2001;

Thorpe *et al.*, 2011). A facilitator is highly recommended to lead meetings and group activities (Griffith *et al.*, 1998), to guide and analyse each stage of the process (Franco & Montibeller, 2010), and to use IT tools (Lagroue III, 2008; S. Thorpe, 2016).

There are several levels of stakeholder participation in a project (Marais & Abi-Zeid, 2021): informative (simple explanation of the project), consultative (consideration of stakeholders' opinions), collaborative (partial integration of stakeholders in the process) or co-decisive (decisions taken by stakeholders). A final level would be to let the stakeholders conduct the process autonomously. Stakeholders are identified and characterised by a stakeholder analysis (Marais & Abi-Zeid, 2021) and this can be done using an imperative approach (stakeholders are affected by the problem) or a positional approach (stakeholders occupy formal positions linked to the problem) (Puchol-Salort *et al.*, 2020). The effectiveness of the participatory process depends on many parameters, such as the social relations between the stakeholders, their ability to communicate and exchange information and knowledge, and the skills, methods and tools that can help them to do so (Voinov & Bousquet, 2010).

Approaches such as Soft Systems Methodology (SSM) (Checkland, 2000), the Strategic Options Development and Analysis (SODA) (Mingers & Rosenhead, 2001), Group Model Building (GMB) (Vennix, 1996) or Participative Modelling (PM) (Voinov & Bousquet, 2010), Decision Conferencing (Phillips, 2008), the Strategic Choice Approach (SCA) (Friend, 2011), more generally known as Problem Structuring Methods (PSM), advocate the use of tools, also known as Group Support Systems (GSS), to help stakeholders visualise and illustrate each stage of the decision support process. These approaches are based on different tools, schematically represent the context of the problem, such as cognitive and causal maps (e.g., Rich Picture in the SSM method), causal loop diagrams, stock and flow images, graphs and decision trees (Checkland, 2000; Eden, 1988). All these different approaches refer to the concept of Collaborative Learning (CL), which enables all stakeholders to learn together and simultaneously during the decision-making process and to become co-researchers in the project (Paillé & Mucchielli, 2016).

In order to facilitate stakeholder involvement, IT communication tools such as Microsoft Teams, Skype, Zoom, Dropbox, Google drive, CISCO, AT&T Connect, Podio and GoToMeeting have been developed in recent years, sometimes simultaneously enabling discussion, virtual meetings, data sharing and access to online tools/software (Van Ostrand *et al.*, 2016). Finally, more specifically related to public participation and citizen involvement, there are voting and survey tools that can easily be coupled with multicriteria decision support methods (Mendoza & Martins, 2006). The development of participatory or public participation GIS is also a useful tool for communication between stakeholders (Kuller *et al.*, 2021). Participatory approaches can be linked to a transdisciplinary process referring to the cooperation of researchers and non-academic stakeholders to create new knowledge and answer a common spatial planning question, which has been identified as one of the key success factors of projects (Albert *et al.*, 2021; Atiqul Haq *et al.*, 2021).

1.2.3 The robustness of MCDA methods and tools

The use of MCDA methods or tools must be robust to provide good results. According to Roy (2010), the term "robust" can be applied to a selected action or procedure, to a ranking of potential action or procedure, or to the allocation of a potential action to predefined categories or to a sorting procedure. Thus, one of the first elements to check is the independence between criteria in order to avoid multiple influences ("double counting") on the result. Bottero *et al.* (2015) identify three cases of interaction between criteria:

i. the reinforcing effect (e.g. investment cost; profitability)
ii. the weakening effect (e.g. environmental impacts; sustainable landscape)
iii. the antagonistic effect (e.g. sustainable landscape; profitability).

In order to deal with the interaction between criteria, non-additive integrals such as the Choquet integral and the Sugeno integral can be used (Bottero *et al.*, 2015). Moreover, it is recommended not to exceed ten or so criteria in an MCDA method so that the relative importance of the criteria has a considerable influence on the results (Liquete *et al.*, 2016).

Sensitivity analysis is an essential step in the analysis to validate the results and must be applied both to the uncertainties in the input data and to any variations in the weights assigned (Cortinovis *et al.*, 2021; Haag *et al.*, 2019; Liu *et al.*, 2014). This analysis can be conducted in several ways. One method is to hold all variables (weights) constant in the model, except for the one being tested, and vary it over its likely range of values (Alves *et al.*, 2018; Liquete *et al.*, 2016; Ustaoglu & Aydınoglu, 2020). In complex models, the Monte Carlo method is frequently used to perform sensitivity analysis, changing the weight values, and evaluating the variation of scores in the ranking of measures (Alves *et al.*, 2018). Another simple and highly effective method is to iteratively combine the extreme weights (maximum and minimum) proposed by the stakeholders and, knowing that the weights have a linear relationship with the final scores of each alternative, analyse what would be the final performance of each alternative under the new combination of weights (Liquete *et al.*, 2016). Other methods can also be used, such as excluding a criterion from the model and renormalizing the weights, or reclassifying the criteria without weighting (Haag *et al.*, 2019). A robust model will have variations in its results during these different tests and it is recommended to perform as many as possible to ensure the reliability of the analysis (Haag *et al.*, 2019; R. Liu *et al.*, 2014). Some methods (e.g., PROMETHEE, MACBETH) offer a sensitivity analysis integrated in their tools. A final validation step can be done by submitting a list of real or fictitious options for stakeholders to rank intuitively according to their preferences. The results of this classification are compared with the results obtained with the multicriteria model. If the classification is similar, the model is validated. If not, participants are asked to explain their ranking so that the model can be calibrated if necessary.

1.3 A critical review of MCDA practices in planning of urban green spaces and NBS

Keywords: MCDA, NBS, green spaces, planning support

Authors: Morgane Bousquet[a], Martijn Kuller[b], Sandrine Lacroix[c], Peter A. Vanrolleghem[d]

a) modelEAU, Université Laval, Département de génie civil et génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada, morgane.bousquet.1@ulaval.ca (corresponding author)

b) Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands, m.kuller@uu.nl

c) Department of Civil, Geological, and Mining Engineering, Polytechnique Montreal, Montreal, Quebec, H3C 3A7, Canada, sandrine.lacroix@polymtl.ca

d) modelEAU, Université Laval, Département de génie civil et de génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada, peter.vanrolleghem@gci.ulaval.ca

Highlights:

- MCDA methods help to consider all NBS benefits and evaluate planning alternatives
- Environmental and social criteria are more represented than economic and technical ones
- Stakeholders are rarely involved throughout the entire MCDA process
- MCDA tools for NBS planning are rarely accessible and adaptable to various contexts
- MCDA processes are mainly conducted in countries of the Global North

1.3.0 Résumé (français)

Les espaces verts et les solutions fondées sur la nature (SFN) sont de plus en plus pris en compte dans les politiques d'aménagement du territoire pour répondre aux nombreux défis liés au développement durable. Les multiples avantages apportés par les SFN rendent l'utilisation de l'aide multicritère à la décision (AMCD) essentielle pour optimiser leur planification et leur implantation. L'AMCD offre un catalogue de méthodes permettant de structurer des problèmes à objectifs multiples et d'accompagner les décideurs dans le choix de la solution optimale. Cependant, la planification des SFN est une discipline récente et la recherche est encore en cours pour rendre cette pratique plus courante.

Nous avons effectué une revue critique de la littérature sur les outils et pratiques AMCD-SFN. Nous avons effectué notre recherche documentaire en suivant la méthode PRISMA sur la base de données Web of Science et nous avons sélectionné 124 articles sur le sujet entre 2000 et 2022.

Nous présentons un état des lieux des approches AMCD pour la planification des SFN et des espaces verts en examinant où ces pratiques sont appliquées, pourquoi et comment ce processus est mené, et qui y est impliqué. Nous avons constaté que les études sont généralement menées dans l'hémisphère nord, sur une étude de cas unique avec l'aide d'experts engagés dans la phase de pondération des critères et à l'aide d'outils SIG-AMCD qui intègrent souvent une méthode de pondération directe ou la méthode AHP.

1.3.1 Abstract

Green spaces and Nature-Based Solutions (NBS) are increasingly considered by land-use planning policies to respond to the multiple challenges related to sustainable development. The multiple benefits brought by NBS make the use of multicriteria decision analysis (MCDA) essential to optimally balance their use. MCDA offers a catalog of methods allowing to structure problems with multiple objectives and to help adopting the optimal solution. However, NBS planning is a recent discipline and research is still ongoing to make this practice more common.

We carried out a critical literature review on MCDA-NBS tools and practices. We conducted our literature research following the PRISMA method on the Web of Science database and we selected 124 papers on the subject between 2000 and 2022.

We present a state-of-the-art of MCDA approaches for NBS and green space planning by looking where these practices are applied, why and how this process is conducted, and who is involved in it. We found that studies are usually conducted in the global North on a single case study with the help of experts involved in the criteria weighting phase and the help of GIS-MCDA tools often integrating a direct ranking method or the AHP method.

1.3.2 Introduction

1.3.2.1 Background

Green spaces play an important role in urban climate adaptation. Nature-based solutions (NBS) are explicitly designed to optimise climate adaptation potential and are increasingly considered as an innovative and more sustainable alternative to current urban stormwater management by gray infrastructures (Hamouz *et al.*, 2020; Steis *et al.*, 2020). They are engineered green systems such as rain gardens, green roofs and walls, ponds, swales, constructed wetlands and urban forests which allow stormwater control at source by enhancing functions of infiltration, evapotranspiration, retention, conveyance, and water quality enhancement (Kuller *et al.*, 2017). Some of the primary benefits include surface water quality protection, flood reduction, resource recovery (e.g., water reuse).

Green spaces bring many co-benefits (Dagenais *et al.*, 2017; Skrydstrup *et al.*, 2020) such as improving aesthetics, reducing the urban heat islands effect, and increasing biodiversity. The multifunctional potential of NBS highlights the need for careful spatial planning, considering the three pillars of sustainable development: environmental, social, and economic sustainability (Brasil *et al.*, 2021; Dorst *et al.*, 2019; Goodspeed *et al.*, 2022; Monteiro *et al.*, 2020). Most studies focus on environmental aspects (e.g., biodiversity, soil recovery) and stormwater management (Meerow, 2020; Monteiro *et al.*, 2020), and only consider a single benefit such as water quantity control (Meerow, 2019; Meerow & Newell, 2017). Moreover, opportunistic NBS planning leads to unintended results that do not maximize the potential of the multiple benefits of NBS (Kuller, Farrelly, *et al.*, 2018; Li *et al.*, 2020; Meerow, 2020). Multicriteria decision analysis (MCDA) is well suited to counter this issue by evaluating multiple objectives simultaneously, involving multiple stakeholders and preferences, as well as technical information.

The United Nations conference on Sustainable Development in Rio de Janeiro (Brazil) on 20-22 June 2013 sparked global interest in NBS and led to numerous studies about strategic urban planning, attempting to frame this new practice (Hanna & Comín, 2021; Meerow, 2020). Nature-Based Solutions in urban climate adaptation plans are also referred to as Green Infrastructure (GI) or Blue-Green Infrastructure (BGI) planning, Low Impact Development (LID), Best Management Practices (BMP), Sustainable Urban Drainage Systems (SUDS), Water Sensitive Urban Drainage (WSUD), or Sponge City, depending on the study location (Fletcher *et al.*, 2015). The term Ecosystem Services (ES) is also widely used in this field and refers more broadly to environmental and socio-economic benefits that any type of green space (e.g., natural forests, wetlands, grassland or engineered systems like the ones mentioned above) can provide to the urban environment (Billaud *et al.*, 2020; Dagenais *et al.*, 2017). In this paper, the term NBS will be used, as it is the term used by the United Nations since the Convention on Biological Diversity COP15 in Montreal in 2022. However, we will conduct our research by considering both purposefully designed (e.g., NBS, GI, BGI) and other (covered by the concept of ES) green urban spaces to address the broad palette of these spaces.

1.3.2.2 MCDA methods and tools

Multicriteria decision analysis (MCDA) is a systematic approach to incorporate multiple objectives and combine subjective preferences with objective information in order to reach a rational decision. MCDA can help decision-makers analyze a complex decision problem that involves different stakeholders. It offers a rich collection of methodologies for structuring planning problems with conflicting objectives, allowing the design, evaluation, and prioritization of decision alternatives from a multicriteria model representing stakeholders' preferences (Ferretti & Montibeller, 2016; Marttunen *et al.*, 2017). Obtaining subjective preferences on a problematic situation, including objective weightings, is one of the main parts of MCDA (Aubert *et al.*, 2020). A participatory (Schein, 2017) and constructivist (Landry, 1995) approach involving stakeholders is recommended by the scientific community (Belton & Pictet, 1997), because it is expected to lead to the implementation of 80% of the decisions (Nutt, 1999). By "participatory", we refer to a collaborative process in which relevant stakeholders are involved in all steps of decision-making from objective definition to alternative development and preference elicitation. By "constructivist", we refer to a process that consists of several steps that build towards a result.

Table 2 - MCDA categories by the type of model (value measurement, aspiration, outranking) based on Belton & Stewart (2002).

Type of model	Characteristics	Method examples
Value measurement models	Numerical preference scores are synthesized to perform aggregation into preference models.	Simple Multi-Attribute Rating Technique (SMART), Swing, Technique for order preferences by similarity to ideal solutions (TOPSIS), Ordered Weighted Averaging (OWA)
Aspiration models	Criterion weights are obtained from pairwise comparisons between criteria, using an eigenvector technique. Weights are aggregated to obtain the global relative weights of the alternatives describing their global preference compared to the other alternatives.	Analytic Hierarchy Process (AHP)
Outranking models	Preferences are obtained by asking whether the advantages of one alternative over another are sufficient to overcome its disadvantages. The degree of dominance is calculated between the alternatives, describing whether an alternative is at least as good as another.	Preference Ranking Organization Method for Enrichment and Evaluation (PROMETHEE), Potentially All Pairwise Rankings of all possible alternatives (PAPRIKA), Elimination And Choice Translating Reality (ELECTRE)

Belton & Stewart (2002) classified MCDA methods into three categories based on the type of model used (Table 2). Some methods are at the intersection of these models (e.g., MACBETH method) (Lavoie *et al.*, 2016). On the other hand, the work of Cinelli *et al.* (2022) classified the MCDA methods looking at their measurement scale types for criteria: the ordinal scale (qualitative, only considering the order of performance), the cardinal (qualitative, considering the difference between performances) and the relative scale (comparing alternatives to express preference intensity). Therefore, the value measurement model methods in the work of Belton & Stewart (2002) use an ordinal scale and most of the aspiration model and outranking model methods use a cardinal scale. The MACBETH method for example uses a relative scale (Cinelli et al., 2022).

1.3.2.3 Existing literature reviews on MCDA for green space planning

The content of this section is based on 28 literature review papers we found during our research related to MCDA for NBS and green space planning (see section 2.1). We summarise the main results of this analysis here.

MCDA has been a relevant tool applied in a wide range of fields in the past years, proving its value, particularly in environmental projects where multiple stakeholders and trade-offs are at play between the economic, environmental, and social spheres (Kiker *et al.*, 2005).

Since 2000, five reviews focused on application of MCDA for forest management planning (FMP) approaches, either on the integration of ES (Blattert *et al.*, 2017; Uhde *et al.*, 2015), of biodiversity objectives (Ezquerro *et al.*, 2016), of multiple uses (Baskent, 2018) or on forest economics of silviculture (Campos *et al.*, 2017). Facing complex challenges, agricultural systems have also become a topic of interest for MCDA, either in agriculture models classification (Therond *et al.*, 2017), in model-based scenarios for biodiversity changes (Chopin *et al.*, 2019) or in sustainability assessment methods (Soulé *et al.*, 2021). Previous reviews also focused on MCDA for ecosystem services, either on current research performed in cities (Haase, Larondelle, *et al.*, 2014), on emerging areas of interest and related key themes (Torres *et al.*, 2021), or on a specific service like decision support tools for urban heat island mitigation (Qureshi & Rachid, 2021) or flood risk management (Membele *et al.*, 2022; Perosa *et al.*, 2022). Trade-offs in ecosystem services also received attention in a review by Deng *et al.* (2016) where analysis tools and approaches across spatial and temporal scale were studied, and in a review by Smyth & Drake (2022) where trade-offs within freshwater and marine ecosystems were classified. Chatzinikolaou *et al.* (2018) proposed a review of valuation methods and tools to assess the diversity of ES values in rural landscape management through the lens of MCDA. Natural resources management has been addressed in recent reviews, for example by Cook *et al.* (2019) for geothermal power projects or by Allain *et al.* (2017) for landscape management methods covering land-use planning, ecosystem conservation, water management and forest management. Another predominant field of application of MCDA approaches is spatial modelling in land use planning. Yang *et al.* (2007) reviewed GIS-MCDA-based evaluations models for land-use evaluation. Legesse Gebre *et al.* (2021) studied MCDA methods for land allocation problems covering papers from agricultural, forest, ecotourism, conservation, and protected area management. Gomes *et al.* (2021) reviewed land-use changes and their impact for ES provisioning. Some reviews have a broader scope, for example, Galychyn *et al.* (2020) who reviewed scientific literature on urban metabolism considering flows of materials, energy, resources, food, and people in cities, whereas some other studies focused on a specific context review, e.g., Escobar-Camacho *et al.* (2021) who studied the threats of the marine and terrestrial ecosystems of the Galapagos.

On stormwater management infrastructures specifically, Islam *et al.* (2021) focused on the review of LID approaches and their optimization, performance, and resilience to climate change. Kuller *et al.* (2017) reviewed existing Planning Support Systems (PSS) for WSUD using GIS and MCDA, providing a comprehensive view of the purposes of those tools and their relevance. More recently, Wu *et al.* (2020) reviewed sustainable stormwater management (SSWM) concepts in the Global North comparing eight existing decision support tools. Jelokhani-Niaraki *et al.* (2021) worked on reviewing and categorizing spatial multicriteria evaluation (SME), also called GIS-based Multicriteria Evaluation (GME) tools and approaches, operated in a collaborative context, according to either a parallel or sequential method, including all fields not necessarily for green spaces or NBS.

Although MCDA in NBS planning is increasingly recognized, no study was found that aimed to comprehensively review MCDA for NBS planning in terms of (i) method, (ii) involvement of stakeholders, (iii) criteria and (iv) tools used in the studies. NBS and green space planning is a spatial problem and the use of Geographic Informatic Systems (GIS) such as ArcGIS (Esri) or QGIS can assist the decision process. By coupling MCDA and GIS, we can transform and combine geographical data and value judgements expressed by the different criteria. GIS-MCDA applications are increasingly used in NBS and green space planning studies and are thus given special attention to support decision makers and planners in their use.

1.3.2.4 Aims and objectives

NBS and green space planning remains underemphasized in planning policies (Hanna & Comín, 2021; Langemeyer *et al.*, 2016). Decision-making processes around policies and governance for NBS and green space planning leave room for improvement (Langemeyer *et al.*, 2016). More specifically, decision-makers have expressed a need for knowledge, methods, and tools on planning and design of NBS (Ferreira *et al.*, 2021; Mubeen *et al.*, 2021; Voskamp *et al.*, 2021). They lack appropriate guidelines (Voskamp *et al.*, 2021), as well as training and expertise on strategic urban NBS planning, resulting in the adoption of sub-optimal approaches (Albert *et al.*, 2021; Voskamp *et al.*, 2021). This systematic literature review thus aims at providing a comprehensive picture of MCDA practices for NBS and green space planning. The objectives are to analyze:

1. <u>Where</u> MCDA is applied, by looking at case study location and the number of case studies conducted.

2. Why this process is conducted, by looking at the problem definition, the criteria selected, and the results obtained.
3. Who is involved in the process, by looking at the stakeholder type and engagement.
4. How this process is conducted, by looking at the MCDA methods and tools.

This work aims to provide knowledge on MCDA practices for NBS and green space planning and to give decision makers tools and recommendations for their applications. The review will also highlight gaps and limitations in MCDA practices and will provide leads for future research.
First, the research approach is presented, followed by a presentation of the results, a discussion regarding the study's objectives and a section with recommendations for future work. In this paper, an NBS-MCDA "tool" refers to any software, model, module, application, or method providing assistance with MCDA-based planning of NBS or green spaces.

1.3.3 Research approach

1.3.3.1 Literature selection

We conducted this literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method developed by Moher *et al.* (2009). This method consists of four main steps (Moher et al., 2009): i) defining and specifying the search key words and the parameters of the analysis, ii) reading the abstract to select articles to be considered for the analysis and using inclusion and exclusion criteria, iii) reading articles to refine the selection and extracting relevant information using predefined parameters and iv) synthesizing results for analysis. Using Web of Science, we conducted our literature search on the 1st of September 2022 and searched for papers published between 2000 and 2022.

We considered any type of urban green space and infrastructure, whether intentionally created to provide ecosystem services (e.g., LID, WSUD, NBS) or not (e.g., parks, forests, natural wetlands), using MCDA as the strategic planning tool. In order to cover this broad palette of green urban spaces, we included terminologies related to constructed green spaces with the purpose of climate adaptation (i.e. NBS, GI, WSUD, SUDS, LID, BGI) and other green spaces (covered by the search term ES). As supplementary material we provided the research iterations, the final research formula, the 474 returned papers, the exclusion criteria for abstract screening and the exclusion rules for full-text screening. We analyzed literature reviews (28) separately (see section 1.3.2.3). The final number of articles included in this review is 124.

We performed an analysis of the 124 papers using a spreadsheet, following the framework on ecosystem service assessments and land-use planning developed by Langemeyer *et al.* (2016). We adopted this framework because it was specifically developed for MCDA approaches in the green space planning process instead of the framework of Belton & Stewart (2002) which focuses on the general MCDA process. The adopted framework specifies six key elements (problem definition, stakeholder analysis and engagement, alternative definition, criteria definition, criteria weighting and, alternative prioritization), each explained below, in section 2.2. We also collected statistics on year of publication, and geographical location of the authors and the case study.

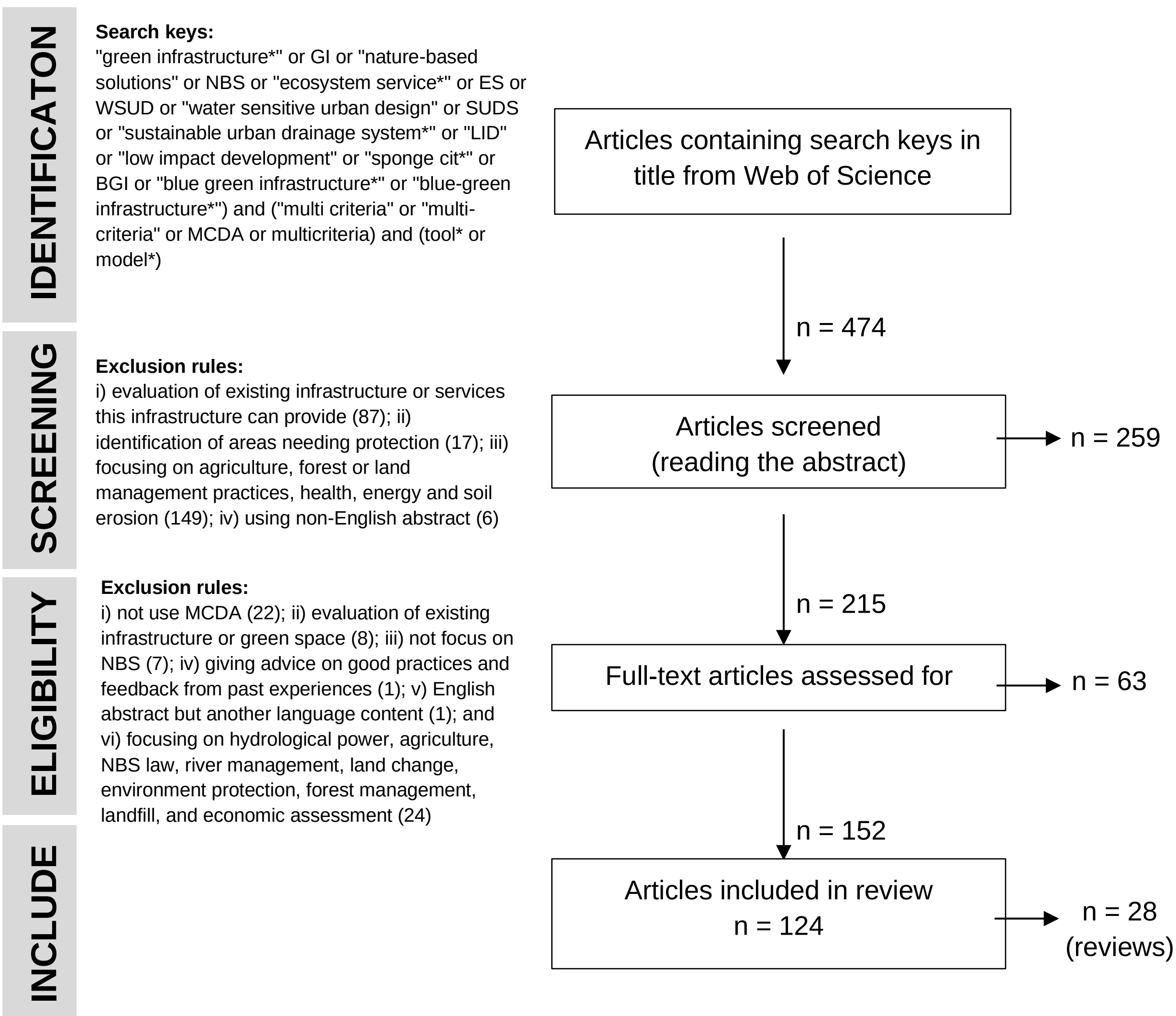


Figure 1 - Literature review method flow diagram, following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis; Moher et al. (2009))

1.3.3.2 Analysis

The framework by Langemeyer *et al.* (2016) helped to select the relevant data for the analysis and to classify them according to the six key elements (problem definition, stakeholder analysis and engagement, alternatives definition, criteria definition, criteria weighting and, alternative prioritization). We have slightly modified this guide by further developing the “stakeholder analysis and engagement” element, combining the “criteria weighting” and “alternative prioritization” elements, and adding a “results” analysis element. For a more in-depth analysis, we used the work of Sarabi *et al.*, (2019) and Skrydstrup *et al.* (2020), which present an analysis of relevant stakeholders to consider for green space planning. Skrydstrup *et al.* (2020) also present an analysis of relevant criteria to consider for NBS and green space planning.

The first element, the problem definition, describes the scope (assessment, investment, selection, prioritization, etc.) and the scale. We classified scale into national (e.g., country), region, basin, local (e.g., city, municipality, metropolitan area) and site (e.g., lot).

The second element, stakeholder analysis and engagement, refers to the type of participation that stakeholders make during the process (workshop, interview, survey, etc.). In this element we also specified how criteria were selected: a) defined by the research team, b) elicited by expert(s) or c) elicited by stakeholders. We organized the processes of stakeholder engagement based on the moments of involvement: problem definition, alternative definition, criteria definition, criteria weighting, alternative prioritization, based on the elements provided in Langemeyer *et al.* (2016).

The third element, alternatives definition, specifies whether a paper describes a) an evaluation of alternative policies, infrastructures, or management practices or, b) a selection of geographical sites (i.e. GIS application).

The fourth element, criteria definition, provides an analysis on the selected criteria in the studies. We used the framework presented by Skrydstrup *et al.* (2020) (figure 5), which classifies criteria following the United Nations' sustainability aspects (environmental, economic, social, and technical) similar to most papers evaluated in our literature review. While criteria classification is often based on the type of ecosystem services they provide (regulating, provisioning, cultural services), we opted to go for the abovementioned framework for its understandability for lay people and the application to the reviewed literature. Besides the class of criteria, we also assessed the number of criteria considered in the studies.

The fifth element, criteria weighting, refers to the MCDA process, and includes both the aggregation rules used to calculate the performance of the alternatives to reach the objectives and the MCDA methods applied for preference elicitation, i.e. regarding the relative importance of the objectives. Those aggregation rules either come directly from the MCDA method (e.g., rank and prioritize one alternative with a pair-wise comparison using the AHP method) or using aggregation methods, especially in the case of GIS-MCDA. Langemeyer *et al.* (2016) identified two different types of aggregation that are the most used in studies: the linear or non-linear aggregation (i.e. the sum of all normalized values) and the ideal point approaches (i.e. the sum of normalized differences between the actual and an ideal performance on the criterion) (Langemeyer *et al.*, 2016). Regarding MCDA methods, we used the three categories and the accompanying methods by Belton & Stewart (2002), provided in Section 1.2. We furthermore looked at the method used to create value functions, used to compare criteria on a common scale.

We have added a sixth element that analyses the type of results obtained from the studies (e.g., scores, maps).

We recorded the year of publication and compared the geographical location of the authors and the geographical location of the case study. We did not only consider the geographical location of the first author but all geographical locations represented by the authors, as there was a notable diversity in their location. We counted a location only once when an article was authored by several researchers from that location. We considered decision-aid tools, selecting MCDA tools specifically developed to assist the application of MCDA methods and other tools which integrate MCDA to generate alternatives (e.g., GIS tool with MCDA plug-in).

1.3.4 Results

1.3.4.1 Date

While our search window spanned from 2000 to 2022, we found no papers dating before 2010. The number of publications increased recently, with 80% of papers published between 2016 and 2022. It shows that MCDA for NBS planning is a recent topic of interest to the scientific community (Figure 2).

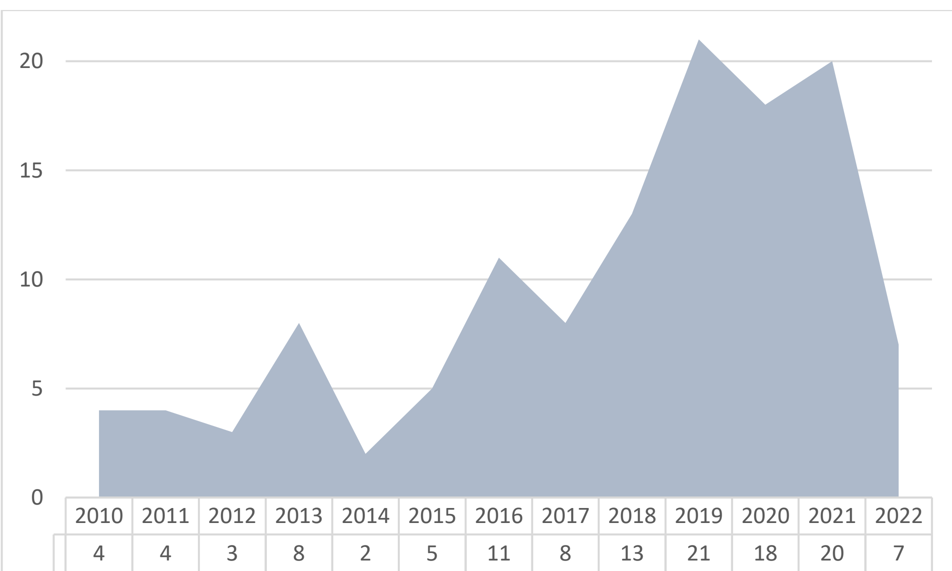


Figure 2 - Number of papers by year of publication

1.3.4.2 Location

We evaluated the location of the authors and case studies separately, as we found no clear relation between them. For example, almost half (48%) of the studies are conducted by authors in Europe but only 30% of the case studies are in Europe (Figure 3). Moreover, most papers (84%) are based on a single case study, with only 16 papers considering multiple case studies.

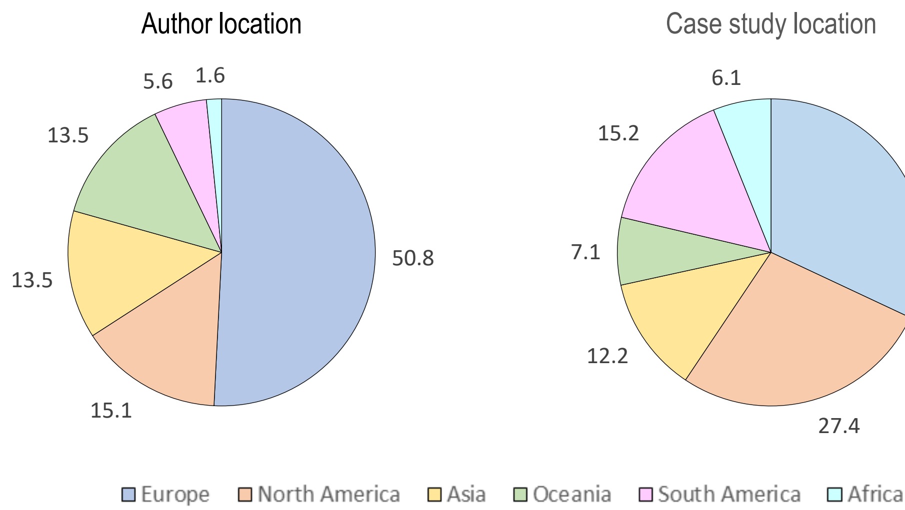


Figure 3 - Statistics regarding all authors' location and case study location in the reviewed papers (% of papers)

The research is mainly conducted in Europe, followed by North-America, Oceania, Asia, South-America and Africa. Most case studies were conducted in Europe, followed by North-America, South-America, Asia, Africa and Oceania. Regarding countries, the USA itself counts 49 case studies representing 25%, followed by Italy (9%), Spain (8%) and China (6%).

1.3.4.3 Process

Statistics on the reviewed papers with respect to the six key elements of the Langemeyer *et al.* (2016) framework (section 2.2) are summarized in Table 3Table 4.

Table 3 - Statistics (number and % of reviewed papers) for the first, second and third key elements of the Langemeyer et al. (2016) framework (problem definition, stakeholder analysis and engagement, alternative definition)

i) Problem definition		
Scope	Number	%
ES	*64*	*52*
GI	*19*	*15*
LID	*14*	*11*

NBS	*8*	*6*
SUDS	*4*	*3*
WSUD	*5*	*4*
Other	*10*	*8*
Scale	Number	%
Global	*9*	*7*
Region	*22*	*18*
Basin	*22*	*18*
Local	*50*	*40*
Site	*17*	*14*
ii) Stakeholder analysis and engagement		
Type		
Research team	*99*	*80*
Expert(s)	*12*	*10*
Stakeholders (group)	*22*	*18*
No information	*7*	*6*
Involvement phase	Number	%
Problem definition	*15*	*12*
Alternative definition	*23*	*19*
Criteria definition	*25*	*20*
Criteria weighting	*85*	*69*
No involvement	*36*	*29*
Involvement type	Number	%
Survey	*26*	*21*
Interview	*19*	*15*
Workshop	*40*	*32*
Individual exercise	*16*	*13*
None/no information	*23*	*19*
iii) Alternative definition		
Alternative type	Number	%
Selection of suitable geographical sites	*63*	*51*
Evaluation of alternative policies, plans or management practices	*69*	*49*

Note 1 - ES: Ecosystem Services; GI: Green Infrastructures; LID: Low Impact Development; NBS: Nature-Based Solutions; SUDS: Sustainable Urban Drainage Systems; WSUD: Water Sensitive Urban Design

We found that 52 % of the papers use the term ES, ecosystem services. The terms GI, LID, NBS, SUDS, SUDS are less present and articles do not usually specify the technologies considered (e.g., green roof, raingarden). There is an equal number of papers evaluating alternative policies, plans or management practices for NBS and green space implementation (49%) on the one hand and selecting geographical sites suitable for NBS and green space implementation on the other (51%).

The MCDA process is often performed by the research team (80%) and rarely involved stakeholders (18%) who are mainly solicited during the weighting phase. Moreover, when a group of stakeholders takes part in the MCDA process, their expertise is rarely specified. The research team involved was often mentioned as expert stakeholder, but other potential stakeholders (Skrydstrup *et al.*, 2020, figure 4) are usually not mentioned or described in sufficient detail.

Table 4 - Statistics (number and % of reviewed papers) for the fourth, fifth and sixth key elements of the Langemeyer et al. (2016) framework (criteria definition, criteria weighting, results)

iv) Criteria definition			
Number of criteria		Number	%
x ≤ 10		*74*	*60*
10 < x ≤ 20		*29*	*29*
20 < x ≤ 30		*10*	*8*
Above 30		*4*	*3*
No information		*2*	*2*
Criteria type		Number	%
SOC.	*Aesthetics*	*35*	*28*
	Recreation	*42*	*33*
	Mobility	*13*	*10*
	Health	*60*	*48*
	Safety and security	*58*	*46*
	Connectedness	*22*	*18*
	Education	*22*	*18*
	Occupation	*32*	*26*
ENV.	*Water quality*	*49*	*39*
	Resources	*62*	*26*
	Nature	*80*	*64*
ECO.	*Business development*	*31*	*25*
	Low cost	*42*	*34*

TEC.	*Integration with existing infrastructures*	*22*	*18*
	Flexibility	*11*	*9*
	Simple & transparent	*16*	*13*
	Supply safety	*34*	*27*
v) Criteria weighting			
Aggregation method		Number	%
Linear aggregation		*64*	*52*
AHP		*44*	*35*
PWC		*51*	*41*
Ideal Point		*9*	*7*
MCDA method		Number	%
1st	*Direct ranking*	*57*	*46*
	TOPSIS	*11*	*9*
	MAVT	*4*	*3*
	SMART	*3*	*2*
	SWING	*1*	*1*
2nd	*AHP*	*44*	*35*
3rd	*PROMETHEE*	*4*	*3*
	ELECTRE	*2*	*2*
Other	*NAIADE*	*5*	*4*
	DELPHI	*3*	*2*
	VIKOR	*2*	*2*
	MACBETH	*1*	*1*
Value function scale		Number	%
$0 < x \leq 1$		*41*	*33*
$1 < x \leq 9$		*11*	*9*
$1 < x \leq 5$		*10*	*8*
$1 < x \leq 100$		*9*	*7*
$0 < x \leq 5$		*5*	*4*
$0 < x \leq 10$		*2*	*2*
$0 < x \leq 1000$		*1*	*1*
No information		*45*	*36*
vi) Results			

Output	Number	%
Numerical score	*124*	*100*
Maps	*73*	*59*
Graphs & Figures	*66*	*53*
Result	Number	%
Ranking of alternative	*81*	*65*
Master Plan	*29*	*23*
Equitable alternatives	*16*	*13*

Note 2 - AHP: Analytic Hierarchy Process; PWC: PairWise Comparison; TOPSIS: Technique for Order Preferences by Similarity to Ideal Solutions; MAVT: Multi-Atribute Value Theory; PROMETHEE: Preference Ranking Organization Method for Enrichment and Evaluation; EL

Regarding the criteria elicitation process, 60% of the studies include a maximum of 10 criteria and rarely more than 20 criteria (83%). The criteria considered most often cover social aspects (90%) and environmental aspects (84%). During the weighting phase of the MCDA process, linear aggregation rules such as the Simple Additive Weighting (SAW) method, are used in half of the studies. We also found that 35% of the studies follow the AHP method. The 1st MCDA method category by Belton & Stewart (2002) is predominant and concerns 65% of the studies, with almost half of the studies not relying on a specific method and using a direct ranking process. Notably, some case studies used more than one method. When applying MCDA methods, an important decision concerns the value function, i.e. the conversion of the criteria's attribute data scales into a common and numerical scale. We found various types of value functions being used, and most frequently a scale between 0 and 1, which appears in 33% of the reviewed papers. Finally, for the prioritization of alternatives, linear aggregation is used in 56% of the case studies. However, this information is not often given.

1.3.4.4 Tools

GIS tools are used in 43% of the case studies, but references on the tools are usually lacking or the tools are not available in open source (13% not available). Tools are generally developed for specific cases, using a specific MCDA method and the model based on the selected MCDA method.

MCDA tools developed to facilitate MCDA method application are only mentioned in 13% of the studies. 26% of the studies do not use any tool or provide no mention of a tool (Table 5).

Table 5 - Statistics on tools used for MCDA application

Tools		Number	%
MCDA	*Logical/Super decision*	*3*	*2*
	PROMETHEE II	*2*	*2*

	NAIADE	*2*	*2*
	HUGIN	*1*	*1*
	D-sigh	*1*	*1*
	PEST	*1*	*1*
	Vector MCDA	*1*	*1*
	Optamos	*1*	*1*
	DPSIR	*1*	*1*
Spatial	*GIS-based*	*53*	*43*
	LIAM/LISAM/SUSAM (GIS plug-in)	*5*	*4*
	GIPS (GIS plug-in)	*3*	*2*
	ILWIS (GIS plug-in)	*3*	*2*
	IDRISI (GIS plug-in)	*2*	*2*
	GISM (GIS plug-in)	*1*	*1*
	SSANTO (GIS plug-in)	*1*	*1*
	ARIES (GIS plug-in)	*1*	*1*
	UrbanBEATS	*2*	*2*
Other	*InVest*	*8*	*6*
	No tool/No information	*32*	*26*

1.3.5 Discussion

1.3.5.1 Case study objectives

MCDA methods are often used for landscape management integrating environmental, economic and social issues (Allain *et al.*, 2017). The MCDA process for NBS and green space planning is applied to rank alternative policies, plans or management practices for NBS and green space implementation or to select geographical sites suitable for NBS and green space implementation. It aims to combine objectives that are measured using different types of information, both qualitative as well as quantitative data. This facilitates the use of social criteria (90% of papers) which are often expressed qualitatively (e.g., aesthetics). Indeed, the literature review of Haase *et al.* (2014) on ecosystem services assessment found that studies often focused on biophysical aspects and undervalued social aspects because they are subjective and difficult to quantify. This trend is also reflected in tools for NBS and green space planning which often integrate biophysical factors only (Kuller *et al.*, 2017). However, technical and economic data are less present in the studies, possibly reflecting a lack of knowledge in the design and the cost of NBS. Indeed, research on NBS is recent (no paper found before 2010) but other studies may have been carried out under a different name, without appearing in our research.

Most studies (60%) are limited to 10 criteria which is consistent with the recommendations of the field of multi-criteria decision science (Liquete *et al.*, 2016) as too many criteria would reduce their individual impact on the multi-criteria model and lead to less obvious results.

1.3.5.2 Case study location

Almost all papers included in this literature review (120) are built around case studies. However, the adaptation of the MCDA methods to a different context (cultural, geographical, climate, politics) has not been really explored yet as most of the papers (104) only evaluate them in single case studies which means that the research remains context-specific and not global.

The studies are mainly conducted in the Global North with 57% of them made in Europe and North-America. The other continents are under-represented, which may reflect a lack of resources and capacity available for research and implementation in Africa and South America. Indeed, Kuller *et al.* (2022) found that studies for NBS implementation in the Global South are hampered by the lack of relevant institutional capacity and stakeholder involvement in planning processes, available data and government policies. These results can be biased by the fact NBS and associated terms are European and North-American and the research focused on articles in English only. Furthermore, there could be a general lack of knowledge and research about NBS and the potential of MCDA to support their strategic planning. Nevertheless, NBS and green spaces in general are a sustainable alternative to traditional planning that have the potential to mitigate the impacts of climate change and environmental degradation due to urbanization and are worth to be studied globally.

Moreover, the author and study case locations are not always linked; which leads to situations where studies from the Global North are sometimes conducted in the Global South (Africa, South-America, and parts of Asia), providing a possibly incomplete perspective. Indeed, local actors have a better knowledge of the issues, policies and culture of their territory, which probably leads to more appropriate results. Working with local partners when a research group is based on a case study abroad could lead to a better acceptance and application of the results. There may also be more interest in using NBS and MCDA than can be reported from the peer-reviewed literature consulted in this review. Indeed, much of the work may remain hidden in design reports and technical documentation.

1.3.5.3 Stakeholders

MCDA is intended to be a participative process. However, 29% of the reviewed studies did not integrate stakeholders at all. This is still more common than in the literature review of Chatzinikolaou *et al.* (2018) which concluded that 60% of the studies for ecosystem services assessment do not involve stakeholders. Moreover, stakeholders are often only solicited during the criteria weighting phase (69% of papers) and very little during the other stages which reflects a lack of knowledge and experience in conducting a MCDA process. Indeed, Jelokhani-Niaraki *et al.* (2021) found that the participatory steps are often limited to the determination of weights in 46% of the case studies. It would be relevant to integrate an expert in MCDA in order to be able to lead the MCDA process and to guide the stakeholders through each step.

The value of the MCDA participatory process is that it brings together stakeholders with different fields of expertise. In the papers, this aspect is never developed, and the stakeholders presented usually have an academic background, posing fundamental problems regarding representativeness. Most of studies involve 1 to 5 experts who carry out the criteria weighting exercises and sometimes help in the choice of criteria. Allain *et al.* (2017) also found in their literature review that the process of stakeholder selection is not often formally addressed. Furthermore, 80% of the studies use the expertise of the research team to carry out the MCDA process partially or fully. It is important to bring together stakeholders with different expertise in order to bring knowledge on all aspects of sustainable development through the implementation of NBS and obtain a relevant multi-criteria model. This is also reflected in the way stakeholder opinion is collected with only 24% of the studies organizing workshop sessions, with 44% of the studies not even describing the process and the remaining studies using surveys, interviews, or individual exercises. This contradicts the intention for MCDA to be deliberate processes that lead to collective as opposed to individual decision-making. Allain *et al.* (2017) showed that workshops are the best way to interact with stakeholders when doing a participative and collaborative study. However, the literature review is essentially based on scientific publications, certainly from the academic field, and remains limited to that.

1.3.5.4 MCDA methods and tools

A direct ranking method, following a Simple Additive Weighting (SAW) aggregation rule is used in 46% of the papers which is confirmed by the research of Allain *et al.* (2017). The Analytic Hierarchy Process (AHP) combined with pairwise comparison is the second most used MCDA method (35% of the papers) even if it is highly criticized by the MCDA community for its important bias risks (Belton & Pictet, 1997). Unlike the MACBETH method or the PROMETHEE method, the AHP method does not come with a tool to facilitate its application and the consistency of judgements. In addition, this method offers little transparency in the justification of the final results, which may confuse stakeholders. Other advanced methods (3rd category of Belton & Stewart (2002)) are rarely used, which may reflect a lack of knowledge and expertise in the application and selection of MCDA methods. As mentioned in section 4.3, it would be relevant to include an expert in MCDA in the research team for the choice of the method and its application.

MCDA tools are not (yet) commonly used for NBS and green space planning (13% of the papers reviewed) and GIS-MCDA tools are common (43% of the papers). This is consistent with Ezquerro *et al.* (2016) who found that 50% of the studies explicitly include GIS data or software. The main issue is that there is not one particular GIS-MCDA tool that gets preference in the field which leads to the development of tools that are built for a particular study context and are not developed in view of its transfer to another context. Moreover, we found that 56% of papers rely on linear aggregation which is the most often used decision rule for GIS-MCDA tools (Jelokhani-Niaraki, 2021) for its simplicity in collaborative spatial decision making (Malczewski, 2006). The MCDA for NBS and green space planning research is still in its infancy with a predominance of water management and spatial tools which is in line with the literature review of Lerer *et al.* (2015) and do not represent well all the social, environmental, technical and economic aspects of a situation.

1.3.5.2 Recommendations and future work

It would be interesting to study in more detail the impact of the case study context on the MCDA process for the implementation of NBS or green spaces by applying it to several case studies, in different geographical locations and exposed to different issues. There is a need to develop more studies outside of Europe and North-America to gain insight in the context of the Global South and the good practices to adopt in that context.

The technical knowledge of NBS and the return on investment of these new infrastructures seems to be missing in the literature. More research on the subject could help in the development of new indicators or understand why they are underrepresented in studies.

In order to better represent the different visions of the spatial planning issue for NBS and green spaces, it would be relevant to conduct case studies involving several types of stakeholders in the MCDA process through participatory workshops (Belton & Pictet, 1997; Nutt, 1999; Skrydstrup *et al.*, 2020). Indeed, none of the studies mention the presence of municipal or citizen representatives nor do they include private sector professionals. Furthermore, for a good application of the MCDA process, it is recommended to involve stakeholders at each step, leading to better ownership of the results and transferability of the method in the future (Nutt, 1999).

Advanced methods (i.e. 3rd category and other as MACBETH) have been rarely explored in the studies, although they have shown good results in other spatial planning studies (Lavoie *et al.*, 2016). The impact of the MCDA method itself (SMART, AHP, MACBETH, PROMETHEE, etc.) on the results of a same case study for NBS and green space implementation has not been studied in current literature. This could provide new knowledge on the strengths and limitations of each method and allow a more informed choice on the MCDA method for practitioners. This research could help determine the best method to use in NBS or green space planning.

Finally, various GIS-MCDA tools have been developed for a specific context but their adaptation to other contexts has rarely been explored. Rather than creating new tools, resources may be better spent in adapting and improving existing and available tools. Moreover, no tools for NBS or green space implementation exist that integrate different MCDA methods and could help evaluate the impact of the chosen method on the results obtained. This research could also help determine the best method to use in NBS or green space planning and would simplify the development and improvement of existing tools.

Another point researchers and practitioners need to be aware of concerns the use of the term ecosystem services (ES). It is ambivalent as it designates services (i.e. benefits, criteria) a green space (which can also be a technology, designated as NBS) can provide.

1.3.6 Conclusion

This literature review includes 124 papers published between 2000 and 2022 related to the use of MCDA process for NBS and green space planning. Those studies are usually conducted in Europe and North-America on a single case study and a specific context. Stakeholders are not systematically integrated into the MCDA process and when they are, it is usually a few experts from academia who are called upon for the criteria weighting phase and are not involved in the whole process, as recommended. The criteria considered for the evaluation of alternatives are environmental or social, but only few are technical or economic. One of the most used MCDA methods in the studies is the AHP method despite its high risk of bias. Generally, studies apply a direct ranking method following Simple Additive Weight (SAW) rules. Mapping results are produced using GIS tools that integrate the algorithms of the relevant MCDA method.

Research opportunities arise of testing NBS and green space planning approaches and advanced MCDA methods to various contexts, integrating a group of stakeholders with profiles covering all the relevant field for NBS and green space planning, and developing existing tools for better flexibility and adaptation to a wide variety of contexts.

Chapter 2: Problems and objectives

2.1 Problems

The literature review presented a state of the art for current urban planning of NBS including the scenario approach and water engineering design and planning tools, MCDA methods and tools involving the active participation of stakeholders and finally a section on the MCDA processes specifically developed for NBS planning and green spaces.

The review of the current NBS planning practices (see section 1.3) showed that there are gaps in the decision-making process around policy and governance for NBS planning (Hanna & Comín, 2021; Langemeyer *et al.*, 2016). Although the many benefits associated with NBS are well known, the majority of studies usually focus on environmental aspects and stormwater management (Meerow, 2020; Monteiro *et al.*, 2020; Qiu *et al.*, 2022), according to a single benefit such as water quantity control (Graça *et al.*, 2022; Meerow, 2019; Meerow & Newell, 2017). Hydraulic modelling tools such as SWMM and MUSIC support the design of NBS based on the biophysical and climatic characteristics of a defined area. In order to meet the need for larger-scale territorial planning, NBS planning tools such as UrbanBEATS, SSANTO, SUSTAIN-EPA, AST, GISP are the most popular tools. These tools are based on a principle of spatial suitability analysis and select, evaluate and rank NBS according to their ability to provide the required services in certain locations or contexts (Mubeen *et al.*, 2021). The scenario assessment uses cost-benefit methodologies in the short-term, with an underestimation of the benefits provided by NBS. This leads to prioritize the economic growth as a key criterion for decision-makers (Dorst *et al.*, 2019; Engström *et al.*, 2018; Hanna & Comín, 2021; Seddon *et al.*, 2020). Moreover, most studies focus on quantitative or qualitative aspects of analysis but rarely combine the two aspects (Boggia *et al.*, 2018; Hanna & Comín, 2021). Opportunistic planning of NBS leads to unintended outcomes that do not maximise the potential of the multiple benefits of NBS (Li *et al.*, 2019; Meerow, 2020) hence the interest in adopting a multicriteria approach for decision support for NBS implementation.

The review of the MCDA process highlighted the importance of stakeholder participation in the successful application of MCDA. Consequently, in order to properly represent each view of a problematic situation, the decision-making process tends to become multidisciplinary by involving various stakeholders (Belton & Stewart, 2002). Collaboration between governmental actors and citizens is also important but requires changes in municipal organisation and departmental coordination (Ferrans *et al.*, 2022; Monteiro *et al.*, 2020; Neumann & Hack, 2019; Sarabi *et al.*, 2019; Sturiale & Scuderi, 2018a; Voskamp *et al.*, 2021). Collaboration between researchers and decision-makers requires a realignment of research questions, methods, and results to better respond to practice (Graça *et al.*, 2022). These changes involve devoting more time to the planning process, which can vary depending on the number of stakeholders involved (Arciniegas & Janssen, 2012; Marais & Abi-

Zeid, 2021). Moreover, to facilitate the application of MCDA methods, several tools have been developed that are based on matrix tables to capture data relating to stakeholder preferences and allow the results to be visualised in the form of diagrams or curves (Mustajoki & Marttunen, 2017). It is noteworthy that there are no MCDA tools specifically developed for spatial planning (Mustajoki & Marttunen, 2017).

The review of the MCDA process for NBS and green space planning conducted as part of this PhD study (see section 1.3) includes 124 papers published between 2000 and 2022. It showed that such studies are usually conducted in Europe and North America and involve only a single case study and a specific context. Stakeholders are not systematically integrated into the MCDA process and when they are, it is usually a few experts from academia who are called upon for the criteria weighting phase and are not involved in the entire process as is in fact recommended. The criteria considered for the evaluation of alternatives are environmental or social, but only few are technical or economic. One of the most used MCDA methods in the studies is the AHP method despite its high risk of bias. Studies applied a direct ranking method following Simple Additive Weight (SAW) rules. Results are visualized using GIS tools that integrate the algorithms of the relevant MCDA method.

The main obstacles to planning NBS, identified by Sarabi *et al.* (2019), are insufficient financial resources, a lack of common guidelines, an unclear political and governance structure, a lack of information and knowledge, a lack of space and available time. Indeed, cities express a need for knowledge, methods and tools on how to plan and design NBS (Voskamp *et al.*, 2021) but are limited by the lack of appropriate guidelines to guide them in planning and implementing NBS (Ferreira *et al.*, 2021; Voskamp *et al.*, 2021), as well as the lack of training and experts for strategic urban planning of NBS, which leads to inappropriate approaches and unsuccessful results (Albert *et al.*, 2021; Nguyen *et al.*, 2019; Sarabi *et al.*, 2019; Voskamp *et al.*, 2021). Policy initiatives could accelerate NBS implementation strategies, but very few studies address the policy, governance and decision-making aspects of NBS strategic planning, such as citizen participation, decision-making, project communication and knowledge transfer (Hanna & Comín, 2021; Mendonça *et al.*, 2021; Voskamp *et al.*, 2021). In addition, current planning systems and traditional governance structures are very rigid, which would require a great deal of effort to change and are difficult to transpose to other contexts (Neumann & Hack, 2019; Voskamp *et al.*, 2021). Therefore, research opportunities exist to test NBS planning approaches and advanced MCDA methods to various contexts, integrating a group of stakeholders with profiles covering all the relevant fields for NBS and green space planning, and developing existing tools for better flexibility and adaptation to a wide variety of contexts.

2.2 Objectives

The main objective of this research is to improve the decision-making process for NBS planning by developing a new method which can be used in various contexts worldwide. This new method combines applied sciences with existing water engineering tools for NBS planning and the social sciences with existing MCDA methods and tools, using a participative and collaborative transdisciplinary approach. The concept of "transdisciplinarity" refers to several sciences that transcend their respective disciplinary boundaries and come together to address a problem (Choi & Pak, 2007). The aim of approaches based on this concept is to resolve a complex problem by considering all possible perspectives in order to achieve a good overall understanding of the problem and thus develop a consensus and apply sustainable actions. An important aspect in transdisciplinary approaches is the inclusion of society (Brink *et al.*, 2016).

In order to improve the decision-making process for NBS planning, the MCDA-NBS method that is proposed aims to answer four research questions:

1) How can MCDA methods and approaches be adapted for NBS planning?
2) How can existing water engineering tools be combined with MCDA methods to evaluate NBS planning alternatives?
3) How can the combination of MCDA with existing water engineering tools improve the results for NBS planning?
4) How can the MCDA-NBS method be flexible enough to be adapted to other geographical, socio-political, and urban contexts?

Relative to the four research questions to be addressed, the development of the MCDA-NBS method is based on four objectives to be attained by the end of the PhD:

1) A participatory and collaborative approach involving decision-makers, researchers, and relevant stakeholders for NBS planning following the MACBETH MCDA method.
2) A method that combines the UrbanBEATS water engineering tool and the MACBETH MCDA method for evaluating NBS alternatives.
3) Guidelines for decision-makers in the use of results, methods, and tools to facilitate knowledge transfer and the usability of results.
4) A demonstration of the flexibility and adaptability of the proposed MCDA-NBS method in different geographical, socio-political, and urban contexts.

The first objective, "*A participatory and collaborative approach involving decision-makers, researchers, and relevant stakeholders for NBS planning following the MACBETH MCDA method"*, aims to analyze the dynamics of collaboration between decision-makers, researchers, and stakeholders, and to propose a roadmap for the application of the MCDA-NBS method (see section 4.2). It also enables analyzing the relevant stakeholders to be integrated in the process, in order to properly represent the different visions around NBS planning, as well as the potential criteria to be considered for NBS planning (see sections 4.1 and 4.2).

The second objective, "*A method that combines the use of the UrbanBEATS water engineering tool with the MACBETH MCDA method for evaluating NBS alternatives*", is based on the UrbanBEATS tool (see section 3.1) and the MACBETH method (see section 3.2), and proposes a five-step MCDA-NBS method: identifying the stakeholders, conducting the MCDA process, obtaining the NBS alternatives, evaluating the alternatives, presenting and discussing the results (see section 4.2).

The third objective, "*Guidelines for decision-makers in the use of results, methods, and tools to facilitate knowledge transfer and appropriate use of results*", focuses on the final stage of the MCDA-NBS method, when the results are presented and discussed. It evaluates the satisfaction of decision-makers and stakeholders with the results and suggests avenues for future improvement (see section 4.3). It examines how the results can be used in decision-making for current or future projects. It also looks at how to transfer knowledge (see section 4.3).

The fourth objective, "*A demonstration of the flexibility and adaptability of the proposed MCDA-NBS method in different geographical, socio-political, and urban contexts*", is obtained through an application of the MCDA-NBS method to the case studies of Trois-Rivières (Quebec, Canada), Toulouse (France) and Melbourne (Victoria, Australia) (see section 3.3). It analyzes similarities and differences in the process and assesses whether the method delivers satisfactory results despite the different contexts (see section 4.3).

The next chapter will present the materials and methods used, i.e., the UrbanBEATS planning-support model, the MACBETH method and the three case studies. Then, the following chapter will present the results of the development of the MCDA-NBS method, with a focus on the implementation of a participative and collaborative process, and finally a comparison between the three case studies while applying the MCDA-NBS method.

Chapter 3: Materials and methods

3.1 The UrbanBEATS model

3.1.1 A NBS planning tool

The literature review of water engineering tools for NBS implementation (see section 1.1.2) identified several tools for NBS planning. We chose to carry out the research with the UrbanBEATS tool because the research team had already collaborated on several projects with Dr. Peter M. Bach and these have always shown satisfactory and successful results.

UrbanBEATS (Urban Biophysical Environment And Technologies Simulator) (Bach *et al.*, 2018; Bach *et al.*, 2020) is an integrated modelling tool to support the planning of urban NBS. It was first developed in an Australian context but has since been applied outside of Australia (e.g., Nguyen *et al.*, 2022). It generates spatial maps of different alternatives of NBS layouts in an urban context according to stormwater management objectives chosen by the user. These objectives include runoff volume reduction, annual pollution load reduction (total suspended solids, total nitrogen, and total phosphorus) and volumetric reliability of harvesting and reuse of rainwater for specific end uses (e.g., irrigation). The definition of these objectives is called a "scenario". The same scenario can propose several alternatives. UrbanBEATS currently simulates wetlands, ponds & basins, swales, bioretention/raingardens, infiltration systems, and rain tanks which are the most studied technologies due to their effectiveness and ease of implementation (Wang *et al.*, 2023). Systems are sized based on pre-developed design curves and can be adapted according to the study context.

With the help of four input maps: land use, population, elevation and soil classification, UrbanBEATS represents the urban environment conceptually (Bach *et al.*, 2018), using a gridded map of 'Blocks' (usually 200m to 500m in resolution) as its smallest explicit spatial unit, each containing a database of urban characteristics. Determining the size of the blocks is part of model calibration to test the resolution required to obtain reliable, sufficiently accurate and varied results. For NBS planning, the model considers solutions at four different scales:

i. the allotment;

ii. the streetscape, which encompasses a group of several lots around one or more access roads;

iii. the neighborhood, which is essentially the 'Block' and encompasses mixes of land uses;

iv. the sub-basin, which is a combination of 'Blocks', which are located within the same urban sub-catchment defined by topographic input.

To conceptualize the urban environment to obtain information necessary for NBS planning (e.g., impervious area, roof area, open and available spaces for NBS), UrbanBEATS uses its *Urban Planning Module* (Bach *et al.*, 2018) which follows three steps:

1. Collation and aggregation of input spatial data spatial data (more details about these data can be found in the supplementary material) to the simulation grid of 'Blocks'.

2. Identifying spatial relationships ('Block' neighbourhoods and sub-catchments)

3. Characterisation of urban characteristics generated procedurally using spatial planning ordinances (characteristics include building height and footprint, street widths, garden and available green space, impervious area, etc.).

Following this conceptualization, the *NBS Planning Module* (Bach *et al.*, 2020) then generates layouts in two steps:

1. Identifying possible NBS systems at the four different scales across the simulation boundary, testing different system sizes for stormwater management objectives and checking for available space in the urban environment to accommodate these systems. System designs are represented as performance curves that are pre-generated using long-term historical climate data (rainfall and evapotranspiration).

2. Generation of NBS alternatives using the Monte-Carlo approach and the pre-established systems from the first step, generating thousands of siting options for different types of NBS and filtering these based on a multi-criteria matrix that reflects stakeholder preferences towards specific types of NBS systems. The user can choose the number of alternatives to be presented by the model.

These proposed alternatives are all technically feasible according to user-defined modelling objectives (i.e., runoff volume reduction, pollution reduction and water harvesting). As such, to differentiate and rank these, stakeholder preferences are incorporated. To date, this has solely been based on the choice of NBS technology, disregarding its spatial context. Combining the use of UrbanBEATS with MACBETH therefore allows for a broader consideration of objectives as well as the spatial context, that should result in better-informed NBS layouts.

The minimum input data required to obtain the results of strategic scenarios for the implementation of NBS are:

i. "elevation.txt", which is topographical spatial data for the area;

ii. "landuse.txt", which is a spatial dataset of land use categories according to the classification required by UrbanBEATS (CIV-civic, COM-commercial, RES-residential, HI-heavy industry, LI-light industry, ORC-mixed commercial/residential, PG-parks and gardens, RD-roads, REF-reserves and forests, TR-transport, SVU-public infrastructure, UND-undeveloped/agricultural, NA-other);

iii. "population.txt", which is spatial data representing the distribution of the population over the territory;

iv. "soilclassification.txt", which is a spatial dataset of soil categories according to the classification required by UrbanBEATS (sandy soil, sandy/clayey soil, clayey soil);

v. "rainfall.csv", which is hourly climatic precipitation data over a 10-year period;

vi. "evapotranspiration.csv", which is daily climate data for evapotranspiration over a 10-year period;

vii. "mcatoolern.csv", which is the NBS performance matrix.

Dr. Peter M. Bach is currently working on a new version of UrbanBEATS, which will incorporate a number of improvements, including a dynamic land simulation mode (forecasting future changes in the land), greater flexibility in the expression of input data, the consideration of new objectives and the inclusion of new input data (e.g. biodiversity, urban heat island), as well as an improved interface for the spatial visualisation of the results.

3.1.2 Illustration of UrbanBEATS: A Canadian case-study

During an internship in 2020, a preliminary case study was conducted in the municipality of Trois-Rivières (Québec, Canada) to test the UrbanBEATS model in another context (i.e., cold climate). Indeed, the UrbanBEATS tool already demonstrated good results in the case study of Melbourne during Dr. Peter Bach's thesis, which was further exploited by the project's collaborating researchers and it was a good opportunity to further develop the tool. This section presents the kind of results UrbanBEATS can provide illustrated by the Trois-Rivières case study.

Spatial data were provided directly by the municipalitý of Trois-Rivières and climate data were prepared and calculated from data collected by Environment Canada and the NASA database. To calculate evapotranspiration, the Penman-Monteith method was applied (Zotarelli *et al.*, 2010). This method requires data at 2 metres above ground of wind speed (m/s), temperature (°C), relative humidity (%) and solar radiation (MJ/m^2). Details of the calculations are given in Annex A.

The various parameters that characterise urban areas were found in various local urban planning documents such as the *Schéma d'aménagement et de Développement* (SAD), the *Plan de Développement de la Zone Agricole* (PDZA), the *Plan d'adaptation aux changements climatiques*, the *Plan Directeur de l'Eau* (OBV) and the *Plan d'Urbanisme* (PU) (*Règlement sur le plan d'urbanisme, Règlement sur l'utilisation de l'eau, Règlement sur le rejet d'eaux usées dans un réseau d'égout ou dans un cours d'eau, Règlement sur la gestion de l'écoulement des eaux des cours d'eaux municipaux, Règlement sur le lotissement*).

The results obtained include a water flow map (Figure 4) of the territory of the Municipalitý and five maps of strategic NBS implementation scenarios (Figure 5) (Bousquet, 2020).

However, these results present several uncertainties:

i. evapotranspiration data were calculated from NASA data, which are global data and are probably not very accurate ;

ii. rainfall data contained around 5% missing data;

iii. some parameters were chosen from the literature or according to our own scientific opinion (targets, objectives, levels of service);

iv. some parameters, such as the performance of NBS in cold climate, biodiversity and urban heat island effects, would have been relevant to take into account;

v. simulations were adapted manually from the Melbourne case study. This is because some parameters and design standards are based on Australian regulations, which are not expressed in the same way around the world (e.g. appliance standards, employment distribution, water use and consumption). For example, the standards for domestic appliances (dishwashers, toilets, showers, etc.) are different from Quebec standards, and a correlation must be found between actual Quebec values and the Australian system.

The results and feedback from this preliminary study provided the basis for the PhD project to develop the new MCDA-NBS method, in particular the need to incorporate new criteria for NBS planning.

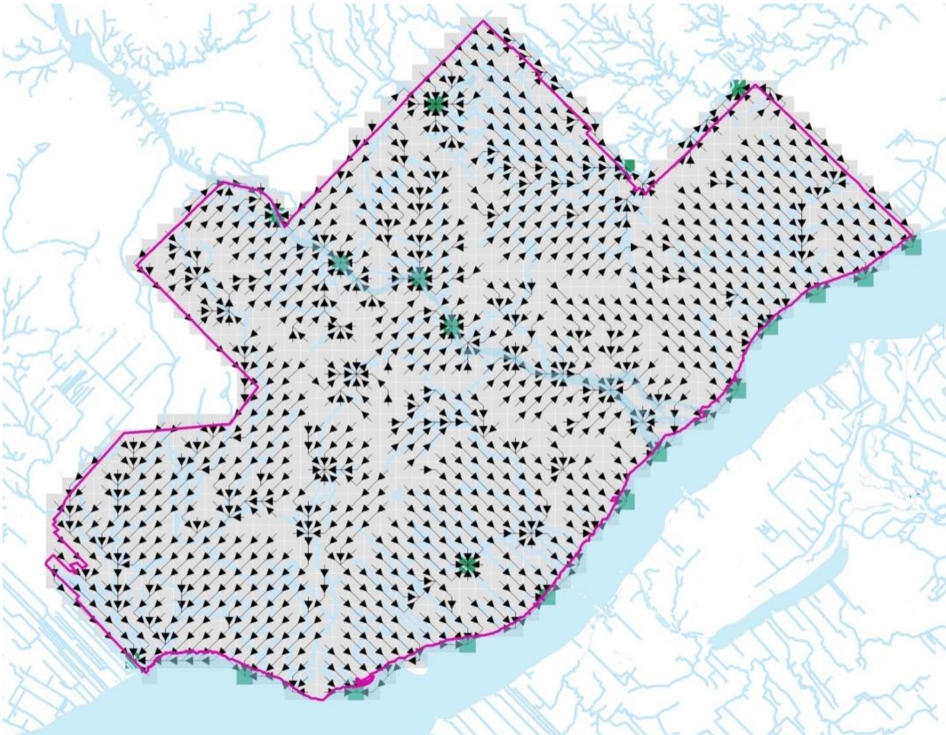


Figure 4 - Water flow simulation of Trois-Rivières (Québec, Canada)

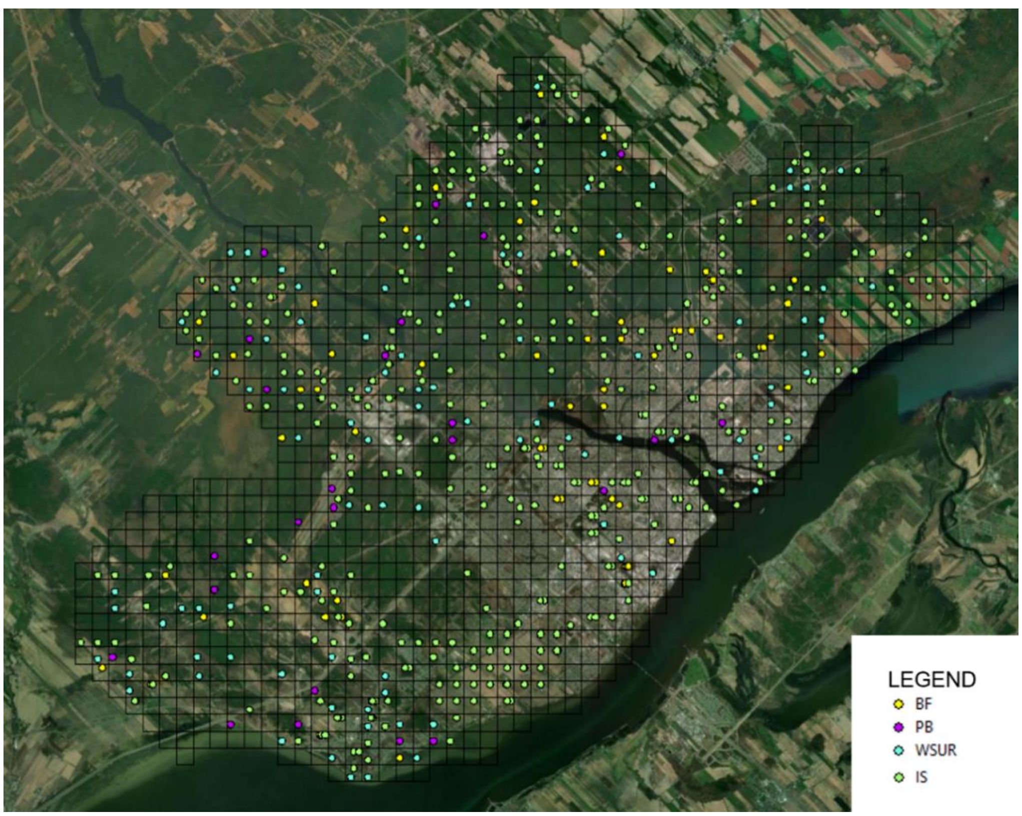


Figure 5 - UrbanBEATS simulation map for NBS planning in Trois-Rivières (Québec, Canada) where BF is biofiltration systems, PB pond and basin systems, WSUR wetland systems and IS infiltration systems.

3.2 The MACBETH method

3.2.1 An advanced MCDA method

The MACBETH method (Measuring-Attractiveness by a Category-Based Evaluation TecHnique) helps decision makers to reflect, communicate and discuss their value systems and preferences (Costa *et al.*, 2003). It enables the construction of criteria weights and cardinal scales to evaluate the performance of alternatives. This is done by making qualitative judgements about criteria attractiveness (performance) and obtaining a final score for each alternative, ranked in decreasing order of overall attractiveness (Costa *et al.*, 2012, 2019). The M-MACBETH software enables the application of the MACBETH method and automatically checks the consistency of judgements as they are entered into the software (Costa *et al.*, 1999). The M-MACBETH tool can also be used to perform a sensitivity analysis, but this was not explored in this research project. The method has been tested for transport (Marleau Donais *et al.*, 2019) and water management (Lavoie *et al.*, 2016) challenges in Canada but also in other fields such as agriculture, energy, environment, health, administration, military, and others, with case studies mainly in Europe but also in North America (Ferreira & Santos, 2021). These studies showed significant results in representing stakeholders' preferences accurately, reducing the risk of bias and helping decision makers take effective actions. The presence within the research team of an expert (Prof. Roxane Lavoie) in the use of the MACBETH method and its tool M-MACBETH was another determining factor in the choice of this method over another. During the first workshop with the municipality of Trois-Rivières, the expert was able to train the doctoral candidate (Morgane Bousquet).

To apply the MACBETH method, the following steps are taken together with a group of stakeholders (Costa *et al.*, 1999, 2003):

1. **Brainstorming to select the criteria to be considered for the study.** All aspects of a case study can be addressed in a quantitative or qualitative way and the assessment of criteria is very flexible (e.g., numbers, percentages, words, etc.). The economic aspect is not included in the criteria, as it is usually calculated separately at the end in a cost-attractiveness ratio. In line with scientific recommendations (Liquete *et al.*, 2016) and observed practices (Bousquet *et al.*, 2023), the number of criteria chosen should be less than 10 as too many criteria would reduce their individual impact on the multi-criteria preference framework and lead to less significant results. Care is taken at this stage to ensure that there was no interaction between the criteria to avoid double counting.

2. **Defining two benchmarks on each criterion.** The 'neutral' benchmark refers to the 'just satisfactory' value, and the 'good' benchmark to the 'fully satisfactory' value. By convention, the 'neutral' benchmark is assigned an attractiveness value of 0 and the 'good' benchmark a value of 100. Attractiveness of an

option's performance on a criterion can be larger than 100 or less than 0 (Marleau-Donais *et al.*, 2019) if it is above the 'good' benchmark or below the 'neutral' benchmark, respectively.

3. **Defining additional values around the two benchmarks to construct a value scale.** Reference values (e.g., status quo, policy objectives) can help stakeholders in constructing the scale and defining the benchmarks. Reference values, the 'neutral' benchmark and the 'good' benchmark arranged in order of attractiveness, represent levels of performance for that criterion.

4. **Defining the difference in attractiveness between the reference values**. Semantic categories (extreme, very strong, strong, moderate, weak, very weak, null) are used to translate the attractiveness scale into cardinal (quantitative) values. The difference in attractiveness refers to the transition from one reference value to another. The stakeholders are asked to qualify the difference between reference values using the semantic categories. Those preferences are input into a matrix in the M-MACBETH software, which automatically verifies the consistency of judgements with one another. Thus, when an incompatible judgement is entered, M-MACBETH will present all the ways found to obtain a consistent matrix with a minimal number of changes. More details about this consistency check can be found in (Costa *et al.*, 1999).

5. **Constructing the weight of the different criteria.** The weights in the MACBETH method do not express the relative importance of a criterion, but the relative importance of going from 'neutral' to 'good' on one criterion (Lavoie *et al.*, 2016). Pairwise comparisons of alternatives with different criteria performance (neutral/good) are presented by the M-MACBETH software to the stakeholders using a participative and simplified interface for alternatives. The relative importance is evaluated according to the same semantic categories as in the previous step (extreme, very strong, strong, moderate, weak, very weak, null). The judgements are again input into a matrix.

6. **Calculating the score of an alternative on every criterion.** The formula is: $Score = W_{criterion} * A_{criterion}$, where $W_{criterion}$ is the criterion weight and $A_{criterion}$ is the alternative's performance on the criterion.

7. **Aggregation of criteria scores to obtain the overall score for an alternative.** The overall score of an alternative is the additive sum of criterion scores. At the end of this final step, we obtain a ranking of alternatives.

During the MACBETH method process, we obtain several types of information on the criteria and their preferences (i.e., weighting, attractiveness scale, etc.). This information can help in decision making and in comparing scenarios with each other for NBS planning. This method is considered less complex than the outranking methods (PROMETHEE, ELECTRE, PAPRIKA, DCE, CA) because it is accompanied by the computer tool M-MACBETH and/or, more recently, a platform called Web-Delphi (Costa *et al.*, 2019), specifically developed to support the MACBETH method. In this way, decision-makers do not need to have experience in MCDA to participate in the construction of a model. The M-MACBETH tool can also be used to carry out a sensitivity analysis for each criterion by varying the weights graphically (Teotónio *et al.*, 2020). Moreover, every step of the method can be easily explained to stakeholders, thus eliminating the "black box effect". The mathematics used in the method are also simple and can therefore be understood by stakeholders.

3.2.2 The M-MACBETH tool

In this section, we will illustrate the MACBETH process using the M-MACBETH tool with a simple and theoretical case study: *Choice of a MCDA method*. We will use the studies by Belton & Stewart (2002), Mustajoki & Marttunen (2017) and Németh *et al.* (2019) cited in the first part of the literature review to get the characteristics and performances of MCDA methods (see section 1.2). We will compare four methods: SWING, AHP, ELECTRE and MACBETH.

The first step is to choose the criteria. In this example, we consider three criteria, i.e., complexity, risk of bias and time investment. The complexity and risk of bias criteria are qualitative (i.e., semantic scale) while the time investment criterion is quantitative expressed in hours. The complexity criterion studies the difficulty of reproducing the method. The risk of bias criterion considers the chances of error and confidence in the results. Finally, the time investment criterion analyses the involvement of stakeholders needed to conduct the method.

The second and third steps is the definition of the reference values, the 'neutral' benchmark and the 'good' benchmark. For the qualitative criteria we use a three-level scale (i.e., low, moderate, high) and for the time investment criterion the time required to conduct the four methods arranged in ascending order. Then, the 'neutral' and 'good' benchmarks must be defined. For qualitative criteria, we put the 'neutral' as "moderate" and the good as "low". For the quantitative criteria, we put the 'neutral' as 50 hours and the 'good' as 20 hours. The references for the good and neutral levels are chosen arbitrarily for this example.

The fourth stage is the construction of attractiveness scales for the criterion, presented in matrix form in the M-MACBETH software (Figure 6). Users must indicate the preference between two levels according to the MACBETH semantic scale (i.e., extreme, very strong, strong, moderate, weak, very weak, null). Then the M-MACBETH software translates the semantic values into numerical values in the form of scales. It is not necessary to fill in the whole matrix, but at least the diagonal and the difference between the 'neutral' and 'good' benchmarks. M-MACBETH checks the consistency of the judgements as the matrix is completed. If the software indicates inconsistencies in the preferences expressed, it will propose solutions to these inconsistencies (Gómez & Carnero, 2016). In Figure 6, we can notice the quantitative criterion as the scale is linear.

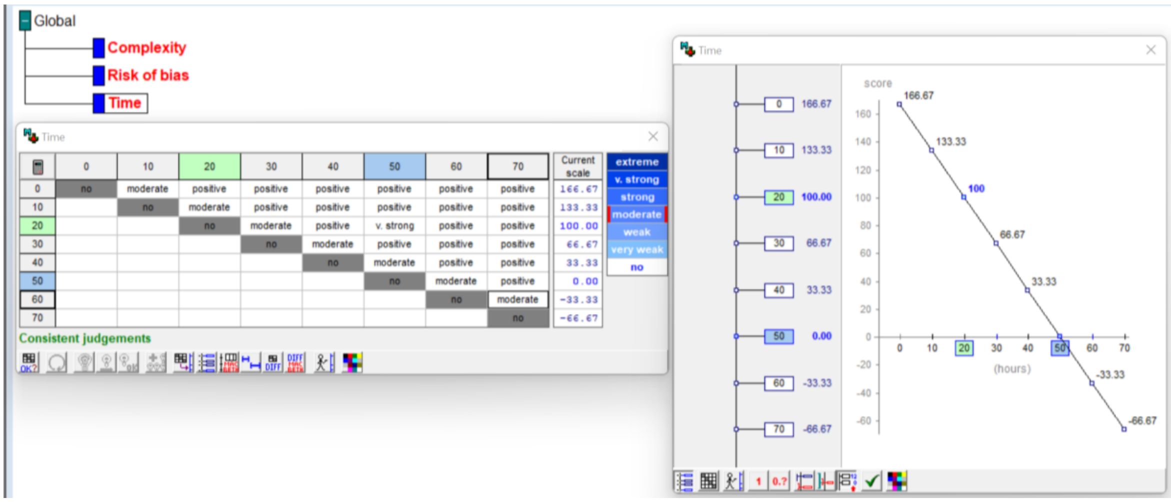


Figure 6 - Example of attractiveness scale on the time investment criterion

Figure 7 - Example of pairwise comparison between the risk of bias and the time investment criteria

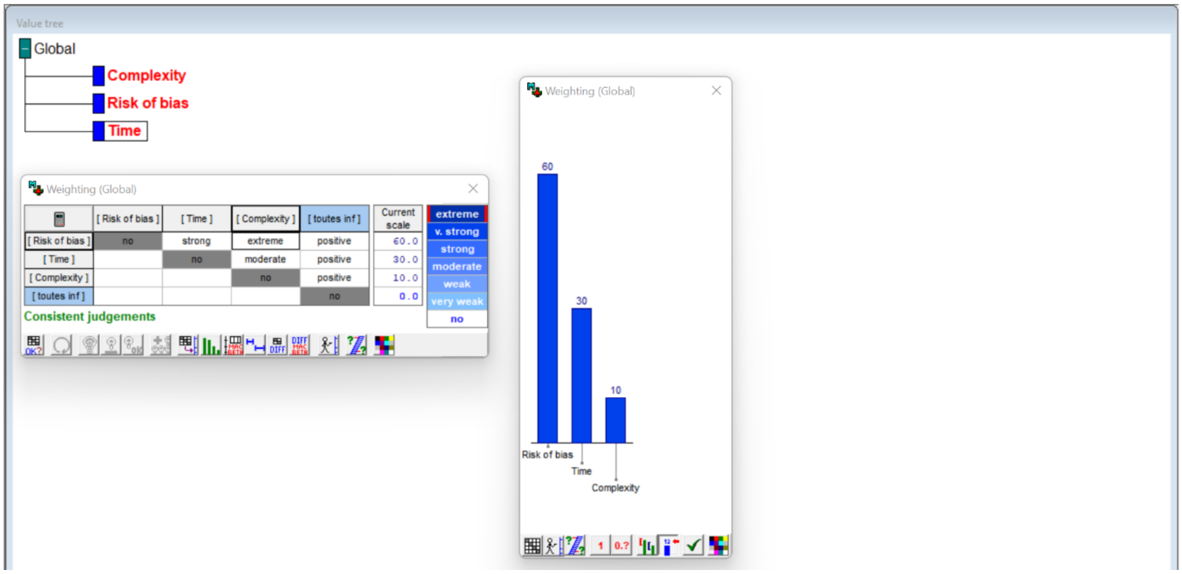


Figure 8 – Matrix and weighting obtained after the pairwise comparison

The fifth stage is the pairwise comparison between the criteria, which is presented by the M-MACBETH software. In the example shown in Figure 7, alternative A has a 'good' level on the complexity criterion and a 'neutral' level on the time criterion, while option B has a 'good' level on the time criterion and a 'neutral' level on the complexity criterion. Here, alternative B is seen as moderately more attractive dans alternative A. Once the matrix is complete with sufficient pairwise comparisons, the weights of the criteria are calculated by the M-MACBETH software. Here the risk of bias criterion has a weight of 60, the time criterion of 30 and the complexity criterion of 10 (Figure 8).

The multicriteria model is now completed and the alternatives (i.e., SWING, AHP, ELECTRE and MACBETH) can be evaluated. The performance of each of the alternatives is entered into the M-MACBETH software, and a score is then assigned to each option based on the multicriteria model constructed (Figure 9). In our example, none of the four alternative is entirely satisfactory as there is always at least one criterion that is below the 'neutral' benchmark. The results show that good performances on criteria are balanced by very poor performances on other criteria, giving them a final score below neutral, even though they have good ratings on certain criteria. The SWING method is perceived as the least complex method and the ELECTRE and MACBETH methods as those with the lowest risk of bias. AHP method is not a good alternative regarding our example.

At the end of the process, we can add a cost analysis, expressed in $/year and based on commercial licences available for the method and the supporting tools. The SWING and ELECTRE method are free, unlike the other methods which are under commercial licences.

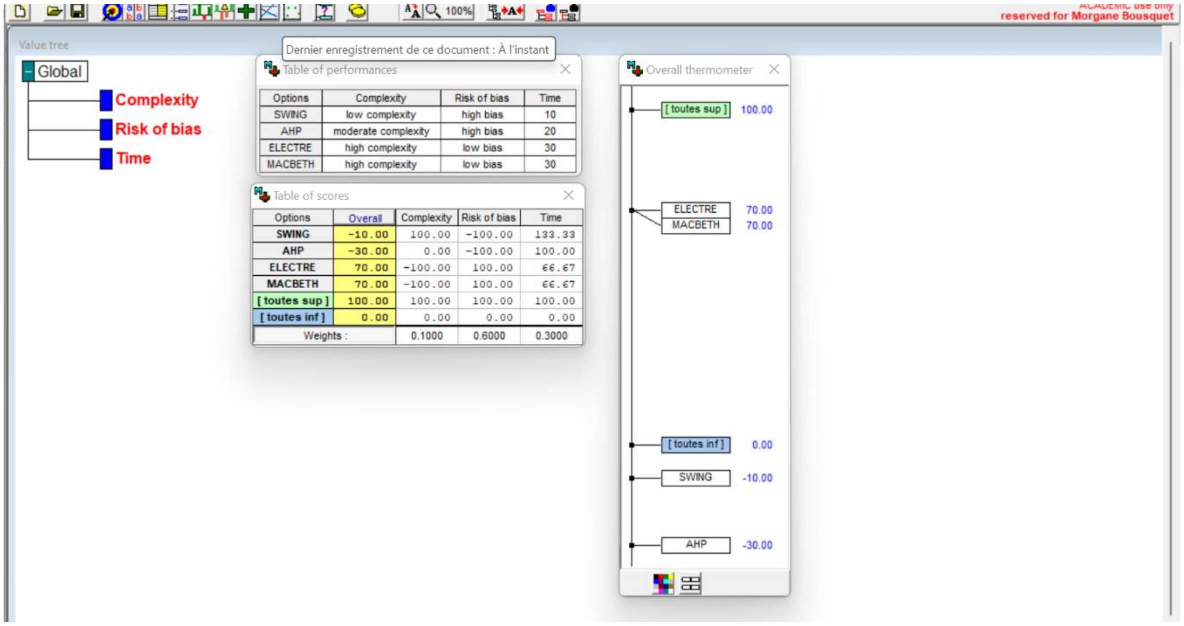


Figure 9 - Scores for the SWING, AHP, ELECTRE and MACBETH alternatives

In this example, we used the MACBETH method and its tool M-MACBETH that help decision-making and allows complex alternatives to be compared in a systematic and comprehensible way. It aims to build a consensus on a project value, but the users need to interpret the results carefully and always check why and how the final scores are obtained.

3.3 Case studies

The research project is based on three case studies: Trois-Rivières in Canada, Toulouse in France and Melbourne in Australia. The choice of these countries is based on the objective of having different geographical, biophysical and climatic conditions (cold continental, Mediterranean, oceanic, arid) (Table 2). Partnerships already in place through the preliminary internship in Trois-Rivières, the Institut National des Sciences Appliquées (INSA) Toulouse and Dr. Peter Bach with his connexion with the Melbourne Water Institute facilitated the support of the three city partners for the research project. The case study with the municipality of Trois-Rivières in Canada was used to develop the MCDA-NBS method. The study was conducted between September 2020 and December 2022 and brought together 12 municipal employees for workshops in virtual mode due to the health crisis. The case study with the Toulouse Metropole in France was conducted between May 2022 and May 2023 and brought together 8 stakeholders for workshops. It aimed to adapt the MCDA-NBS method once it is in another context to integrate other stakeholders than municipal employees (e.g., technician, urban planner, biologist). Finally, the case study with Melbourne was conducted between February 2023 and November 2023 with 10 stakeholders for workshops. It aimed to validate the MCDA-NBS process.

Table 6 - Summary of case studies regarding climate, area, population, water consumption and main issues

City	Climate	Area (km^2)	Population (hab)	Total precipitation (mm/year)	Residential water consumption (l/pers/day)	Main issues
Trois-Rivières (QC, Canada)	Continental, Cold	289	136,470	845	389	Flooding, Pollution
Toulouse (France)	Mediterranean, Oceanic	458	796,203	640	146	Urban Heat islands, Droughts
Melbourne (VIC, Australia)	Coastal, Arid	870	1,530,000	605	247	Bushfires/ Biodiversity, Droughts, Flooding

Founded in 1634, Trois-Rivières is the second oldest city in the province of Quebec. It is characterised by two main sources of water: the Great Lakes (i.e., catchment area of 770,500 km^2) and the St Lawrence River (i.e., catchment area of 1,610,000 km^2) (Hébert & Belley, 2005). The 2020 census carried out by the MAMH (*Ministère des Affaires Municipales et de l'Habitation*) indicated a total population of 136,470 people and a density of 472 pers/km^2 for a territory of 289 km^2. Population trends predict an 18% increase by 2040 (*Census Profile, 2016 Census*, 2017) and the residential average water consumption is 389 l/person/day, 11% higher than the national average of 350 l/Canadian/day, but still lower than the average for the province of Quebec which is 400 l/person/day (Trois-Rivières, 2022). Canada's climate forecasts predict warming that is twice as large as in most other countries (between +275K and +279K) due to the loss of the ice cover, which usually reflects 90% of solar radiation (Bush *et al.*, 2019). One of the consequences is less snowfall in winter and more rainfall in both winter and summer (Rayfield *et al.*, 2016). Therefore, Trois-Rivières faces major flooding risks, as well as major pollution risks from the paper factories that are very present in the area.

Toulouse Metropole is inhabited since prehistoric times and was officially founded by the Romans. The OTM (*Observatoire Toulouse Metropole*) published an annual report with key information about demography, environment, water management, waste management, energy, etc. The following statistics come from the 2022 report (Toulouse Metropole, 2022). Toulouse Metropole comprises 37 communes and a total population of 796,203 inhabitants in an area of 458,2 km². The city of Toulouse alone has 493,465 inhabitants in an area of 118.3 km². Its demographic evolution is one of the most important in France (+6.2% between 2013 and 2018). In 2016, the average annual consumption of drinking water per inhabitant was 146 l/pers/day. The Garonne is a major river and landscape element in the landscape of the Metropole. Major historical floods (e.g., 26 June 1875) have led to the construction of infrastructure to minimise the losses they could cause. Recently, the risk of flooding increased in both winter and spring. The Garonne River is also the main source of drinking water production from three plants that supply a network of 3,317 km carrying an average daily volume of 145,596 m^3 of water. Unlike other large French cities, Toulouse Metropole has a separate sewer network, with separate sewer collectors for wastewater (i.e., 17 treatment plants) and rainwater. Rainwater is collected in a specific network before being discharged into the natural environment (the Garonne River). Summer temperatures are among the highest in France, reaching up to 44 degrees, and remain positive during the winter. Toulouse Metropole faces drought risks and urban heat island effects. Disturbances are related to Atlantic weather systems with an average of 150 rainy days per year, but a low annual rainfall of 700 mm. Toulouse Metropole is conducting projects and actions to move towards a more resilient and sustainable territory (e.g., 100,000 Tree Plan, Grand Parc Garonne Project).

Melbourne was founded by settlers in 1835, 47 years after the first European penal colony was established in Sydney. It is a coastal city on the Bass Strait between the Tasman Sea and the Indian Ocean. The Greater Melbourne covers an area of almost 10 000 km^2 and has a population approximately 5 million. Melbourne Water oversaw the water management and produced an exhaustive report in 2020-2021 (Melbourne Water, 2022). Water management in the greater Melbourne area is divided into 5 catchments (i.e., Werribee, Maribyrnong, Yarra River, Dandenong and Westport) following the main rivers. In this study, we will focus especially on the Dandenong catchment which has 1.53 million inhabitants in an area if 870 km^2. The water treatment system is operated by two major treatment plants and 400km of sewers and nine sewage pumping stations. Those treatment plants produce recycled water to customers for a range of non-drinking purposes. The drinking water system is operated with 16 treatment plants across Greater Melbourne. Residential water consumption in Greater Melbourne decreased significantly, from 247 l/pers/day in 2000 to 160/pers/day in 2020 thanks to the Victorian Government initiative which fixed a target of 155 litres. With climate change, the climate becomes hotter and drier bringing less rainfall, more drought and more risk of bushfires which can compromise the water quality in the water supply reservoirs. Moreover, flooding risks are increased by the rise of sea level caused by climate change and the exponential urbanisation of Greater Melbourne. The councils of Greater Melbourne are engaged into a few greening projects to protect biodiversity, mitigating urban heat island effects, reducing flood risks and ensuring good water quality.

Chapter 4: Results

4.1 MCDA-NBS: combining rigorous multi-criteria decision analysis and engineering tools for nature-based solutions planning

Morgane Bousquet[a], Peter M. Bach[b], Françoise Bichai[c], Roxane Lavoie[d], Peter A. Vanrolleghem[e]

a) modelEAU, Université Laval, Département de génie civil et génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada, morgane.bousquet.1@ulaval.ca (corresponding author)

b) Institute of Environmental and Process Engineering (UMTEC), Eastern Switzerland University of Applied Sciences (OST) Obserseestrasse 10, 9640 Rapperswil SG, Switzerland, peter.bach@ost.ch

c) Department of Civil, Geological, and Mining Engineering, Polytechnique Montreal, Montreal, Quebec, H3C 3A7, Canada, fbichai@polymtl.ca

d) Graduate School of Land Management and Regional Planning, Université Laval, Pavillon Félix-Antoine-Savard, 2325 rue des Bibliothèques, Local 1616, Québec (Québec) G1V 0A6, Canada, roxane.lavoie@esad.ulaval.ca

e) modelEAU, Université Laval, Département de génie civil et génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada, peter.vanrolleghem@gci.ulaval.ca

Highlights

- Stakeholder analysis presents the preferred profiles for NBS planning
- The MACBETH method is a robust MCDA method showing good results for NBS planning
- The UrbanBEATS planning-support tool for generating NBS options can be combined with MACBETH
- The Toulouse study provided opportunities for decision-making and future research

Keywords: nature-based solutions; planning support systems; decision making; ecosystem services; stakeholder engagement

4.1.0 Résumé (français)

Les solutions fondées sur la nature (SFN) sont des systèmes techniques inspirés de la nature qui fournissent de multiples services écosystémiques urbains. L'aide multicritère à la décision (AMCD) est de plus en plus utilisée dans la planification des SFN car elle permet la prise en compte des préférences des parties prenantes. Cependant, les études scientifiques sur la planification des SFN négligent souvent l'implication des parties prenantes, s'appuient sur des études de cas uniques, utilisent des méthodes AMCD simplistes et des outils basés sur le SIG ne pouvant s'adapter à d'autres territoires. Cet article présente une nouvelle approche AMCD-SFN intégrant la méthode AMCD MACBETH, et son outil M-MACBETH, et le modèle d'aide à la planification UrbanBEATS. MACBETH favorise une approche participative couplée à des algorithmes complexes, ce qui permet d'obtenir un modèle multicritère représentatif des préférences des parties prenantes tout en tenant compte des contradictions inhérentes possibles. UrbanBEATS génère systématiquement des alternatives de planification des SFN pour la gestion des eaux pluviales, qui peuvent être évaluées à l'aide du modèle AMCD afin d'identifier les alternatives les mieux classées en fonction des préférences des parties prenantes. La méthode AMCD-SFN se décline en cinq étapes : (1) l'identification des parties prenantes, (2) le développement du modèle multicritère, (3) la génération des alternatives NBS, (4) l'évaluation des alternatives NBS, et (5) la présentation des résultats et discussion avec les parties prenantes. Dans le cadre d'un projet pilote mené à Toulouse Métropole (France), huit parties prenantes ont participé à l'élaboration d'un modèle de 11 critères permettant de classer les alternatives de planification des SFN d'UrbanBEATS. Les résultats démontrent que cette méthode fournit un processus robuste et structuré, harmonisant les préférences des parties prenantes tout en restant flexible et compréhensible pour les municipalités. Elle aide les décideurs et les chercheurs dans leur planification des SFN et peut s'appliquer à d'autres outils et approches MCDA et de planification.

4.1.1 Abstract

Nature-based solutions (NBS) encompass engineered, nature-inspired systems delivering multiple urban ecosystem services. Multi-criteria decision analysis (MCDA) is increasingly used in NBS planning to align with stakeholder preferences. Yet, scientific studies on NBS planning often neglect stakeholder involvement, rely on singular case studies, employ rudimentary MCDA methods and location-specific GIS tools. This paper introduces a novel MCDA-NBS approach integrating the advanced MACBETH technique, using its software implementation M-MACBETH, and the open-source UrbanBEATS planning-support system. MACBETH fosters a participatory approach coupled with intricate algorithms, yielding a more representative multi-criteria model reflecting stakeholders' preferences accurately while accounting for inherent contradictions. UrbanBEATS systematically generates NBS layouts for stormwater management, simplistically filtered and appraised using MCDA to identify best-ranking alternatives according to stakeholder preferences. MCDA-NBS involves five steps: (1) stakeholder identification, (2) multi-criteria model development, (3) NBS alternative generation, (4) NBS alternative evaluation, and (5) results presentation and discussion with stakeholders. A pilot project with Toulouse Metropole, France, engaged eight diverse stakeholders in constructing an 11 criteria model to refine UrbanBEATS' NBS layout ranking. Findings demonstrate that this method provides a more robust and structured process, harmonizing stakeholder preferences while remaining actionable and transparent for municipalities. It

aids decision-makers and researchers in NBS planning, with applicability to other MCDA and planning tools and approaches.

4.1.2 Introduction

Nature-based solutions (NBS) (Cohen-Shacham *et al.*, 2016) are engineered green systems such as rain gardens, green roofs and walls, ponds, swales, constructed wetlands, porous pavement, and urban forests, which can provide many beneficial ecosystem services when they are well implemented in an urban context. They are also frequently known worldwide as Green infrastructures (GI), Blue-green infrastructures (BGI), Low Impact Developments (LID), Sustainable Urban Drainage Systems (SUDS) or Water Sensitive Urban Drainage (WSUD) among other terms (Fletcher *et al.*, 2015). NBS have a positive impact on water management (e.g., controlling stormwater at the source, protecting surface water quality, reducing flood risks), city aesthetics, urban heat mitigation, biodiversity and land value (Dagenais *et al.*, 2017; Kuller *et al.*, 2017; Lienert *et al.*, 2015; Qiu *et al.*, 2022; Skrydstrup *et al.*, 2020). As opportunistic NBS planning leads to unintended results that do not maximize their multiple potential benefits (Kuller, Bach, *et al.*, 2018; L. Li *et al.*, 2020; Meerow, 2020), multi-criteria decision analysis (MCDA) methods are increasingly proposed to support this process (Bousquet *et al.*, 2023). These methods aim to incorporate multiple objectives and combine subjective preferences into a framework that represents stakeholders' preferences and allows the development, evaluation, and prioritization of alternatives (Ferretti & Montibeller, 2016; Marttunen *et al.*, 2017).

MCDA methods for NBS planning have been mostly applied for forest (Baskent, 2018; Blattert *et al.*, 2017; Campos *et al.*, 2017; Ezquerro *et al.*, 2016; Uhde *et al.*, 2015), agriculture (Chopin *et al.*, 2019; Soulé *et al.*, 2021; Therond *et al.*, 2017), and stormwater management purposes (Islam *et al.*, 2021; Jelokhani-Niaraki, 2021; Kuller *et al.*, 2017; Wu *et al.*, 2020), as well as to deal with specific issues such as urban heat islands (Qureshi & Rachid, 2021) or flood risks (Membele *et al.*, 2022; Perosa *et al.*, 2022).

In relation to urban planning, a recent review of MCDA-NBS planning practices (Bousquet *et al.*, 2023a) highlighted a lack of participative methods involving various stakeholders that have been developed for a specific context without considering their adaptability to other contexts. Indeed, this review showed that studies are often conducted on a single case study and based on tools developed to meet the challenges of that study context exclusively. Moreover, it was found that the diversity of existing MCDA methods has rarely been explored and studies often use direct ranking methods (46% of the studies) or the Analytic Hierarchy Process (AHP) (35% of the studies). However, these methods have well-known limitations, leading to a high risk of bias, and are not recommended by experts in the decision science (Alves *et al.*, 2018). More in-depth details about different MCDA methods can be found in Cinelli et al. (2022), Belton & Pictet (1997) or Belton & Stewart (2002).

Another important consideration when applying MCDA methods is the involvement of stakeholders throughout the process (Belton & Pictet, 1997). In literature, stakeholders are often experts (80% of the studies analyzed by Bousquet *et al.* (2023a) and are mostly involved only during the weighting phase of individual decision criteria, which is contradictory to a MCDA process, which, by definition, is participatory (Belton & Stewart, 2002). Indeed, 29% of the studies analyzed by Bousquet *et al.* (2023a) do not involve stakeholders in the process. Furthermore, many existing tools employing MCDA in support of NBS planning rely predominantly on GIS software (i.e., ArcGIS, QGIS) with an integrated algorithm, especially developed for a specific method, multi-criteria approach and context (Bousquet *et al.*, 2023a; Qiu *et al.*, 2022). Overall, there is a lack of MCDA tools for NBS planning that can be adapted to various contexts and account for inherent bias in expert judgements even though existing tools and methods could potentially accommodate these.

The aim of this paper is to present a new decision process for NBS planning using MCDA methods that can be adapted to various contexts, involves stakeholders from different fields with different visions, and applies existing tools for better flexibility and adaptation. This new MCDA-NBS method can help decision-makers (e.g., municipalities, urban planners) in their NBS planning practice and researchers in supporting the process.

In this paper, we present the development and testing of this new MCDA-NBS planning method which:

i. is based on an advanced MCDA method, MACBETH (Costa *et al.*, 2003, 2019), which reduces the risk of bias in the multi-criteria preference framework, and facilitates consensus building throughout the process;
ii. is based on an existing planning-support tool for NBS planning, UrbanBEATS, (Bach *et al.*, 2018; 2020) and expands its scope and capabilities;
iii. requires and creates opportunity for a participatory approach with a stakeholder group during the whole planning process through workshop sessions; and
iv. is adaptable and independent of geographical, socio-political and urban context.

Our new MCDA-NBS method involves five steps: (1) stakeholder identification, (2) multi-criteria model development, (3) NBS alternative generation, (4) NBS alternative evaluation, and (5) results presentation and discussion with stakeholders. We illustrate this approach on the case study of Toulouse Metropole (France).

4.1.3 Overview of models

4.1.3.1 The MACBETH MCDA method

The MACBETH method (Measuring-Attractiveness by a Category-Based Evaluation TecHnique) helps decision makers to reflect, communicate and discuss their value systems and preferences (Costa *et al.*, 2003). It enables the construction of criteria weights and cardinal scales to evaluate the performance of alternatives. This is done by making qualitative judgements about criteria attractiveness (performance) and obtaining a final score for each alternative, ranked in decreasing order of overall attractiveness (Costa, 2012; Costa *et al.*, 2019). The M-MACBETH software enables the application of the MACBETH method and automatically checks the consistency of judgements as they are entered into the software (Costa *et al.*, 1999). The method has been tested for transport (Marleau Donais *et al.*, 2019) and water management (Lavoie *et al.*, 2016) challenges in Canada but also in other fields such as agriculture, energy, environment, health, administration, military, and others, with case studies mainly in Europe but also in North America (Ferreira *et al.*, 2021). These studies showed significant results in representing stakeholders' preferences accurately, reducing the risk of bias and helping decision makers take effective actions.

To apply the MACBETH method, the following steps are taken together with a group of stakeholders (Costa *et al.*, 1999, 2003):

1. **Brainstorming to select the criteria to be considered for the study.** All aspects of a case study can be addressed in a quantitative or qualitative way and the assessment of criteria is very flexible (e.g., numbers, percentages, words, etc.). The economic aspect is not included in the criteria, as it is usually calculated separately at the end in a cost-attractiveness ratio. In line with scientific recommendations (Liquete *et al.*, 2016) and observed practices (Bousquet *et al.*, 2023a), the number of criteria chosen should be less than 10 as too many criteria would reduce their individual impact on the multi-criteria preference framework and lead to less significant results.

2. **Defining two benchmarks on each criterion.** The 'neutral' benchmark refers to the 'just satisfactory' value, and the 'good' benchmark to the fully satisfactory value. By convention, the 'neutral' benchmark is assigned an attractiveness value of 0 and the 'good' benchmark a value of 100. Attractiveness of an option's performance on a criterion can be larger than 100 or less than 0 (Marleau Donais *et al.*, 2019) if it is above the 'good' benchmark or below the 'neutral' benchmark, respectively.

3. **Defining additional values around the two benchmarks to construct a value scale.** Reference values (e.g., status quo, policy objectives) can help stakeholders in constructing the scale and defining

the benchmarks. Reference values, the 'neutral' benchmark and the 'good' benchmark arranged in order of attractiveness, represent levels of performance for that criterion.

4. **Defining the difference in attractiveness between the reference values**. Semantic categories (extreme, very strong, strong, moderate, weak, very weak, null) are used to translate the attractiveness scale into cardinal (quantitative) values. The difference in attractiveness refers to the transition from one reference value to another. The stakeholders are asked to qualify the difference between reference values using the semantic categories. Those preferences are input into a matrix in the M-MACBETH software, which automatically verifies the consistency of judgements with one another. Thus, when an incompatible judgement is entered, M-MACBETH will present all the ways found to obtain a consistent matrix with a minimal number of changes. More details about this consistency check can be found in (Costa *et al.*, 1999).

5. **Constructing the weight of the different criteria.** The weights in the MACBETH method do not express the relative importance of a criterion, but the relative importance of going from 'neutral' to 'good' on one criterion (Lavoie *et al.*, 2016). Pairwise comparisons of alternatives with different criteria performance (neutral/good) are presented by the M-MACBETH software to the stakeholders using a participative and simplified interface for alternatives. The relative importance is evaluated according to the same semantic categories as in the previous step (extreme, very strong, strong, moderate, weak, very weak, null). The judgements are again input into a matrix.

6. **Calculating the score of an alternative on every criterion.** The formula is: $Score = W_{criterion} * A_{criterion}$, where $W_{criterion}$ is the criterion weight and $A_{criterion}$ is the alternative's performance on the criterion.

7. **Aggregation of criteria scores to obtain the overall score for an alternative.** The overall score of an alternative is the additive sum of criterion scores. At the end of this final step, we obtain a ranking of alternatives.

During the MACBETH method process, we obtain several types of information on the criteria and their preferences (i.e., weighting, attractiveness scale, etc.). This information can help in decision making and in comparing scenarios with each other for NBS planning.

4.1.3.2 The UrbanBEATS planning-support tool

UrbanBEATS (Urban Biophysical Environment And Technologies Simulator) (Bach *et al.*, 2018; 2020) is an integrated modelling tool to support the planning of urban NBS. It was first developed in an Australian context but has since been applied outside of Australia (e.g., Nguyen *et al.*, 2022). It generates spatial maps of different alternatives of NBS layouts in an urban context according to stormwater management objectives chosen by the user. These objectives include runoff volume reduction, annual pollution load reduction (total suspended solids, total nitrogen, and total phosphorus) and volumetric reliability of harvesting and reuse of rainwater for specific end uses (e.g., irrigation). UrbanBEATS currently simulates wetlands, ponds & basins, swales, bioretention/raingardens, infiltration systems, and rain tanks which are the most studied technologies due to their effectiveness and ease of implementation (Wang *et al.*, 2023). Systems are sized based on pre-developed design curves and can be adapted according to the study context.

With the help of four input maps: land use, population, elevation and soil classification, UrbanBEATS represents the urban environment conceptually (Bach *et al.*, 2018), using a gridded map of 'Blocks' (usually 200m to 500m in resolution) as its smallest explicit spatial unit, each containing a database of urban characteristics. For NBS planning, the model considers solutions at four different scales:

i. the allotment;
ii. the streetscape, which encompasses a group of several lots around one or more access roads;
iii. the neighborhood, which is essentially the 'Block' and encompasses mixes of land uses;
iv. the sub-basin, which is a combination of 'Blocks', which are located within the same urban sub-catchment defined by topographic input.

To conceptualize the urban environment to obtain information necessary for NBS planning (e.g., impervious area, roof area, open and available spaces for NBS), UrbanBEATS uses its *Urban Planning Module* (Bach *et al.*, 2018) which follows three steps:

1. Collation and aggregation of input spatial data (more details about these data can be found in the supplementary material) to the simulation grid of 'Blocks'.
2. Identifying spatial relationships ('Block' neighbourhoods and sub-catchments)
3. Characterisation of urban characteristics generated procedurally using spatial planning ordinances (characteristics include building height and footprint, street widths, garden and available green space, impervious area, etc.).

Following this conceptualization, the *NBS Planning Module* (Bach *et al.*, 2020) then generates layouts in two steps:

1. Identifying possible NBS systems at the four different scales across the simulation boundary, testing different system sizes for stormwater management objectives and checking for available

space in the urban environment to accommodate these systems. System designs are represented as performance curves that are pre-generated using long-term historical climate data (rainfall and evapotranspiration).

2. Generation of NBS alternatives using the Monte-Carlo approach and the pre-established systems from the first step, generating thousands of siting options for different types of NBS and filtering these based on a multi-criteria matrix that reflects stakeholder preferences towards specific types of NBS systems.

These proposed alternatives are all technically feasible according to user-defined modelling objectives. As such, to differentiate and rank these, stakeholder preferences are incorporated. To date, this has solely been based on the choice of NBS technology, disregarding its spatial context. Combining the use of UrbanBEATS with MACBETH therefore allows for a broader consideration of objectives as well as the spatial context, that should result in better-informed NBS layouts.

4.1.4 Materials & Methods

4.1.4.1 Case Study Description: Toulouse Metropole, France

We tested our methodology on the case study of Toulouse Metropole (shown in Figure 10), located in the southwest of France. Data used in this work were obtained from the annual reports (Toulouse Metropole, 2022) compiled by the OTM (Observatoire Toulouse Metropole), a department within the municipality. These reports contain key information about the city's demography, environment, water management, waste management, energy, etc. based on the statistics obtained by the public agency INSEE (Institut national de la statistique et des études économiques).

Toulouse Metropole comprises 37 communes and a total population of almost 800,000 inhabitants in an area of 458 km². The city of Toulouse alone has almost 500,000 inhabitants in an area of 118 km². Its demographic growth is one of the fastest in France (+6.2% between 2013 and 2018).

The *Garonne River* is a major river and landscape element of the Metropole. Major historical floods (e.g., 26th June 1875) have led to the construction of infrastructures to minimise present and future impacts thereof. Generally, the risk of flooding is increased in the winter and spring months. The Garonne River is also the main source of drinking water through three treatment plants, which supply a network of more than 3,300 km carrying an average daily volume of water of almost 150,000 m^3. Toulouse Metropole has 17 wastewater treatment plants spread across the territory. Unlike other large French cities, Toulouse Metropole has separate sewer networks for wastewater and stormwater, where the latter is discharged directly with minimal treatment into the receiving environment (primarily the Garonne River).

Summer temperatures are among the highest in France, reaching up to 44°C, and remain above 0°C during winter months. Disturbances are related to Atlantic weather systems with an average of 150 rainy days per year, but a low annual rainfall of 700 mm.

Toulouse Metropole is currently carrying out projects to move towards a more resilient and sustainable territory (e.g., *100,000 Tree Plan*, *Grand Parc Garonne Project*). NBS planning is therefore an important issue and one that raises interest among decision makers.

All the spatial, climatic, and statistical data required for the study were available as open source or were provided by OTM or other partner organisations of the project. More details about data can be found in the supplementary material.

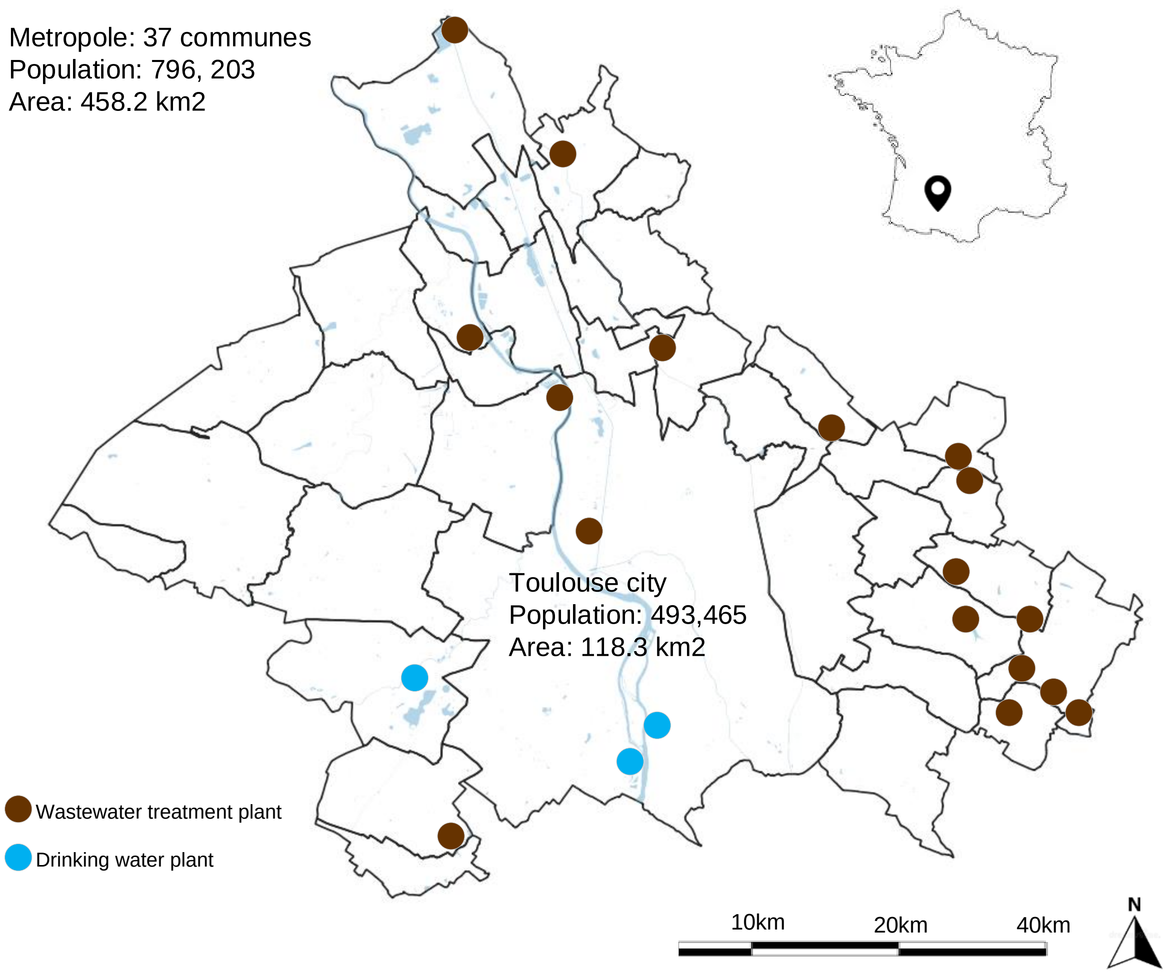


Figure 10 - Toulouse Metropole key statistics and location of main drinking water treatment plants

4.1.4.2 Integration of models to form the MCDA-NBS method

The proposed method was developed to better guide practitioners in their creation of NBS planning strategies using the MCDA method and, thus, linking the decision-making and biophysical sciences (Figure 11). The MCDA process produces the multi-criteria model of stakeholder preferences, and the UrbanBEATS model produces maps of NBS planning alternatives based on local biophysical conditions, which can be evaluated and scored with the multi-criteria model. By combining UrbanBEATS with MACBETH, it becomes possible to add new criteria not covered by UrbanBEATS and to help decision-making on the best NBS implementation strategy. The best scoring alternatives are presented to the stakeholders who discuss and refine the results to satisfaction by revisiting value scales, attractiveness values, weights or re-running the model.

This new MCDA-NBS method consists of 5 steps:

1. Stakeholder identification
2. Multi-criteria model development (using the MACBETH method)
3. NBS alternative generation (using the UrbanBEATS model)
4. NBS alternative evaluation (using UrbanBEATS outputs & multi-criteria model)
5. Results presentation and discussion with stakeholders

Step 1: Stakeholder identification. A recent literature review (Skrydstrup *et al.*, 2020) identified necessary stakeholders that should be involved in the context of urban planning for water management and the implementation of NBS. These different stakeholders can be classified into three levels (Sarabi *et al.*, 2019). The micro level includes citizens, landowners, associations, and non-governmental organisations, which play an important role in influencing decision-making around NBS planning strategies. The meso level includes municipal services, and local actors such as the water agency, which play a role in monitoring, supervision and financial support for the development of NBS. The macro level includes regional and national authorities and international organizations, which play an incentive role to accelerate the transition to NBS. Another level can provide the link between the micro, meso and macro levels and this role can be taken by non-governmental organisations (NGOs) for example. This list of relevant stakeholders forms the basis for our own list of participants which we sought involvement from in workshops for the case study. The final choice of stakeholders is left to the decision-makers. We distinguished the decision-makers from the stakeholders as the beneficiaries of the results (i.e., municipalities).

Step 2: Multi-criteria model development. This step involves applying the MACBETH method following the six steps described in section 2.1 with the help of the M-MACBETH software and a facilitator to guide the process. The criteria are elicited by the stakeholders' group and the facilitator cross-checks that all potential criteria have been included, considering the list of relevant criteria created by Skrydstrup *et al.* (2020) and the work of Qiu *et al.* (2022). Measuring criteria performance can be done using spatial, other quantitative or qualitative data. Criteria must be independent to simplify the MCDA models and care must be taken when choosing how to measure the criteria to avoid double counting, while scoring the alternative during the Step 4. However, these aspects can be considered using methods such as the Choquet integral.

Step 3: NBS alternative generation. Input data for the case study is prepared for the UrbanBEATS model and includes defining the scope of the study (e.g., catchment area, urban area). The first results generated by UrbanBEATS are the simplification of the territory into blocks and water flow network. By overlaying existing watercourses and stormwater networks, impervious areas with the model's outputs, we calibrate the model. Following calibration, we generate final results, which are the maps of NBS alternatives.

Step 4: NBS alternative evaluation. In this step, the MACBETH method and UrbanBEATS are combined. Each criterion developed in the multi-criteria model is calculated individually for each NBS alternative produced by UrbanBEATS. Then, the performance scores for each criterion are entered into the M-MACBETH software to give the overall score for the NBS alternatives. Negative values indicate that the alternative's performance on this criterion did not meet the target set by the stakeholders even if it satisfies its stormwater management objectives. Any spatial data linked to the MCDA model is overlaid with the UrbanBEATS maps of NBS alternatives with the support of GIS software (e.g., ArcGIS or QGIS). In the case of quantitative and qualitative data measures, GIS software can also support the calculations and analysis. Once the performance scores are entered into the M-MACBETH software, the overall score for each map of NBS alternatives is obtained, which is more rigorous than UrbanBEATS' own built-in multi-criteria preference matrix (Bach *et al.*, 2020).

Step 5: Presenting and discussing results. This last important step in the process validates the results. Not only the final scores of the alternatives are considered, but also the intermediate results obtained with the MCDA model and the UrbanBEATS model. These results are presented back to the stakeholders, and they can revisit the multi-criteria model (value scales, attractiveness values, weights) or the NBS alternatives. This may result in re-simulation and revisiting the discussion an additional time. At this stage we also need to think about knowledge transfer for future use. The data, UrbanBEATS, GIS data and M-MACBETH files as well as any Excel file with the detailed calculations should be passed on to the decision-makers. A training session about the use of the multi-criteria model in the future should be offered to the municipalities.

All five steps were applied to the Toulouse Metropole case study, results of which are discussed sequentially in the next section.

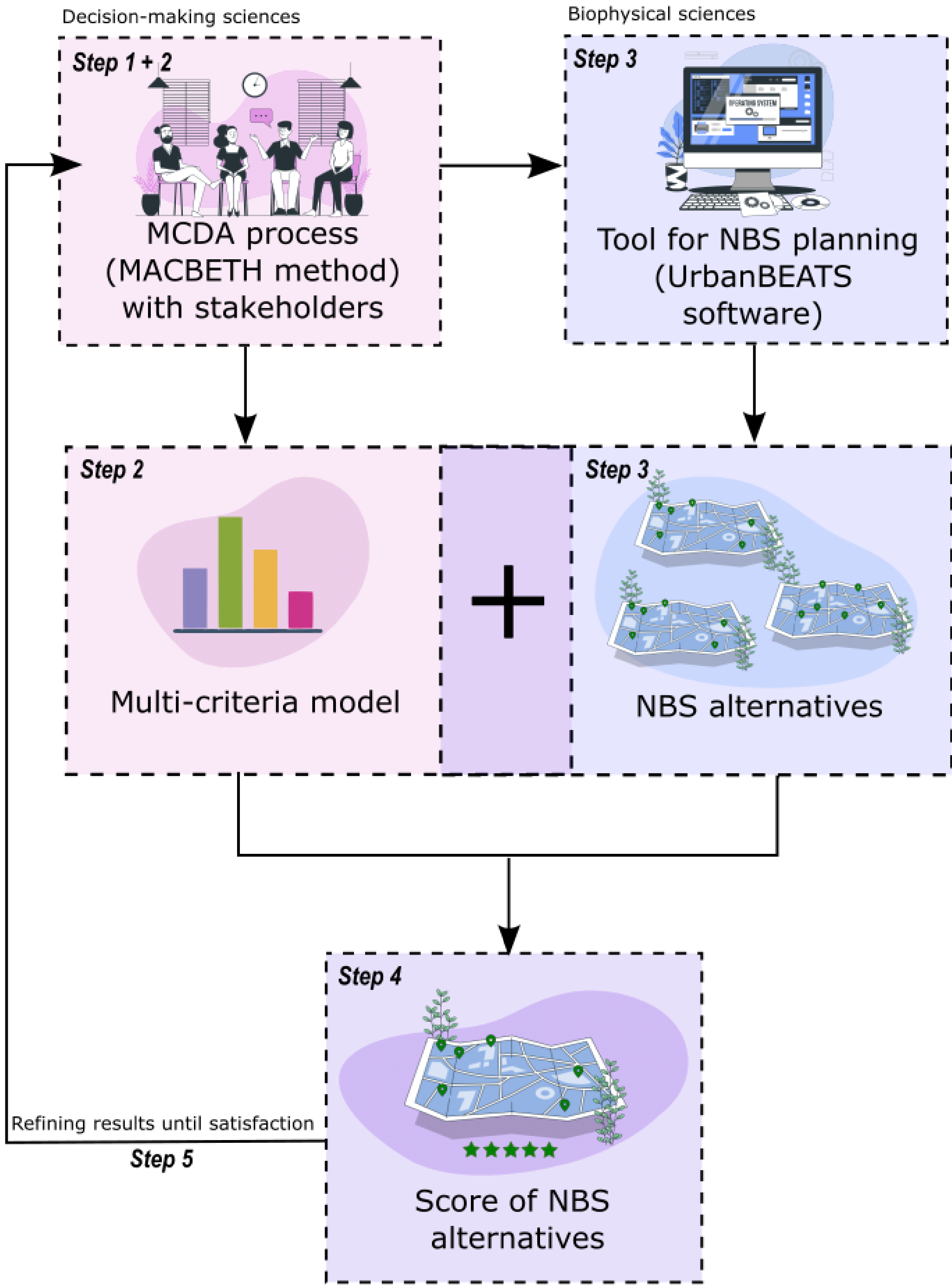


Figure 11 - MCDA-NBS method scheme representing the interaction between the decision-making sciences with the MACBETH process and the biophysical sciences with the engineering tool UrbanBEATS.

4.1.5 Results

4.1.5.1 Stakeholder identification for Toulouse Metropole

Initial contacts with decision-makers in Toulouse Metropole were established in November 2021. After explaining the project and issues involved in the MCDA process, they defined a group of eight stakeholders, who would take part in the workshops. We analyzed the stakeholders' profiles using the Skrydstrup *et al.* (2020) and Sarabi *et al.* (2019) classification (Table 7). Each participant had a different expertise, which helped to better represent the diversity of opinions. Stakeholders from the civil and academic categories as well as those who represent the economic aspects of NBS planning (e.g., real estate agent, investor) were absent. The eight stakeholders participated in three workshops in July 2022 with a final presentation and discussion in June 2023. Each workshop lasted about half a day (i.e., between 3 and 4 hours). Activities, duration, and tools used for the Toulouse Metropole case study are summarised in Table 8.

Table 7 - Stakeholders who participated in the workshops for Toulouse Métropole, based on Sarabi et al. (2019) and Skrydstrup et al. (2020).

Level	Category	Type	Number
Micro	Civil society	Citizen	0
		Association	0
	Professional / Consultant	**Architect-Urban planner**	**1**
		Architect-Landscape planner	**1**
		Engineer (water, environment, urban, climate)	**1**
		Estate agent/ Land manager / Insurance	0
		Investor	0
	Technician	**Water technician**	**1**
	Academic	Researcher (water, environment, climate, risk)	0
Meso	Municipality / City / Metropole	**Water & Environment**	**1**
		Health & Social	0
		Urban planning	**1**
		Traffic & Road	**1**
Macro	Government	Ministry	0
		Governmental agency	**1**

	Politician	0
	International agency	0

4.1.5.2 Workshops for MCDA model development

The main objective of the first workshop was to choose the criteria and start the reflection on their indicators (how the criteria can be measured). The stakeholders selected the 11 criteria presented in Figure 12. More details about the criteria measurement scales can be found in Appendix C. They decided to organize these criteria into three main categories (i.e., social, environmental, and technical). Most of these criteria are evaluated quantitatively as the distribution (%) of NBS in designated areas (e.g., priority biodiversity areas, flooding risk areas). Some criteria were assessed qualitatively (e.g., well-designed infrastructures) based on the expected performance of the NBS by assigning it a score between 0 and 3. Most criteria were measured using spatial data (e.g., urban heat island map or water table map).

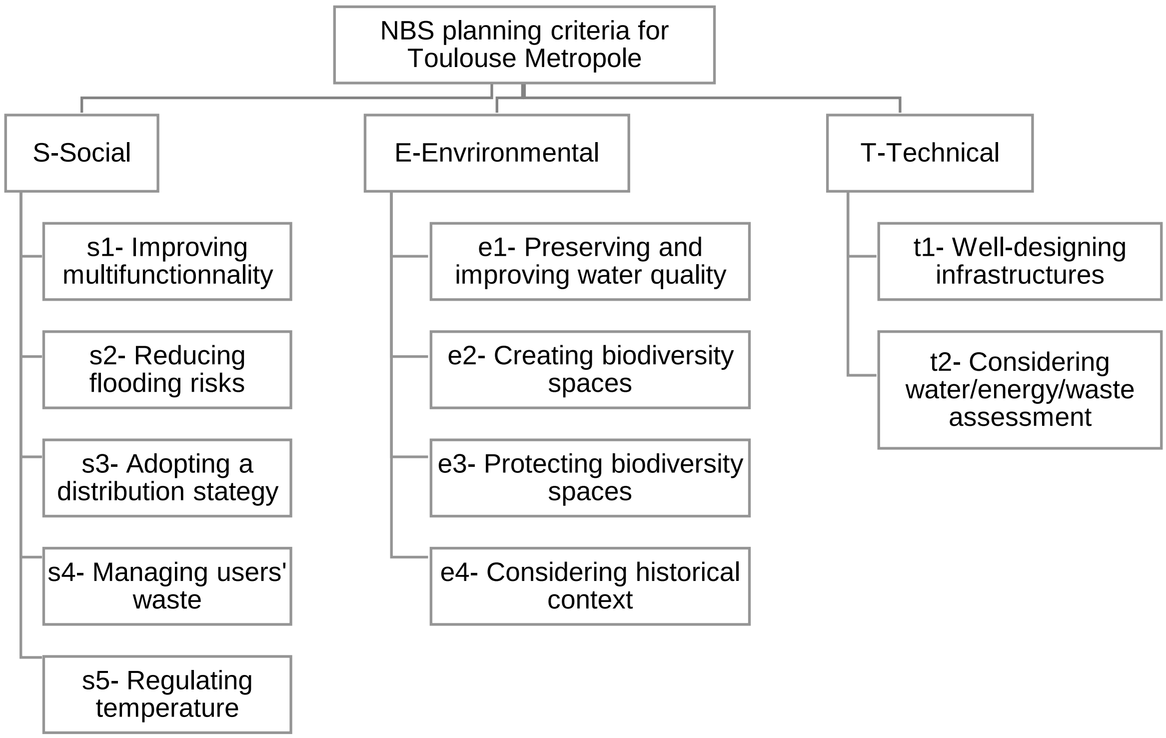
Table 8 - Workshop sessions for Toulouse Metropole case study.

Workshop	Activities	MACBETH step	Duration	Stakeholders	Tool
1	Participant presentation	-	30 min	All	
	Project presentation	-	30 min		Screen projector
	Criteria selection	1	2-3 h		Whiteboard, post-it
2	Criteria scaling	2, 3, 4	3-4 h	Sub-groups	M-MACBETH
3	Criteria weighting	5	3-4 h	All	M-MACBETH

The objective of the second workshop was to build the value scales of each criterion individually, defining the neutral and good benchmarks and the additional values. To minimise the length of these workshops, three sub-groups were formed based on the expertise of the stakeholders.

The objective of the third workshop was to define the weight of each criterion by pairwise comparison. Stakeholders modified two of their responses in the pairwise comparison exercise to arrive at final weights that suited them.

Figure 12 - Criteria selected by Toulouse Metropole stakeholders



4.1.5.3 NBS alternative generation and evaluation

To generate the NBS alternatives for Toulouse Metropole, the decision-makers asked to consider the entire Toulouse Metropole area. We found the simplification of the territory into 500m x 500m Blocks was sufficiently representative of the Toulouse Metropole dynamics. UrbanBEATS modelled the water flow network map, and it was found coherent with the existing watercourses and stormwater networks. This map can be consulted in the supplementary material file.

We ran simulations with a runoff and pollution reduction performance objective of 50% following the stakeholders' request and obtained 10 alternatives implementing 500 to 900 NBS installed over the entire 458 km^2 territory. These alternatives are all equivalent in terms of the objectives, but propose different strategies for implementing NBS (i.e., number, type, and location). The types of NBS most proposed by UrbanBEATS are bioretention, rain gardens, swales and trenches. This selection can be explained by the denser urban environment in Toulouse, which limits the possibility of installing large NBS such as ponds, basins and wetlands.

The evaluation of the 10 NBS alternatives with the multi-criteria model showed that Alternative #8 performs best, fulfilling not only UrbanBEATS' stormwater management objectives, but aligning most closely with the stakeholder MCDA model (see Figure 13). This alternative proposes the implementation of 231 bioretention, 123 trenches, 114 ponds and 55 wetlands. We obtained negative values for criteria s2 (reducing flooding risks), e4 (considering historical context) and t1 (well-designing infrastructures), with no alternative achieving the target. Moreover, criterion s4 (managing user's waste) had no impact on the ranking of alternatives, as its performance was identical for all ten selected alternatives exported by UrbanBEATS. The criteria with the largest impact on the ranking of alternatives are s1 (improving multifunctionality), s3 (adopting a distribution strategy) and e1 (preserving and improving water quality). Indeed, the performance of the alternatives on these criteria is broad, the difference of going from a neutral to a good benchmark and its weight is high for stakeholders. The chosen weights can be found in the supplementary file.

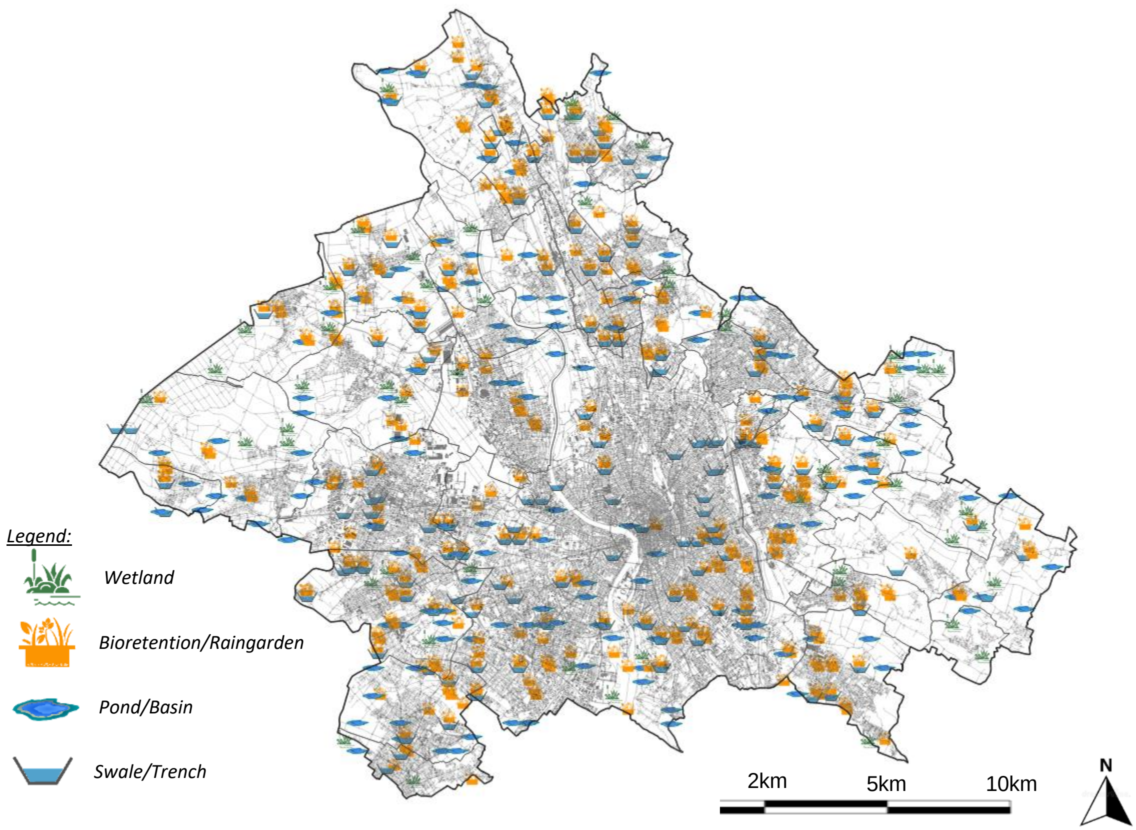


Figure 13 - Alternative 8 for Toulouse Metropole, best scored by the multi-criteria model

4.1.5.4 Presenting and discussing results with stakeholders

When presenting the results, the decision-makers (i.e., Toulouse Metropole representatives) and the stakeholders expressed their confidence in the multi-criteria model they had built (i.e. choice of criteria, indicator, data). However, a few adjustments had to be made, notably to the neutral and good benchmarks, which, in some cases were considered too high in relation to actual feasibility. They also confirmed that the UrbanBEATS output maps (i.e., water flow and NBS alternatives) were consistent with their knowledge of the Toulouse Metropole territory. The ten NBS alternatives proposed by UrbanBEATS imply a considerable number of NBS to be implemented (between 500 to 900 NBS, depending on the alternatives), which worried the stakeholders about the political and economic feasibility of such alternatives in the future. However, it has to also be acknowledged that systems proposed in this number can be grouped and reduced overall. Furthermore, these decision-makers saw opportunities for future research and informed decision in using the results.

Therefore, the next step of this pilot project is to identify which individual NBS has the most positive impact and brings the most benefits. A priority map can be built based on the best scored NBS alternative to help the decision-makers in their decisions and understand where to bring implementing NBS for their desired outcome. The decision-makers saw opportunities of replicating the process with other French cities to provide a basis for comparison and linking the results with projects currently under development (e.g., 100,000 Tree Plan, a strategic plan to plant trees in the metropole).

4.1.5 Discussion

4.1.5.1 Shortcomings and limitation of the MCDA-NBS method

The proposed MCDA-NBS method is the result of transdisciplinary research between the decision-making sciences and the biophysical sciences, combining the MCDA method, MACBETH, and the planning-support system based on engineering design and spatial analysis, UrbanBEATS. This MCDA-NBS method could be modified by replacing MACBETH by another MCDA method, but it would affect the multi-criteria model as other MCDA methods will not use the same algorithm. It will also affect the MCDA process itself as the workshop sessions follow the steps of the selected MCDA method. Notably, the MACBETH method relies on stakeholder's involvement and is especially well-designed to foster discussion and consensus. A facilitator is needed to lead the different steps of the MCDA process and to bring together decision-makers, stakeholders, and researchers. The facilitator should have expertise in MCDA as well as in the software used. It also requires a time investment of the stakeholders for the workshops, 10 to 20 hours per person. The assessment of alternatives by the research team depends on the complexity of the criteria chosen, 50 to 80 hours per person for the different case studies. The MACBETH method comes with the M-MACBETH software to support the method, which allows validation on the robustness of the model by analysing the consistency of stakeholders' judgements, the influence of the criteria on the overall multi-criteria model or on the evaluation of the NBS alternatives. The tool is under a commercial licence (i.e., between 1,500$ and 15,000$ depending on the licence). Other MCDA methods (e.g., PROMETHEE) also offer software to support the process and other tools to support MCDA-NBS method (Bousquet *et al.,* 2023).

Regarding the UrbanBEATS software, it is freely available in its first (current) version, unlike the other tools mentioned in the literature which are under a paying licence or not shared by their developers (Bousquet *et al.*, 2023a). It easily allows visualizing different alternatives of NBS locations on a territory with little input data and was designed to be adaptable to various contexts, which is rarely the case with other tools in the literature (Bousquet *et al.*, 2023a). As with most models, UrbanBEATS depends on data accessibility and quality, which can be an issue in some applications. Moreover, UrbanBEATS does not directly integrate MCDA models other than its simplified preference matrix for different NBS technologies, which means that the performance of each alternative must be calculated separately. Some independent GIS-based tools have been developed that integrate MCDA analysis (Table 2, Bousquet *et al.*, 2023a), but this approach is inconsistent with a full MCDA process where the first step is the selection and definition of criteria, which depends on the context. Indeed, the choice of criteria, their evaluation and the objectives are not the same from one context to another and it is therefore difficult to generalise it within a model.

Finally, it is worth mentioning that, in addition to the Toulouse Metropole case, this method was also tested in Trois-Rivières (Canada) and Melbourne (Australia), two other different climatic, urban, and socio-political contexts (Bousquet *et al.*, 2023b). The decision-makers were convinced that the results of this study can help them to take some decisions about NBS planning.

4.1.5.2 Toulouse Metropole feedback

The case study of Toulouse Metropole was used to test and illustrate the MCDA-NBS method. The choice of stakeholders who will participate in the workshop sessions was left to the decision-makers (i.e., Toulouse Metropole representatives). Thus, the stakeholder group was composed of eight people with different profiles as recommended by the scientific community, because they understood the benefits of representing a diversity of opinions and not an over-representation of one aspect. However, some profiles were missing such as the civil society category and economic experts (i.e., investor, land developer), deemed by the decision-makers irrelevant or too complex to integrate. Also, researchers were not represented, even though they are relatively easy to approach and a research partnership with some of them had already been established in Toulouse (i.e., INSA Toulouse). Decision-makers found it more important to integrate professionals rather than academic stakeholders and considered that the academic aspect was already present in this research project.

Regarding the choice of criteria by the stakeholders given the recommendation (Figure 13) of Skrydstrup *et al.* (2020), some social (e.g., mobility) and technical (e.g., integration with grey infrastructure) aspects have not been addressed. However, other criteria not included in the list of Skrydstrup *et al.* (2020) were considered, such as the historical context or the impact of user waste. In an MCDA process, the criteria depend on the stakeholder group and are therefore subjective. Nevertheless, recommendations from the literature can be relevant to validate with stakeholders that they have not forgotten an important aspect to consider. Steps 2, 3 and 4 of the MACBETH method (see section 2.1) were carried out in sub-groups during the second workshop sessions. It saved a lot of time for the stakeholders, but it required additional work during the last workshop where the stakeholders had to explain their choices to each other. Furthermore, at the beginning of each of the second workshop's sessions, each subgroup selected the criteria they wanted or felt comfortable working on, which implies that the last subgroup had to work on the remaining criteria. In an ideal process, all participants should be involved in every stage and decision or the allocation of criteria between sub-groups should be done beforehand. The inconsistencies identified by the M-MACBETH software during the process were well understood by the stakeholders after demonstration and explanation by the facilitator, which supports the importance of the role of an external person with expertise in MCDA.

The stakeholders validated the UrbanBEATS results however, the high number of NBS (i.e., between 500 and 800) proposed by the ten selected alternatives is an actual issue because it is not feasible in a 10-50 years action plan. An additional step would be to identify which NBS have the most impact to be implemented first. Toulouse Metropole's decision-makers are interested in sharing this project with other municipalities to persuade them to apply the process themselves and compare their results. They also identified opportunities in linking the NBS planning strategy selected with ongoing projects such as the 100,000 Trees Plan.

4.1.5.3 Recommendations and future work

The MCDA-NBS method is a participatory approach and must include representatives of civil society, researchers, and economic experts in future case studies to follow scientific recommendations. Since such types of stakeholders were missing in the Toulouse case study, it would be interesting to repeat the process after adding these stakeholders and to analyze their effect on the multi-criteria model.

In MCDA methods, the criteria selected by the stakeholders should be measurable from available data or expressed on a qualitative scale. Care must be taken to ensure that these criteria are independent and that there are no interactions between them, which could lead to double counting and, ultimately, unsatisfactory results. MACBETH was developed with exactly this in mind. Moreover, if the MCDA-NBS method is applied in other study cases, it could be interesting to identify criteria which are often selected by the stakeholders and integrate them within the UrbanBEATS model or others. This would improve the quality of the preliminary results produced by these tools by considering an important aspect for all municipalities.

Regarding the use of the UrbanBEATS software, simulations were carried out using a selection of the 10 best alternatives (filtered from 1000 generated options). This selection could be larger (e.g., 100) and could lead to the development of an automatic algorithm based on the multi-criteria model for NBS alternative evaluation rather than manual evaluation. NBS alternatives can also come directly from decision-makers and not from the UrbanBEATS model, based on scenarios developed internally, that would be evaluated using the same multi-criteria model. To take this a step further, the alternative with the highest score using the multi-criteria model could be used to prioritize NBS' implementation. Performance of each NBS could be analysed to identify which NBS brings the most benefits and is therefore the most interesting to prioritize for implementation. This can be done using the multi-criteria model which often integrates this aspect in the criteria evaluation. This analysis can lead to the development of a priority map of the NBS which have the highest impact. UrbanBEATS could then be expanded to integrate NBS preferences based on this analysis. The model could also integrate new NBS such as green roofs, green facades or porous pavements which are increasingly considered by decision-makers but beyond the model's scope.

In its current state, the proposed MCDA-NBS method does not include costs because the research on this aspect is still in its infancy for NBS options. Recent research (e.g. carried out by CERIU (*Centre d'Expertise et de Recherche en Infrastructures Urbaines*)) is conducting interviews with experts in several countries to estimate the costs involved in implementing NBS. It would be interesting to integrate this recent work into the Toulouse case study and add a benefit-cost analysis to the results of the MCDA-NBS method. Finally, future work could also test the MCDA-NBS method in other contexts to demonstrate the relevance of MCDA for NBS planning. This is the subject of current work that evaluates the method in different geographical, socio-political and urban contexts.

4.1.6 Conclusion

This paper presented a new MCDA-NBS method which aims to improve the decision-making process for NBS planning. This new MCDA-NBS method uses five steps that combine the MACBETH method and the engineering-based planning-support model UrbanBEATS. MACBETH is an advanced MCDA method that helps stakeholders build a multi-criteria model representing the preferences of stakeholders. The M-MACBETH software supports the application of the method and automatically verifies judgment consistency which significantly decreases the risk of bias. UrbanBEATS generates spatial layouts of NBS alternatives. It suggests the type of NBS to be implemented regarding their performance in achieving the stormwater management objectives.

We illustrated the application of the MCDA-NBS method with the case study of Toulouse Metropole which brought together eight stakeholders to develop the multi-criteria model and discuss and refine the results. This case study showed the relevance of involving stakeholders to better consider context-specific objectives and to foster implementation of the results in the future. Stakeholders were confident in the results provided by M-MACBETH and UrbanBEATS. Stakeholders identified opportunities of using these results in an ongoing project and for the development of future projects in urban planning and water management at different scales (i.e., city scale for action plan, infrastructure scale for design).

As this is a transdisciplinary project, results can be useful in many fields (e.g., urban planning, water management, sustainable development) by providing new data on specific criteria. Therefore, beyond the final score, each step of this new MCDA-NBS method is relevant as we obtained intermediate results along the process (e.g., value scales on criterion, which can be found in the supplementary material file) which can be useful independently.

Future work should include testing this new MCDA-NBS method in other contexts, conducting multi-criteria assessments based on existing planning alternatives, comparing more than 10 NBS alternatives generated by UrbanBEATS and automating the multi-criteria evaluation, improving UrbanBEATS to integrate other types of NBS and their costs, adding a cost-benefits analysis into the multi-criteria model, and integrating the civil society and researchers in the MCDA process.

4.2 Nature-Based Solutions planning: a collaborative work between researchers and decision-makers[1]

Bousquet Morgane[1*], Vanrolleghem Peter A.[2]

[1]modelEAU, Université Laval, Département de génie civil et génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada – morgane.bousquet.1@ulaval.ca

[2]modelEAU, Université Laval, Département de génie civil et génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada – peter.vanrolleghem@gci.ulaval.ca

[*]morgane.bousquet.1@ulaval.ca ; +33 620611762

Keywords: multicriteria decision aid, nature-based solutions, planning support, participative method, transdisciplinary

4.2.0 Résumé (français)

Les Solutions Fondées sur la Nature (SFN) suscitent de plus en plus l'intérêt des décideurs et des chercheurs notamment par leur capacité à apporter de multiples bénéfices en milieu urbain. Elles sont ainsi une alternative durable intéressante face aux enjeux globaux de développement urbain et de changements climatiques. Une méthode d'Aide à la Décision MultiCritère (AMCD) pour l'implantation des SFN a été récemment développée et appliquée à trois cas d'études aux contextes géographiques, socio-politiques et urbains distincts (Trois-Rivières au Canada, Toulouse en France et Melbourne en Australie). Elle vise à évaluer des options stratégiques d'implantation des SFN avec un modèle de préférence multicritère construit par un groupe de parties prenantes lors d'ateliers participatifs. La mise en place d'une méthode AMCD-SFN demande une collaboration importante entre les chercheurs, les décideurs et les parties prenantes, ce qui en fait une approche transdisciplinaire. Nous présentons dans cet article (i) les caractéristiques et les rôles de ces différents acteurs, (ii) les dynamiques de collaboration tout au long du processus, (iii) une feuille de route et (iv) les avantages et les limites d'une telle approche transdisciplinaire. Il est important de vérifier que l'équipe de recherche possède les connaissances suffisantes, que les profils des parties prenantes impliquées sont diversifiés, que les résultats correspondent aux attentes des décideurs et qu'ils aient la capacité de les exploiter. Ce type d'approche transdisciplinaire offre l'opportunité de créer un dialogue entre les acteurs et de favoriser la prise de décision pour l'implantation stratégique des SFN. Cependant, elle demande un investissement en temps important qui est le frein principal à sa mise en place.

[1] This chapter has been submitted and accepted to the Techniques Sciences Methodes journal (i.e., Astee publishing). It has been traduced from French to English for this thesis.

4.2.1 Abstract

Nature-Based Solutions (NBS) are increasingly attracting the interest of decision-makers and researchers, in particular because of their ability to provide multiple benefits to urban environments. They are an interesting sustainable alternative to deal with the global challenges of urban development and climate change. A Multicriteria Decision Aid (MCDA) method for the implementation of NBS was recently developed and applied to three case studies with distinct geographical, socio-political and urban contexts (Trois-Rivières in Canada, Toulouse in France and Melbourne in Australia). It aims to evaluate strategic alternatives for the implementation of NBS with a multicriteria preference model built by a group of stakeholders during participatory workshops. The implementation of an MCDA-NBS method requires significant collaboration between researchers, decision makers and stakeholders, making it a transdisciplinary approach. In this chapter we present (i) the characteristics and roles of these different actors, (ii) the dynamics of collaboration throughout the process, (iii) a roadmap and (iv) the advantages and limitations of such a transdisciplinary approach. The experience shows that it is important to check that the research team has sufficient knowledge, that the profiles of the stakeholders involved are diverse, that the results correspond to the expectations of the decision-makers and that they have the capacity to exploit them. This type of transdisciplinary approach offers the opportunity to create a dialogue between stakeholders and to improve decision-making for the strategic implementation of NBS. However, it requires a significant investment of time by the stakeholders, which is the main obstacle to its application.

4.2.2 Introduction

Nature-Based Solutions (NBS) (United Nations, 2022) are increasingly seen as an innovative and more sustainable alternative to the current management of urban stormwater by grey infrastructures (Hamouz *et al.*, 2020; Steis *et al.*, 2020).These are vegetated technical infrastructures such as rain gardens, green roofs and walls, ponds, trenches and swales, artificial wetlands and porous pavements, which enable more effective management of stormwater at source by improving the functions of infiltration, evapotranspiration, retention, conveyance and removal of pollution (Kuller *et al.*, 2017). In this way, they reduce the risk of flooding, improve the quality of surface water, and regulate resource consumption by recovering and reusing stormwater. Furthermore, when strategically located in an area, NBS can provide other co-benefits such as regulating temperature and reducing the effects of urban heat islands, improving the aesthetics of a neighborhood and the well-being of citizens, or protecting and creating urban biodiversity (Dagenais *et al.*, 2017; Lienert *et al.*, 2015; Skrydstrup *et al.*, 2020). However, most studies focus on environmental aspects, in particular stormwater management to limit flood risk (Meerow, 2019, 2020; Meerow & Newell, 2017; Monteiro *et al.*, 2020) and do not take into account the other benefits provided by NBS.

Multicriteria Decision Analysis (MCDA) is a participatory approach that is increasingly used for NBS planning (Bousquet *et al.*, 2023a) because it allows several objectives (benefits) to be considered simultaneously. It offers a rich collection of methods (Belton & Pictet, 1997; Belton & Stewart, 2002) to combine the diverse, subjective preferences of stakeholders in a multicriteria model for the design, evaluation and prioritisation of decision alternatives (Ferretti & Montibeller, 2016; Marttunen *et al.*, 2017). A participatory (Schein, 2017) and constructivist (Landry, 1995) approach has been recognised as preferable by the scientific community (Belton & Pictet, 1997), as it would favour the implementation of decisions in 80% of case studies (Nutt, 1999). By "participative", we refer to a collaborative process in which several stakeholders become involved in order to carry out a task. By "constructivist", we refer to a process consisting of several stages which produce a result when they are put together. Strategic planning of NBS requires the alignment of several stakeholders (architects, urban planners, politicians, associations, technicians, etc.), each with different expertise and visions of the problem situation (Albert *et al.*, 2021; Atiqul Haq *et al.*, 2021; Dorst *et al.*, 2019; Eckart *et al.*, 2017; Skrydstrup *et al.*, 2020; Vulbeau, 2014; Webber & Kuller, 2021; Yeo *et al.*, 2022). However, 39% of the MCDA studies for NBS planning found in literature do not involve stakeholders in the process and when they do, it is mainly experts solicited for the criteria weighting phase (Bousquet *et al.*, 2023a).

A new approach to NBS planning (Bousquet *et al.*, 2023b) has been developed around participatory workshops, combining a MCDA method (MACBETH) (Costa, 2012; Costa *et al.*, 1999, 2003, 2019) and planning-support engineering model (UrbanBEATS) (Bach, 2014; Bach *et al.*, 2015a; 2015b; 2018; 2020a; 2020b). This approach was developed so as to be transferable to any geographical, socio-political, environmental and urban context. Between 2021 and 2023, it was applied to three case studies, Trois-Rivières (Quebec, Canada), Toulouse Métropole (France) and Melbourne (Australia), which brought together stakeholders with different profiles around workshop sessions. Collaboration between researchers, decision-makers and stakeholders has therefore been an important element in the process, which sometimes requires a readjustment of research questions, methods and results to better meet the needs and practices associated with a certain context (Graça *et al.*, 2022). Then, the process becomes transdisciplinary and more difficult to implement but is considered as a key success factor by the scientific community (Albert *et al.*, 2021; Atiqul Haq *et al.*, 2021).

The main objective of the study reported in this chapter is to better guide researchers and decision-makers in the implementation and application of a transdisciplinary MCDA approach for NBS planning. It will (i) identify the various actors in the MCDA process for NBS planning (MCDA-NBS), (ii) study the dynamics of collaboration between these various actors, (iii) propose a roadmap for implementing collaborative work and (iv) discuss the advantages and limitations of such an approach. It will use the three case studies (Trois-Rivières, Toulouse Métropole, Melbourne) to illustrate the approach in practice and demonstrate its transferability to other contexts.

4.2.3 Material and method

4.2.3.1 Presentation of the MCDA-NBS method

The MCDA-NBS method is designed to better guide decision-makers in their NBS planning strategy using the MCDA method, MACBETH, and its tool, M-MACBETH, as well as the planning-support engineering model, UrbanBEATS (Bousquet *et al.*, 2023b). This method is organised into five stages: 1) identification of the stakeholders, 2) application of the MCDA process using the MACBETH method, 3) obtaining NBS alternatives using the UrbanBEATS model, 4) evaluation of the alternatives using the multicriteria model, and 5) presentation and optimisation of the results.

On the one hand, the MACBETH method (Measuring-Attractiveness by a Category-Based Evaluation TecHnique) is used to obtain the stakeholders' multicriteria preference model (Costa, 2012; Costa *et al.*, 1999, 2003, 2019). The M-MACBETH tool enables the MACBETH method to be applied and automatically checks the consistency of the data as the judgements provided by the stakeholders are entered into the software. It automatically generates a numerical scale consistent with all the judgements and criteria weightings. At the end of the process, we obtain several types of data on the criteria and their preferences (weighting, utility function, attractiveness scale, etc.). A recent study (Bousquet *et al.*, 2023b) presents a more detailed application of the MACBETH method in a context of NBS planning with the Toulouse Metropolis. However, MACBETH is not the only MCDA method that can be used and more precise descriptions of these can be found in the work of Belton & Pictet (1997) and Belton & Stewart (2002). However, these MCDA methods and the tools that support them (e.g. M-MACBETH) remain complex and are considered inaccessible to a user with no prior experience (Mustajoki & Marttunen, 2017). A facilitator is therefore strongly recommended to lead meetings and group exercises (Griffith *et al.*, 1998), to guide and analyse each stage of the process (Franco & Montibeller, 2010), and to use the tools (Lagroue III, 2008; Thorpe, 2016).

On the other hand, the UrbanBEATS (Urban Biophysical Environment And Technologies Simulator) model (Bach, 2014; Bach *et al.*, 2015a; 2015b; 2018; 2020a; 2020b) allows, with a scenario linked to an urban context, to produce several alternatives for the implementation of NBS on a territory according to the objectives chosen by the user. UrbanBEATS considers three objectives: runoff volume, pollution reduction (suspended solids, nitrogen and phosphorus) and rainwater harvesting for specific uses. Several types of NBS are simulated by the model (wetlands, rain gardens, swales, etc.) and can be easily configured by the user to suit the context studied. These proposed alternatives are all equivalent in terms of water management performance and can be evaluated subsequently using the MACBETH multicriteria preference model. The best-rated alternatives are then presented to the stakeholders, and the results can be refined until satisfaction is achieved. Once again, the study by Bousquet et al (2023b) presents a more detailed application of UrbanBEATS to the context of Toulouse Metropole.

4.2.3.2 Presentation of the study cases

The MCDA-NBS method was developed and tested in three case studies, Trois-Rivières (Quebec, Canada), Toulouse Métropole (France) and Melbourne (Australia), with different geographical, socio-political, environmental and urban contexts.

The first case study is the municipality of Trois-Rivières, located in the province of Québec (Canada) on the banks of the St. Lawrence River. Supplied by the Great Lakes, the river is the municipality's main source of water (Hébert & Belley, 2005). The 2020 census, carried out by the Ministère des Affaires Municipales et de l'Habitation (MAMH) indicated a total population of 136,470 people and a density of 472 people/km^2 for a territory of 289 km^2. Population trends predict an 18% increase by 2040 (Statistics Canada, 2022) and the municipality's average water consumption is 389 l/person/day, 11% higher than the national average of 350 l/Canadian/day, but still lower than the average for the province of Québec (400 l/person/day) (Trois-Rivières, 2022). Canada's climate forecasts predict warming that is twice as strong as in most other countries, due to the loss of the ice cover that usually reflects 90% of solar radiation (Bush *et al.*, 2019). One of the consequences is less snowfall in winter, replaced by more frequent rainfall in winter but also in summer (Rayfield *et al.*, 2016). One of the main challenges identified by the municipality of Trois-Rivières is to reduce the risk of flooding, which is significant due in particular to the proximity of the water table to ground level and the topography, which creates a significant risk of runoff during periods of rain and snowmelt (Figure 14).

The second case study is that of the Toulouse Metropolitan Area, and the statistics given are taken from the latest annual report for 2022 of the OTM (Observatoire Toulouse Métropole). Toulouse Metropole is an area in the south-west of France comprising 37 communes and a total population of 796,203 over a surface area of 458.2 km². The city of Toulouse alone has 493,465 inhabitants over an area of 118.3 km², and its demographic growth is one of the highest in France (+6.2% between 2013 and 2018). Its river, the Garonne, is the metropolitan area's main source of drinking water. Its management requires extra vigilance in winter and spring, when the flood risk is largest, and in summer during periods of drought. The Garonne is also the main collector of stormwater in the area because, unlike other large French cities, Toulouse Metropole has a separate network with separate collectors for wastewater and stormwater. Drinking water consumption per person is around 150l/person/day, less than half that of Trois-Rivières. Climate forecasts predict an increase in temperatures, leading to periods of drought and more severe heat waves. One of the main issues identified by the city is the greening of its territory, which is currently highly impermeable (Figure 15).

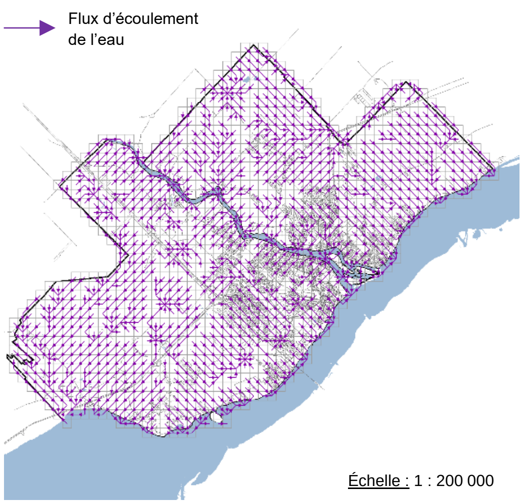


Figure 15 - Water flow in Trois-Rivières (Quebec, Canada), simulated by the UrbanBEATS model (Peter M. Bach)

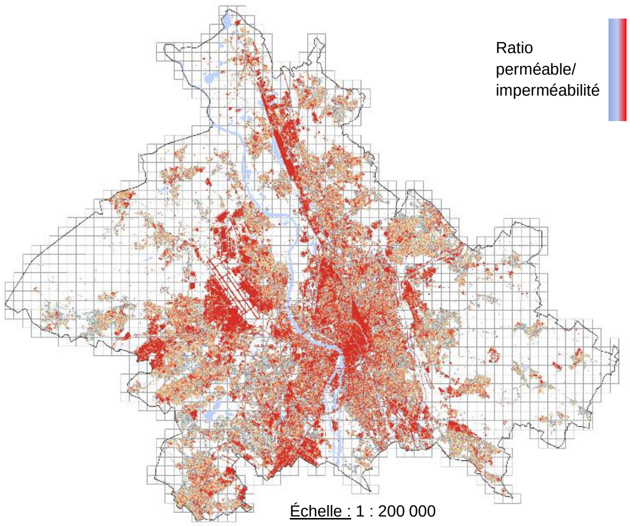


Figure 16 - Level of impermeability in the Toulouse Metropole, simulated by the UrbanBEATS model (Peter M. Bach)

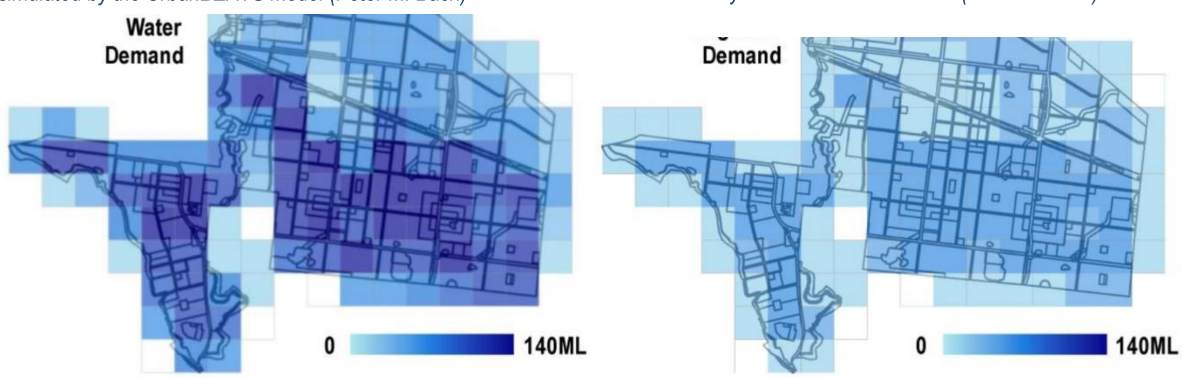


Figure 14 - Total water demand per day in ML (left) and total irrigation demand in ML (right) over a portion of the Greater Melbourne area (Australia), simulated by the UrbanBEATS model (Peter M. Bach)

The third case study is the Great Melbourne area, located in the state of Victoria, in the south of Australia, at the junction of the Indian Ocean and the Tasman Sea. The following statistics are taken from the 2022 Annual Reports of the Victorian State Government and the Metropolitan Water Management Agency, Melbourne Water. Its total population is estimated at over 5 million, spread over an area of 10,000 km² and 37 municipalities. The municipality of Melbourne itself had a population of 183,750 in 2020, covering an area of 37.7 km². As a coastal city, climate forecasts predict a rise in sea levels that could lead to natural disasters. In addition, summer temperatures and periods of drought could increase the risk of forest fires. Water management in the Metropolitan area is divided into five basins according to the major water sources and reserves that cross it. Average consumption is 166l/person/day. One of Melbourne's main challenges is to recover and recycle water to meet the high demand for water in certain areas (Figure 16).

4.2.4 Results and discussion

4.2.3.1 Identification of actors

The first step in the MCDA-NBS method is to identify the stakeholders, who can be classified into the following three categories:

a. The researchers, who lead the research project, and their academic partners
b. The decision-makers, who are partners in the municipality being studied
c. Stakeholders, who are external collaborators in the project and who will take part in the participatory workshops.

The researcher-decision-maker partnership can be set up either by decision-makers who express a particular need to the research community, or by researchers who approach decision-makers as part of their research work. Researchers may work in the academic public sector or in private organisations. The decision-makers, for their part, play a decision-making role in the municipality and are essential to the project in order to encourage the appropriation and application of the results. As part of the research with the three case studies of Trois-Rivières, Toulouse and Melbourne, it was the researchers who approached the decision-makers and convinced them of the relevance of their work to their municipality's objectives.

Regarding the stakeholders who participate in the workshop sessions, an analysis of the relevant stakeholders can be made (Marais & Abi-Zeid, 2021) according to whether they are affected by the problem (imperative analysis) or whether they occupy formal positions related to the problem (positional approaches) (Puchol-Salort *et al.*, 2020). In the context of urban planning for water management through the implementation of NBS, a recent literature review (Skrydstrup *et al.*, 2020) identified the stakeholders that would be relevant. These different stakeholders can be classified according to three levels (Sarabi *et al.*, 2019). The micro level includes citizens, landowners, associations, and non-governmental organisations, which play an important role by influencing decision-making. The meso level includes municipal services and stakeholders who play a role in monitoring, supervision, financial and land support. The macro level includes regional and national authorities and international organisations, which play an incentive role to speed up decision-making and the implementation of actions.

Table 7 presents the profiles of the stakeholders who took part in the workshops for the Trois-Rivières, Toulouse and Melbourne case studies. The Trois-Rivières case study brought together 12 stakeholders for 10 virtual workshop sessions of around 2 hours each between January and April 2022. The Toulouse case study brought 8 stakeholders who took part in 3 workshop sessions each, for a total of approximately 10 hours per stakeholder, between July and August 2022. Finally, following the same sequence as the Toulouse case study, the Melbourne case study brought together 12 stakeholders in May 2023.

Table 9 - Stakeholders who took part in workshops to apply the MCDA-NBS method by Bousquet et al. (2023b), adapted from Sarabi et al. (2019) and Skrydstrup et al. (2020).

Level	Category	Type	Trois-Rivières	Toulouse	Melbourne
Micro	Civil society	Citizen			
		Association			
	Professional / Consultant	Architect – Urban planner	3	1	1
		Architect - Landscaper		1	
		Engineer (water, environment, urban, climate)	3	1	3
		Real estate / Land owner / Insurance			
		Investor			
	Technician	Technician (water)	1	1	1
	Academia	Researcher (water, environment, climate, risk)			3
Meso	Municipality / City / Metropole	Water & Environment	1	1	1
		Health & Social	1		1
		Urban planning	2	1	1
		Road & Infrastructures	1	1	
Macro	Government	Ministry			1
		Governmental organization		1	
		Politician			
		International organization			
Total			12	8	12

Thus, none of the three case studies was able to bring together all the stakeholder profiles suggested by (Skrydstrup *et al.*, 2020) and (Sarabi *et al.*, 2019). Despite the research team's recommendations, the value of having diverse profiles may not have been well understood by the decision-makers, which could explain the absence of stakeholders from the academic world in the Trois-Rivières and Toulouse studies, even though these stakeholders are easy to approach in the context of research projects. Another explanation could be a lack of accessibility for certain stakeholder profiles, or that they are considered by decision-makers to be non-essential to the success of the project. Indeed, the need to have a representative from an international organisation as recommended by Skrydstrup et al (2020) when we are studying a local situation can be questioned. We can also wonder about the relevance of differentiating architects, urban planners and landscape architects because they are generally at the intersection of these aspects. Government representatives, particularly politicians, are often considered to be inaccessible and are therefore rarely present in projects, despite their importance (Skrydstrup *et al.*, 2020).

The presence of these stakeholder profiles in the Toulouse and Melbourne case studies therefore adds real value to the research project. Furthermore, none of the three case studies was able to involve representatives of civil society and economic players (investors, land managers). The decision-makers believe that the stakeholders within the municipalities have the capacity to represent civil society, as surveys and sociological analyses are carried out throughout the year. As for economic stakeholders, they remain relevant because financial knowledge on NBS is lacking in the literature (Bousquet *et al.*, 2023a) and their participation could contribute to enriching knowledge on the subject.

We can also question the value of having several people with the same profile, as was the case in the Trois-Rivières (3 urban planners, 3 engineers) and Melbourne (3 engineers, 3 researchers) case studies. This increases the risk of creating an unbalanced representation of a specific view of the problem by giving more attention to one criterion.

4.2.3.2 Collaboration dynamics

Application of the MCDA-NBS method involves collaboration between the three types of actors identified in the previous section, i.e. researchers, decision-makers and stakeholders (Figure 17). The identification of stakeholders (1) is guided by the researchers, but the choice of stakeholders is made by the decision-makers. The MCDA process following the MACBETH method (2) is applied by the researchers with the stakeholders. The research team uses the UrbanBEATS model (3) to obtain NBS alternatives and uses the multicriteria model (4) to evaluate them. Finally, the presentation of the results and their optimisation (5) brings together the researchers, decision-makers and stakeholders.

The researchers are present at each stage of the MCDA-NBS method, and their areas of expertise are related to water management (more specifically stormwater management), decision sciences, urban planning and engineering (for the development of water engineering models). The research team brings together experts in technical and social sciences. They are responsible for the more technical stages of the method, such as configuring the UrbanBEATS model, generating the NBS alternatives and calculating the criteria scores for each of the alternatives so that they can be ranked.

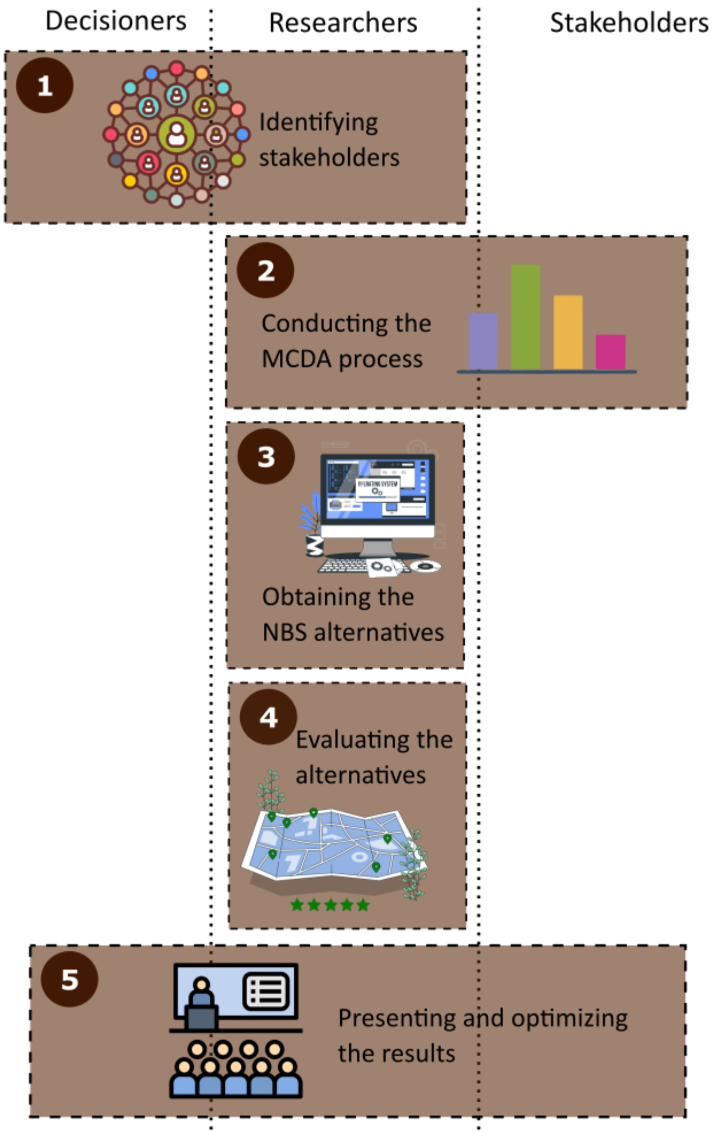


Figure 17 - Interactions between decision-makers, researchers and stakeholders following the steps of the MCDA-NBS method (Bousquet et al., 2023b)

Partners from external institutions (e.g. INSA Toulouse, Melbourne Water) helped to establish the contact between the research team and the decision-makers. These partners were an important asset to the research, helping to convince the decision-makers to participate in the project. Had these partners not been present, additional efforts would certainly have been needed to convince the decision-makers. Subsequently, it is the decision-makers who establish contact between the researchers and the stakeholders.

It is only during the final stage of the MCDA-NBS method that the three stakeholder groups interact directly with each other. All the results (multicriteria model, UrbanBEATS alternatives, scores, etc.) are given to the decision-makers. Beyond the results, it is important to think about knowledge transfer to support decision-making and the application of future strategies based on the results of the research. As part of the Trois-Rivières case study, the decision-makers expressed a need for training so that they could continue to work with the MACBETH multicriteria model in the future. They would also like to present the work to other Québec municipalities and suggest that they carry out the same process in order to have a common approach. In the case studies of Toulouse Metropole and Melbourne, the final results have not yet been presented. This is expected to happen by the end of 2023. However, stakeholders and decision-makers have stated that they have understood the value of such a multicriteria process and that they wish to use the results even if they would require additional research.

Several elements need to be checked before setting up such collaborative work (Figure 18). Before applying the MCDA-NBS method, the composition of the research team and the stakeholders involved in the process must be analysed. Once the MCDA-NBS method has been applied, it is recommended that decision-makers and stakeholders are satisfied with the results and discuss about knowledge transfer.

4.2.3.3 Roadmap

Avant l'application de la méthode AMCD-SFN

1. Est-ce que l'**équipe de recherche** rassemble des experts en…
   - ☐ Génie des eaux ?
   - ☐ Sciences de la décision ?
   - ☐ Génie urbain ?
   - ☐ Génie informatique ?
2. Est-ce que des partenaires pourraient établir le contact avec les **décideurs** ?
   - ☐ Oui
   - ☐ Non

   Si non, l'équipe de recherche doit prendre l'initiative d'approcher les décideurs.
3. Quels profils de **parties prenantes** ont été identifié par les décideurs ?
   - ☐ Représentant de la société civile
   - ☐ Architecte – Urbaniste - Paysagiste
   - ☐ Ingénieur
   - ☐ Agent immobilier / Gestionnaire foncier
   - ☐ Investisseur
   - ☐ Technicien
   - ☐ Chercheur

   Représentant municipal
     - ☐ Eau et environnement
     - ☐ Santé et social
     - ☐ Urbain
     - ☐ Routes et infrastructures
   - ☐ Représentant politique

   Les profils manquants peuvent-ils être ajoutés ?

Après l'application de la méthode AMCD-SFN

1. Est-ce que les **décideurs** et les **parties prenantes** sont satisfaits des résultats…
   - ☐ Du modèle multicritère ?
   - ☐ Des alternatives UrbanBEATS (avant évaluation multicritère) ?
   - ☐ Du classement des alternatives UrbanBEATS (après évaluation multicritère) ?

   Si non, il est nécessaire de revenir sur le modèle multicritère jusqu'à satisfaction.
2. Comment les décideurs envisagent le transfert de connaissances ?
   - ☐ Modèle multicritère en format Excel
   - ☐ Formation sur la méthode MACBETH et le logiciel M-MACBETH
   - ☐ Formation sur UrbanBEATS

   A minima, un rapport de projet est fourni aux décideurs, contenant toutes les informations e résultats du projet.

Figure 18 - Form for setting up collaborative work for NBS planning using the UrbanBEATS model (Peter M. Bach)

4.2.3.4 Benefits and limits

The planning of NBS using a MCDA approach based on a case study enables new links to be established or existing links to be consolidated between actors, as it brings together actors who do not usually discuss directly with each other. This creates an opportunity for the sharing of knowledge between researchers, decision-makers and stakeholders. The researchers contribute their expertise on MCDA methods and existing NBS planning tools, and the decision-makers and stakeholders on the real needs (Graça *et al.*, 2022). The results obtained at the end of the MCDA-NBS method are directly usable by decision-makers (i.e., planning strategy for NBS in their territory) and the active participation of stakeholders promotes the future application of these results (Belton & Pictet, 1997; Landry, 1995; Nutt, 1999; Schein, 2017). Moreover, when stakeholder profiles are diversified, it leads to better decision-making because it integrates all aspects of a problematic situation (Albert *et al.*, 2021; Atiqul Haq *et al.*, 2021).

However, implementing a MCDA approach for NBS planning is more time-consuming because it involves several stakeholders from different organisations. Experience with the three case studies in Trois-Rivières, Toulouse and Melbourne showed that it takes between six months and a year from initial contact with decision-makers to the presentation of results. Despite strong interest in the subject, it is sometimes difficult to convince decision-makers and stakeholders to take part in the process, particularly considering the time commitment involved (between 10 and 20 hours per person). In addition, this type of approach requires extra time at the end of the process for knowledge transfer. As part of the study with Trois-Rivières, a half-day training session is planned before the end of 2023 to train one or more municipality employees to use the UrbanBEATS model and the multicriteria model. Unlike what might be expected, the decision-makers and stakeholders contacted were easily convinced by the research project and agreed to take part. They sometimes doubted their legitimacy in taking part in such a project when their knowledge of NBS and multicriteria potential is limited. For example, technicians or experts in the environment and biology found it more difficult to see the links between NBS planning and their areas of expertise. At the end of the process, all the stakeholders recognised the interest and importance of their contribution to the development of the multicriteria model. The decision-makers were also easy to convince, despite the lack of knowledge on the subject and the fact that the results were not immediately visible. Indeed, planning policies are the result of a long-term process and the impact of decisions taken cannot be measured instantly.

Another aspect that affects the quality of the results obtained is the lack of diversity among the stakeholders at the workshops. In the three case studies, stakeholders from civil society were absent, which raises scientific questions about the representativeness of the sociological results. According to the decision-makers, civil society is normally solicited through online surveys or open discussion sessions during which their opinions are received. They feel that they have sufficient knowledge of the opinions of civil society to be able to represent them in the workshops. Similarly, economic, academic and political representatives were under-represented or even absent, which can lead to shortcomings in the consideration of certain criteria or their accuracy. Finally, it is important to note that the results obtained depend on the choices made by the stakeholders and decision-makers, which are not objective, and which can raise issues about the scientific validity of the multicriteria models and the results obtained.

4.2.3 Conclusion

Applying the MCDA-NBS method requires a transdisciplinary approach between three categories of actors: researchers, decision-makers and stakeholders. The decision-makers first make the link between the researchers and the stakeholders. Then the researchers make sure that the work of the stakeholders is in line with the decision-makers' expectations. These three players will be involved at different stages in the process, creating collaborative dynamics managed by the research team as they have sufficient knowledge of water and urban engineering, decision science and computer science. It is also important to have stakeholders with diverse profiles to represent all the visions of a problem situation. In the three case studies on the basis of which the MCDA-NBS method was developed, representatives of civil society were absent, which may lead to questions regarding the validity of some social aspects. Active participation of stakeholders and collaboration between actors helps validating the final results and their future application, and thus facilitates decision-making. This was observed in all three case studies and for Trois-Rivières, the decision-makers wanted to be trained to use the results and the method in future. However, implementing a transdisciplinary approach requires a significant investment of time from the stakeholders, and it is sometimes difficult to convince them to take part in the process.

4.3 Applying multi-criteria decision analysis for nature-based solutions planning: Findings from three different countries and continents

Morgane Bousquet[a], Irène Abi-Zeid[b], Françoise Bichai[c], Roxane Lavoie[d], Peter A. Vanrolleghem[e]

a) modelEAU, Université Laval, Département de génie civil et génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada, morgane.bousquet.1@ulaval.ca (corresponding author)

b) Universié Laval, Département d'opérations et systèmes de décision, Pavillon Palasis-Prince, 2325 Rue de la Terrasse, Local 2513, QC, G1V 0A6, Canada, irene.abi-zeid@osd.ulaval.ca

c) Department of Civil, Geological, and Mining Engineering, Polytechnique Montreal, Montreal, Quebec, H3C 3A7, Canada, fbichai@polymtl.ca

d) Graduate School of Land Management and Regional Planning, Université Laval, Pavillon Félix-Antoine-Savard, 2325 rue des Bibliothèques, Local 1616, QC, G1V 0A6, Canada, roxane.lavoie@esad.ulaval.ca

e) modelEAU, Université Laval, Département de génie civil et génie des eaux, Pavillon Adrien-Pouliot, 1065 avenue de la Médecine, Québec, QC G1V 0A6, Canada, peter.vanrolleghem@gci.ulaval.ca

Highlights

- A new MCDA-NBS method has been developed for Nature-based solutions planning
- MCDA allows flexibility in adapting to different climatic, urban, and socio-cultural contexts and supports decision-making.
- Results of the method's application to three case studies in three continents reveal similarities and differences.
- Around 10 participants per case study were involved in several workshop sessions, facilitated by the research team to apply the MCDA MACBETH method.
- The results open future case study opportunities and future research regarding implementation of cost-benefit analysis and action plans.

Keywords: multi-criteria decision analysis, nature-based solutions, planning support, participatory decision making, action research

4.3.0 Résumé (français)

Les solutions fondées sur la nature (SFN) sont des systèmes d'ingénierie verte conçus initialement pour la gestion de l'eau pluviale à la source. Elles sont de plus en plus étudiées par la communauté scientifique et considérées par les décideurs comme des solutions durables pour relever de nombreux défis urbains associés au changement climatique et au développement socio-économique des villes, tels que la réduction des effets de l'îlot de chaleur urbain, l'amélioration de l'esthétisme des villes et la préservation de la biodiversité. L'aide multicritère à la décision (AMCD) est une approche qui peut soutenir la prise de décision et la planification par l'évaluation de diverses alternatives de planification des SFN à l'aide de critères quantitatifs et qualitatifs. Une revue de littérature récente des pratiques d'aide multicritère à la décision pour la planification des SFN a mis en évidence certaines lacunes et a servi de base au développement d'une nouvelle méthode AMCD pour la planification des SFN, basée sur le modèle d'aide à la planification UrbanBEATS et sur la méthode MACBETH. La méthode AMCD-SFN s'appuie sur un processus participatif impliquant un groupe de participants autour de plusieurs sessions d'atelier pour la construction d'un modèle multicritère. Un des défis du développement de cette méthode est sa capacité à s'adapter à différents contextes climatiques, urbains et socioculturels. Pour cela, nous l'avons testé dans trois villes situées dans des pays et continents différents : Trois-Rivières au Canada, Toulouse en France et Melbourne en Australie. L'objectif de cet article est de démontrer la pertinence et l'adaptabilité de la méthode AMCD-SFN pour soutenir le processus de prise de décision. Nous analyserons i) les profils des participants impliqués dans le processus, ii) les paramètres de développement des alternatives de planification des SFN avec UrbanBEATS, iii) les modèles multicritères, et iv) les meilleures alternatives de planification NBS évaluées par le modèle multicritère.

4.3.1 Abstract

Nature-based solutions (NBS) are green engineering systems designed to manage stormwater at source. They are increasingly being studied by the scientific community and considered by decision-makers as sustainable solutions to address many of the urban challenges associated with climate change and the socio-economic development of cities, such as reducing urban heat island effects, improving aesthetics and increasing biodiversity. Multi-criteria decision analysis (MCDA) is an approach that can support decision-making and planning through the evaluation of various NBS planning alternatives using quantitative and qualitative criteria. A recent review of MCDA practices for NBS planning highlighted some gaps in the literature and provided the basis for the development of a new MCDA-NBS method based on the UrbanBEATS planning-support model and the MACBETH method. MCDA-NBS is based on a participatory process involving a group of participants around several workshop sessions to build a multicriteria model. One of its challenges concerns its ability to adapt to different climatic, urban and sociocultural contexts. With this mind, we tested the method in three cities located in different countries and continents: Trois-Rivières in Canada, Toulouse in France and Melbourne in Australia. The aim of this paper is to demonstrate the relevance and adaptability of MCDA-NBS based planning to support the decision-making process. We analysed i) the profiles of the participants involved in the process,

ii) the parameters for developing the NBS planning alternatives with UrbanBEATS, iii) the multicriteria models, and iv) the best NBS planning alternatives scored with the multicriteria model.

4.3.2 Introduction

Nature-based solutions (NBS) are also known worldwide as Green infrastructures (GI), Blue-green infrastructures (BGI), Low Impact Developments (LID), Best Management Practices (BMP), Sustainable Urban Drainage Systems (SUDS) or Water Sensitive Urban Drainage (WSUD) (Fletcher *et al.*, 2015). They are engineered nature-inspired systems such as constructed wetlands, green roofs and walls, ponds, swales or rain gardens that could infiltrate, retain, convey, treat or evaporate the stormwater at source (Kuller *et al.*, 2017). They are increasingly considered by decision makers to complement grey infrastructure (e.g. sewers, pipes, gutter) for water management (Hamouz *et al.*, 2020; Steis *et al.*, 2020). In addition to helping with stormwater and rainwater management, NBS also have other advantages such as reducing urban heat island effects, improving aesthetics and increasing biodiversity (Dagenais *et al.*, 2017; Qiu *et al.*, 2022; Skrydstrup *et al.*, 2020).

Green space policy is a main focus of urban planning which integrates the use of NBS (Zwierzchowska & Stępniewska, 2022). The basic NBS implementation approaches focus on building scenarios of NBS implantation in an area (Gielczewski *et al.*, 2011; Urich & Rauch, 2014) that consider short and long reference periods and global and local scales. These considerations are important to assess the sustainability of urban policy and governance (Boggia *et al.*, 2018). Moreover, decision-makers must consider all benefits NBS could provide to an environment and the various types of NBS (e.g. rain gardens, wetlands, etc.). This is a complex problem that makes the use of multicriteria decision analysis (MCDA) relevant.

MCDA offers a rich collection of methods to structure planning problems with conflicting objectives, allowing the design, evaluation, and prioritization of decision alternatives based on a multi-criteria model representing stakeholder preferences (Ferretti & Montibeller, 2016; Marttunen *et al.*, 2017). MCDA methods are often conducted as participative approaches in socio-technical interventions (Abi-Zeid *et al.*, 2023). Indeed, a participatory (Schein, 2017) and constructivist (Landry, 1995) approach involving stakeholders is recommended by the decision analysts' community (Belton & Stewart, 2002) when applying MCDA.

A systematic review of MCDA-NBS planning practices (Bousquet *et al.*, 2023a) analyzed 28 literature reviews and 124 papers. Its findings highlighted a lack of stakeholder participation in the published literature which has been identified as a key success factor by the scientific community (Belton & Stewart, 2002). The review also identified many GIS-based models, developed specifically for given case studies and therefore difficult to adapt to other contexts. In addition, the MCDA methods used in these studies were often based on the AHP method, known to lead to numerous biases and often criticized by decision science experts (Munier & Hontoria, 2021).

Therefore, these gaps in the literature led to the development an innovative MCDA process to support NBS planning and evaluation: MCDA-NBS. It combines a value function-based MCDA method (MACBETH) (Costa *et al.*, 2003, 2019) and a planning-support model for NBS design and implementation (UrbanBEATS) (Bach *et al.*, 2018; 2020).

In order to evaluate the relevance and adaptability of the MCDA-NBS method, we tested it in three cities, located in three different countries and on three different continents: Trois-Rivières (Canada), Toulouse (France) and Melbourne (Australia). These countries were chosen because of their very different geographical, biophysical, and climatic conditions (cold continental, Mediterranean, oceanic, and arid, respectively). Our role as researchers in this action-research project was to facilitate the workshops in which the MCDA-NBS method was applied. Note that it were the decision-makers, i.e., the cities' representatives, that identified the participants who took part in the workshops.

We start by presenting the MCDA-NBS method and the characteristics of the three case studies. Then, we present the results of applying the MCDA-NBS method to the three case studies following its five steps and thus presenting i) the participant profiles involved in the workshops; ii) the NBS planning alternatives generated by the UrbanBEATS model; iii) the multicriteria models developed with the MACBETH method; iv) the NBS planning strategies retained; and iv) the feedback received from the participants and the resources used for knowledge transfer. Finally, we give some recommendations for the application of the MCDA-NBS method and suggest avenues for future research.

4.3.3 Materials and method

4.3.3.1 The MCDA-NBS method

Cities have been expressing the need to develop NBS planning strategies, but current tools for NBS planning do not allow them to consider all the criteria on which NBS can be evaluated in an urban environment. The MCDA-NBS method, developed in Bousquet *et al.* (2023b), combines the MACBETH MCDA method, (Measuring-Attractiveness by a Category-Based Evaluation TecHnique) and its software tool M-MACBETH (Costa *et al.*, 2003, 2019) along with an NBS planning-support model, UrbanBEATS (Urban Biophysical Environment And Technologies Simulator) (Bach *et al.*, 2018; 2020). The overall method consists of five main steps:

1. Identifying stakeholders who will participate in the workshops.

2. Generating NBS planning alternatives (UrbanBEATS model).

3. Constructing a multicriteria model (MACBETH method).
4. Evaluating NBS planning alternatives (UrbanBEATS outputs & multicriteria model).
5. Presenting and discussing the results with the stakeholders.

Stakeholders are selected through an imperative procedure which aims to identify actors that are affected by or can affect the decision-making process (Marais & Abi-Zeid, 2021). In an imperative procedure, a series of questions identifies who is affected by the decision problem, who has an interest in the decision problem, who can affect the project's adoption and who has expressed an opinion on the decision problem. The work of Skrydstrup *et al.* (2020) is used to provide a list of relevant stakeholders to be involved in NBS planning. Their level of involvement in the process is collaborative, which means that decisions regarding the construction of a multicriteria evaluation model are made as a group using participatory techniques, such as participatory workshops, focus groups or scenario analysis (Marais & Abi-Zeid, 2021). According to Marais & Abi-Zeid (2021), the most represented categories of stakeholders are called "standard stakeholders", both affected by and affecting a problem. These types of stakeholders are recognized as active participants in the participatory process. Stakeholder categories with less or no involvement are referred to as "fiduciary stakeholders" (e.g., governmental category), who have strong decision-making power but don't feel personally affected by the problem, or "silent stakeholders" (e.g., civil society), who are affected by the problem but have little impact. The "silent stakeholders" do not participate directly in the decision-making process, although they may have an influence on it. Indeed, in the context of NBS implementation, citizens are users of the space and can express their opinions on the location of these solutions. The choice of participants in the workshops is often made by the decision-makers (i.e., city representatives) who are the project's sponsors. However, the research team is expected to advise and guide them towards certain stakeholder profiles based on the Skrydstrup *et al.* (2020) list.

To generate NBS planning alternatives with the UrbanBEATS model, spatial data such as elevation, population, land use, soil type as well as climate including rainfall and evapotranspiration is required for a 10-year period with an hourly time step for rainfall and a daily time step for evapotranspiration (Bach *et al.*, 2018; 2020). Spatial data for the Trois-Rivières case study were provided by the in-house partners (i.e., the City of Trois-Rivières) as open-source data was limited. For Toulouse and Melbourne, the spatial data was available in open-source on the official government website (i.e., data.gouv for Toulouse and vic.gov for Melbourne). Climate data was purchased by the research team for the Trois-Rivières meteorological station and were available in open-source for Toulouse (i.e., Meteo France) and Melbourne (i.e., Bureau of Meteorology). More details on data and sources are available in the supplementary material. UrbanBEATS also requires some statistics and urban characteristics (e.g., water consumption, urban design) which were provided by the partners or through normative documents such as design guidelines, action plans or statistic reports. Finally, UrbanBEATS generates the NBS planning alternatives regarding water management objectives: runoff reduction, pollution reduction and rainwater harvesting, which are expressed in percentage and defined by the stakeholders involved in the process, hereafter called participants. Based on the bio-physical and climatic conditions of the territory, and the three objectives, the UrbanBEATS model generates alternatives for NBS planning strategies. A NBS planning alternative is a map showing several types of NBS located over a selected territory. The NBS types considered by UrbanBEATS are organized into families, respectively the infiltration systems, the raingardens & bioretention systems, the ponds & basins, the wetlands, the swales & trenches and the rain tanks, which are the most studied technologies due to their effectiveness and ease of implementation (Wang *et al.*, 2023).

Subsequently, the MACBETH method is applied to construct a multicriteria model of participant preferences which will be used to evaluate and rank the various NBS planning alternatives. It enables the construction of criteria weights and value functions by making qualitative judgements about the performances of the various alternatives on the criteria. Value functions represent the preferences of the participants regarding the possible performances on the criteria. They are constructed by defining two benchmarks: the “neutral” (just satisfactory value) and the “good” (fully satisfactory value) benchmarks. The M-MACBETH tool supports the MACBETH method and automatically verifies the judgments of the participants, ensuring the coherence of the multicriteria model. This model provides a final score based on a weighted sum that represents the attractiveness, for the participants, of each NBS planning alternative. These scores can be used to evaluate the various NBS implementation alternatives produced by UrbanBEATS. In the end, the results are presented and shared with the participants. The use of the results, the updating of the multicriteria model and the NBS planning alternatives to be evaluated are discussed to facilitate the transfer of knowledge and the future use of the research results in operational settings.

The participative process of the MCDA-NBS method is designed to optimise the time required for participant involvement. On average, each participant is asked to take part in three workshop sessions of around 3 hours each, as well as a preliminary meeting where the project is presented along with a final meeting to discuss the results. The first workshop session is devoted to defining the criteria and their measurement indicators (i.e., necessary data, reference values for building the scales). The second workshop session takes place in sub-groups, with each sub-group dealing with 3 to 4 criteria to create the value functions associated with the criteria performances. The third workshop session brings together all the participants again to establish the weights of the criteria. The total participation time of each participant is therefore estimated at about 12 hours. More time may be required if additional training is needed for future use of the UrbanBEATS and M-MACBETH tools.

4.3.3.2 Case studies

To test the adaptability of the MCDA-NBS method, we applied it in three case studies: Trois-Rivières in Canada, Toulouse in France and Melbourne in Australia, each differing in terms of climate, urban development characteristics (i.e., study area and population) and urban dynamics (i.e., water consumption) (Table 10). Furthermore, the challenges faced by the three urban areas are also different as described below.

Founded in 1634, Trois-Rivières is the second oldest city in the province of Quebec and is located at the junction of three rivers. Its main source of water is the St-Lawrence River and its residential average water consumption is 389 l/person/day, 11% higher than the national average of 350 l/person/day (MAMH, 2023). According to the 2016-2017 census, population trends predict an 18% increase by 2040. Also, Canada's climate forecasts predict average warming much higher than in most other countries (between +2 °C and +6 °C) due to the loss of the ice cover, which usually reflects 90% of solar radiation (Bush *et al.*, 2019). One of the consequences could be less snowfall in winter and more rainfall in both winter and summer (Rayfield *et al.*, 2016). Therefore, Trois-Rivières faces major flood risks, as well as major pollution risks from the paper and pulp industries that is still very present in the area. In fact, industrial activities are responsible for discharges of a range of pollutants (suspended solids, nitrogen, and phosphorus products), toxic discharges (metals, hydrocarbons…) and ecological imbalances by heating up the water.

Toulouse Metropole was officially founded by the Romans in the 3rd century BC. The Garonne River is a major river and landscape element of the Metropole. Major historical floods (e.g., 26 June 1875) have led to the construction of large infrastructures to minimise the resulting damages. The risk of flooding increases in winter and spring due to more frequent and more intense rainfall than during the rest of the year. This trend is intensified by climate change. The Metropole consists of 37 communes and its demographic evolution is one of the most important in France (+6.2% between 2013 and 2018) (Toulouse Metropole, 2022). A commune is the smallest administrative subdivision of the French territory, administered by a mayor, deputies and a municipal council. Regarding the climate, summer temperatures are among the highest in France, reaching up to 44°C, and remaining above zero during winter. Toulouse Metropole faces drought risks and urban heat island effects.

Founded by settlers in 1835, Melbourne is a coastal city on the Bass Strait, between the Tasman Sea and the Indian Ocean. Water management in the greater Melbourne area is divided into 5 catchments (i.e., Werribee, Maribyrnong, Yarra River, Dandenong and Westport) following the main rivers. Our study focused on the Dandenong catchment which already represents 870 km^2. Its climate is becoming hotter and drier which brings less rainfall, more drought and more risk of bushfires thereby compromising the water quality in water supply reservoirs (Melbourne Water, 2022). Moreover, the Greater Melbourne area and population are growing exponentially, and its urbanisation increases the flood risk as well as the rise of sea levels.

Table 10 - Summary of case studies regarding climate, area, population, water consumption and main issues

City	***Climate***	***Area (km^2)***	***Population (inhab.)***	***Water consumption (l/pers/day)***	***Main issues***
Trois-Rivières (QC, Canada)	*Continental, Cold*	*289*	*136,470*	*389*	*Flooding, Pollution*
Toulouse (France)	*Mediterranean, Oceanic*	*458*	*796,200*	*146*	*Urban Heat islands, Droughts*
Melbourne (VIC, Australia)	*Coastal, Arid*	*870*	*1,530,000*	*247*	*Bushfires/ Biodiversity, Droughts, Flooding*

The first case study, for which the MCDA-NBS method was developed, was conducted in Trois-Rivières between September 2020 and December 2022. It brought together 12 municipal employees for workshops organized in virtual mode due to the Covid health crisis. The Toulouse Metropole case study led us to adapt the MCDA-NBS method to another context and to integrate participants other than municipal employees. It was conducted between May 2022 and May 2023 and brought together 8 workshop participants at the Toulouse Metropole offices. Finally, the Melbourne case study allowed us to further validate the adaptability of the MCDA-NBS method. It was conducted between February 2023 and November 2023 with 10 workshop participants in the Melbourne Water offices.

4.3.4 Results

4.3.4.1 Analysis of workshop participants

A classification of the participants into categories following the work of Skrydstrup *et al.* (2020) shows 7 distinct stakeholder types in Trois-Rivières, 8 distinct types in Toulouse and 7 distinct types in Melbourne (Table 11). In the case of Trois-Rivières, the participants were all municipal employees, unlike in Toulouse and Melbourne, where participants were also external to the city administration. The stakeholder categories most represented across the three case studies were professionals (e.g., urban planner, engineer) and consultants (external to the city), technicians, and city representatives (municipal employees). According to Marais & Abi-Zeid (2021), they are "standard stakeholders", both affected by and affecting a problem and they usually participate in the decision processes. The political and governmental category was poorly represented. Moreover, academia, other than the researchers involved in the project, was represented only in the Melbourne study. Finally, none of the three studies included participants representing civil society, also called the "silent stakeholders”.

Table 11 - Presentation of type and number of participants for Trois-Rivières, Toulouse and Melbourne

Category	***Type***	***Trois-Rivières***	***Toulouse***	***Melbourne***
Civil society	*Citizen representative*			
	Association			
Professionnal / Consultant	*Architect-Urban planner*			*1*
	Architect-Land planner			
	Engineer (water, environment, urban)	*3*	*1*	*3*
	Real estate / Insurance / Investor	*3*	*1*	
Technician	*Technician (network, infrastructures)*	*1*	*1*	*1*
Academic	*Researcher (water, environment, climate)*			*2*
City / City / Metropole	*Water & Environment*	*1*	*1*	
	Health & Social	*1*		*1*
	Urban planning	*2*	*1*	*1*
	Roads & Infrastructures	*1*	*1*	
Governmental	*Ministry*			
	Governmental organisation			*1*
	Politician		*1*	
	International organisation			
Total		***12***	***8***	***10***

4.3.4.2 NBS planning alternatives generation

One of the major inputs needed for UrbanBEATS are the objectives of runoff volume reduction, pollution reduction (i.e., Total Suspended Solids, phosphorus, nitrogen) and rainwater harvesting, determined by the participants (Table 12) in each case study. Since Trois-Rivières is facing major flooding problems due to the accumulation of snow during the winter and the subsequent melting of snow and precipitation in spring, the goal of reducing runoff had therefore a high priority. As for Toulouse, it was decided to adopt a reduction strategy of 50% for all the above objectives. Finally, Melbourne chose to focus on the reduction of total suspended solids and phosphorus, since the protection of water resources is a major issue for the Greater Melbourne area and its catchments.

The research team configured the three UrbanBEATS models to generate 20 NBS planning alternatives based on spatial, climatic, statistical, and objectives data. We chose to base our analysis on the 20 best alternatives because, after several tests, we found that the differences between the alternatives were less perceptible when more than 20 alternatives were considered. In addition, as the MCDA evaluation is carried out manually rather than automatically, it was not possible to consider too many alternatives. These 20 alternatives are all equivalent in terms of the objectives to be achieved, but propose different strategies for implementing NBSs (i.e., number, type, and location). For example, the alternatives provided maps with numbers of installations ranging from 200 to 700 NBS for Trois-Rivières, 500 to 900 for Toulouse and 500 to 1400 for Melbourne. In Trois-Rivières and Melbourne, bioretention, rain gardens, wetlands, ponds, and basins were the types of NBS that were most proposed by UrbanBEATS, unlike in Toulouse where bioretention, rain gardens, swales and trenches were more frequent. This difference can be explained by the denser urban environment in Toulouse, which limits the possibility of installing large NBS such as ponds, basins, and wetlands. For example, an NBS planning alternative could propose the installation of 100 bioretention cells, 50 trenches, 40 infiltration systems and 20 wetlands. More details on alternative NBS planning for the three case studies (i.e., type and number of NBS for each alternative) can be found in the supplementary material file.

Table 12 - UrbanBEATS objectives for Trois-Rivières, Toulouse and Melbourne

	Runoff reduction	***Pollution reduction***			***Rainwater harvesting***
		TSS	***Phosphorus***	***Nitrogen***	
Trois-Rivières	90%	80%	40%	40%	X
Toulouse	50%	50%	50%	50%	50%
Melbourne	50%	85%	70%	50%	56%

4.3.4.3 Presentation of the multicriteria models

The next step in each case study was to evaluate and rank the 20 planning alternatives (i.e., NBS maps) based on multiple criteria. Participatory workshops were therefore conducted to construct multicriteria models following the MACBETH method. Trois-Rivières proposed 10 criteria, Toulouse 11 criteria and Melbourne 7 criteria. Figure 19 organises the criteria according to the aspects (e.g., biodiversity, aesthetic, recreativity) the criteria refer to. This helps visualising the similarities and differences between the three case studies. The criteria are expressed as objectives to be achieved for NBS planning (see Annexes A, B, C).

Looking at the criteria developed for the three case studies (Figure 19), we notice that some aspects are common to all case studies, such as biodiversity, recreation, and water management. However, even if these criteria seem similar, the way they are measured, and the performance scales differ from one study site to another. For example, for the biodiversity aspect common to the three case studies, Trois-Rivières expressed the criterion as the "distribution (%) of NBS within the urban perimeter located within 100 m of an existing green corridor", Toulouse as "distribution (%) of NBS in defined protected sectors" and Melbourne as "distribution (%) of NBS located within 200m from biodiversity areas". Nonetheless, certain aspects are unique to a case study, such as the implementation on public lands for Trois-Rivières, restrictions on the implementation of NBS in areas of historical value for Toulouse and carbon sequestration by NBS for Melbourne. More details on the measurement indicators, criteria performance scales and criteria weights can be found in the supplementary materials file.

For the three case studies, the criteria's performances can be evaluated considering two dimensions, which can sometimes be used in combination to evaluate a criterion:

i. the spatial dimension (i.e., the location of NBS in an area based on spatial data) and;

ii. the technical dimension (i.e., a score given to NBS types regarding their performance on a criterion).

Most of the criteria consider the spatial dimension, which are measured by looking at the spatial location of NBS on the 20 maps according to the preferred land use types of area (e.g., residential areas, public parcels, priority biodiversity areas, etc.). For example, the criterion of encouraging green corridor links (a Trois-Rivières criterion) is assessed by the ratio of NBS implemented within a 100-m distance from an existing green corridor. This ratio is expressed as a percentage by looking at the number of NBS installed in these areas compared to the total number of NBS proposed by the alternative. Thus, Trois-Rivières set a ratio of 25% (i.e., "good" benchmark), meaning that they would be fully satisfied if an alternative proposed 25% of NBS close to an existing green corridor. The spatial dimension is based on spatial data converted for processing in a GIS (Geographic Information Systems) software such as ArcGIS or QGIS.

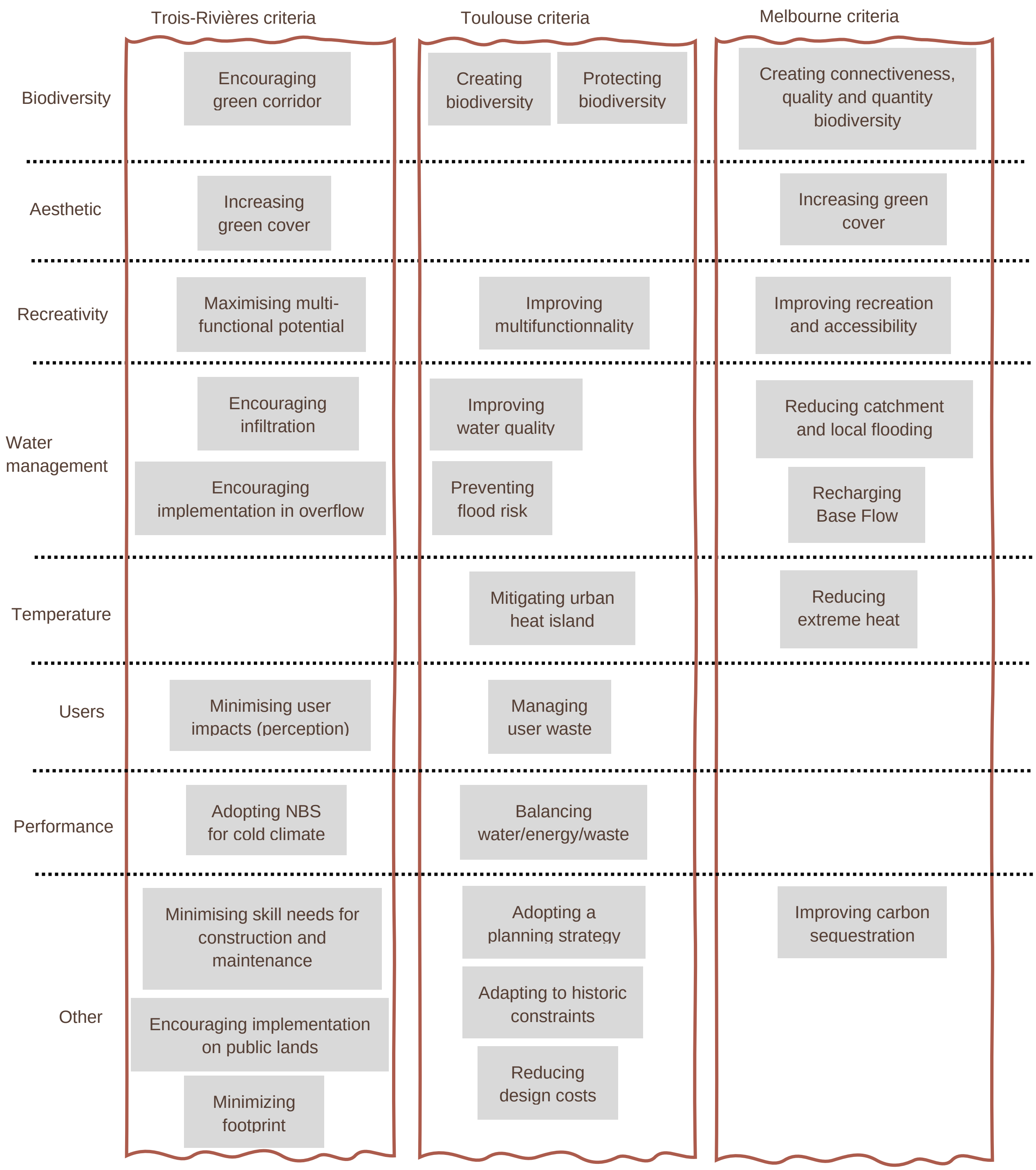


Figure 19 - Analysis of case studies regarding the criteria selected by the stakeholders for Trois-Rivières, Toulouse and Melbourne

Other criteria (e.g., multi-functional potential, performance, aesthetics) focus more on the type of NBS and assign a score to the NBS type according to their ability to perform on the criterion. The types of NBS considered by the participants were bioretention & raingardens, wetlands, green roofs, green façades, infiltration systems, ponds & basins, porous pavement, rain tanks and trenches & swales. For example, the criterion of reducing carbon emissions (a Melbourne criterion) assigned a score of 3 to wetlands, a score of 2 to ponds & basins, green roofs, green facades and bioretention, a score of 1 to infiltration systems and trenches & swales, and a score of 0 to rain tanks and porous pavements. Thus, an NBS planning alternative which implements more wetlands will get a higher score on this criterion according to Melbourne's preferences.

Some criteria (e.g., groundwater recharge, footprint, urban heat island effects) are evaluated through the dimensions by evaluating both the distribution of NBS in preferred areas and the most favorable type of NBS. For example, the criterion of mitigating urban heat islands (a Toulouse criterion) is based on both the map of urban heat island effects and the ranking of NBS types. Thus, Toulouse set a ratio of 50% of bioretention cells, wetlands or green facades to be implemented in the priority areas (i.e., where there is highest urban heat island effects).

4.3.4.3 Assessment of NBS planning alternatives

The criteria based on spatial dimension required additional datasets (i.e., 8 maps for Trois-Rivières, 12 maps for Toulouse and 6 maps for Melbourne). The groundwater table heights and high flood risk maps were common to all three cases. Urban heat island data were used for the Toulouse and Melbourne studies.

The 20 alternatives proposed by UrbanBEATS for each case study were evaluated using the multicriteria model developed by the participants. The GIS tool QGIS was used to assess the performance of each criterion by overlaying the NBS planning alternative maps produced by UrbanBEATS with the additional spatial maps relating to the evaluation of each criterion. Once the criteria performance had been entered into M-MACBETH for each NBS planning alternative, the software was able to compute the global scores and the ranking of the 20 NBS planning alternatives.

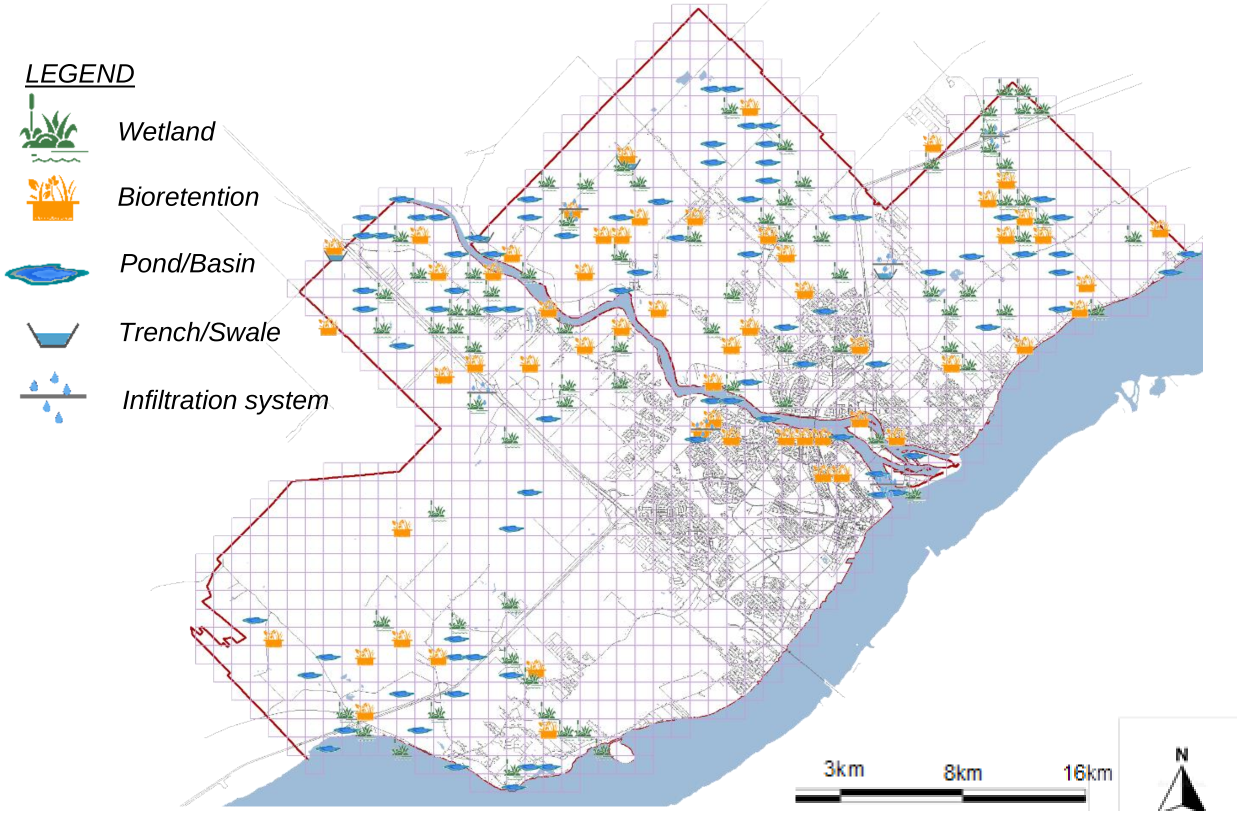


Figure 20 - The NBS planning alternative with the highest attractiveness score for Trois-Rivières.

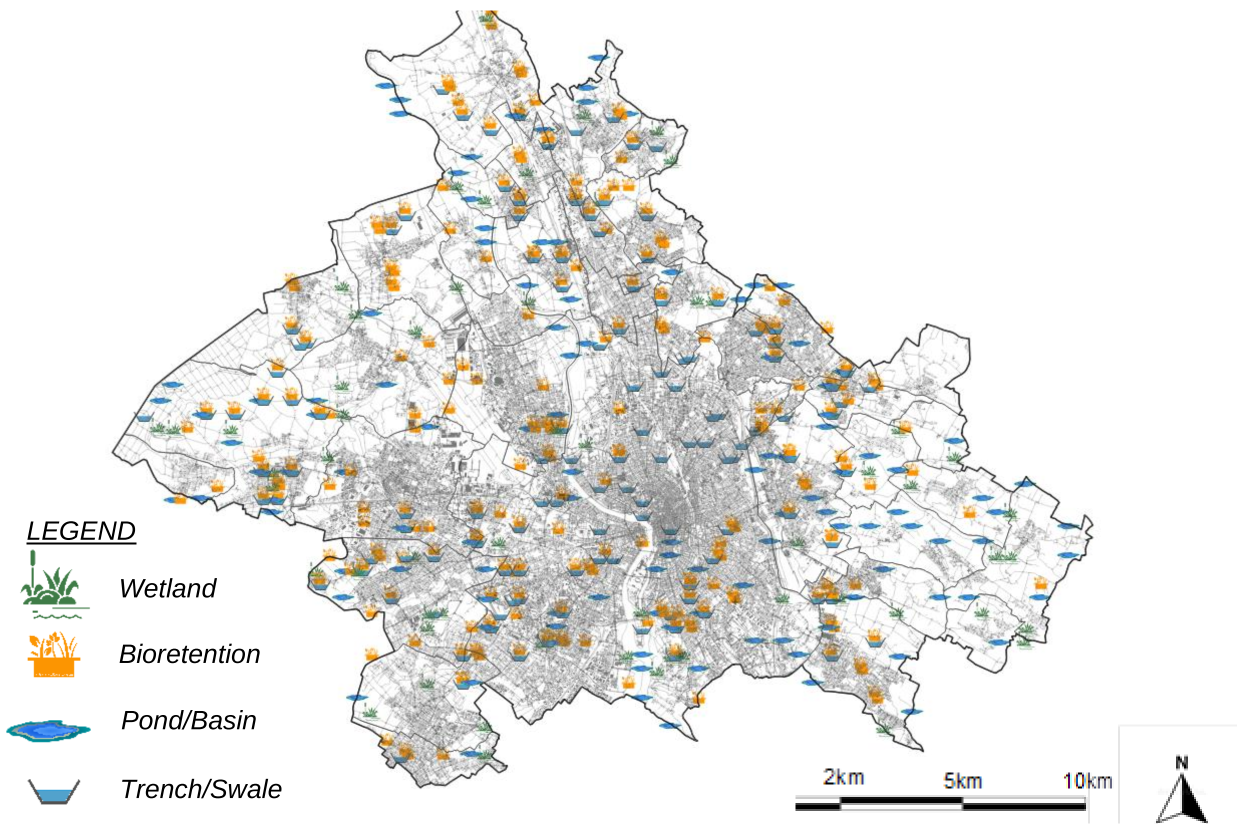


Figure 21 - The NBS planning alternative with the highest attractiveness score for Toulouse.

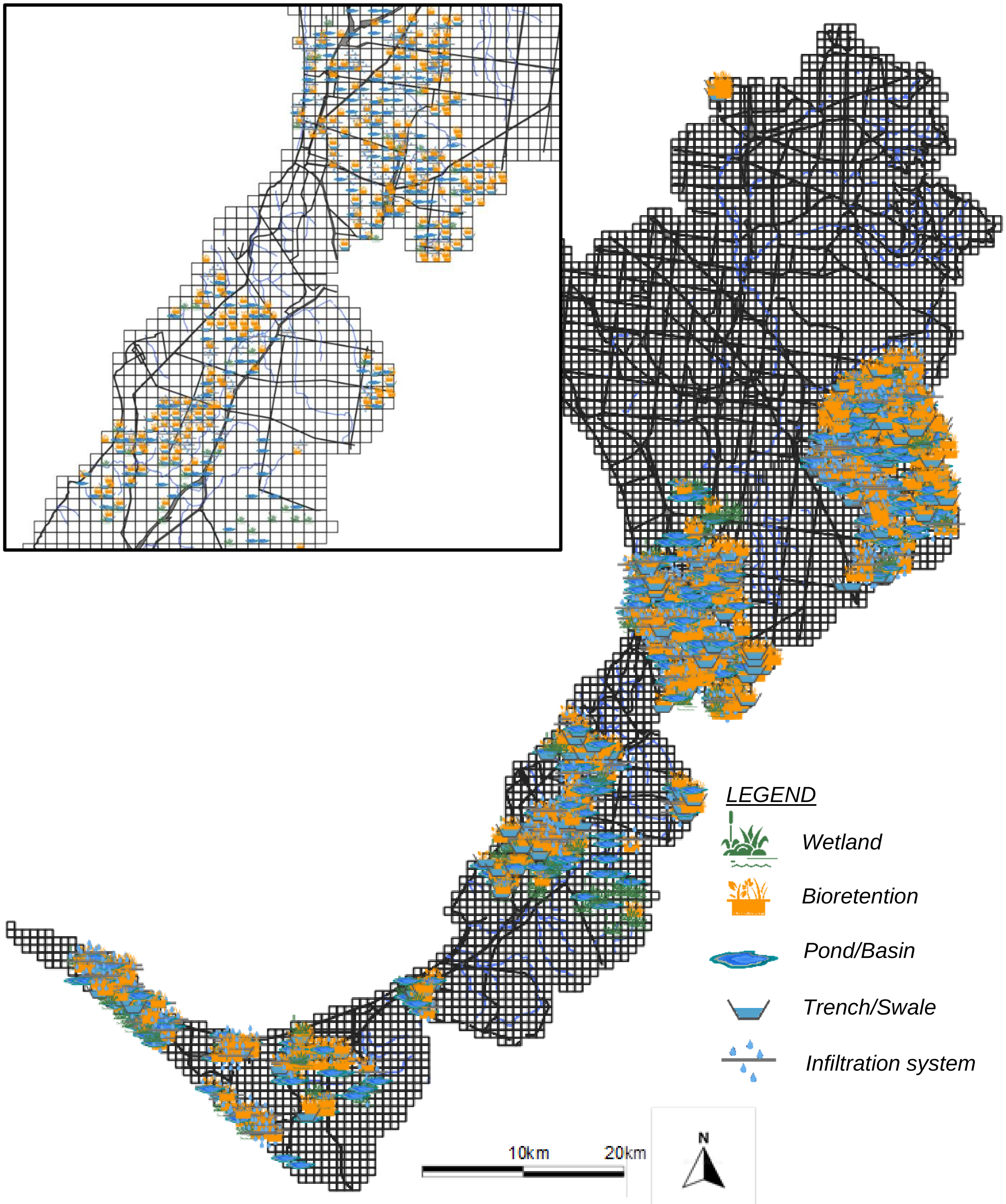


Figure 22 - The NBS planning alternative with the highest attractiveness score for Melbourne.

For the Trois-Rivières case study, all NBS planning alternatives exceeded the fully satisfactory level. The alternative with the highest attractiveness score was also the one consisting of the fewest NBS to be installed. This alternative proposes the installation of 82 ponds, 78 wetlands, 73 bioretention areas, 46 trenches and 28 infiltration systems (Figure 20). Notably, this alternative proposes no NBS for a large area in the southwest of the city. This is due to the limited infiltration capacity because groundwater levels are very high in this area.

For the Toulouse case study, some NBS planning alternatives were below the fully satisfactory level and only one is below the just satisfactory level. The alternative with the highest attractiveness score proposed the implementation of 231 bioretention areas, 123 trenches, 114 ponds and 55 wetlands (Figure 21). This can be explained by the urban context, which is very dense, with limited space for large-scale infrastructures such as wetlands and ponds. This alternative proposed no NBS in the eastern centre of the dense urban area. This is the densest and most historical part of the metropole, with a variable topography that makes it difficult to implement NBS.

For the Melbourne case study, all the NBS planning alternatives are above the fully satisfactory level. The alternative with the highest attractiveness score proposed the implementation of 535 bioretention areas, 275 ponds, 273 infiltration systems, 193 swales and 84 wetlands (Figure 22). NBS are concentrated in certain areas (i.e., the southern peninsula, along the coast and in the central west) which are major residential areas with a medium density (i.e., around 80 inhabitants/km^2) which makes it possible to implement NBS.

4.3.5 Discussion

4.3.5.1 Participant feedback

The results were presented in November 2022 in Trois-Rivières, in July 2023 in Toulouse and in November 2023 for Melbourne. A report and an Excel file listing all the data and a translation of the multicriteria model were provided.

During the final presentation, the multicriteria models were validated by the participants. The assessment of the 20 NBS planning alternatives produced by UrbanBEATS themselves also interested the participants and decision-makers and the NBS planning alternative with the highest multicriteria based attractiveness score was confirmed by them the most preferred. The participants acknowledged the importance of having a facilitator to guide them throughout the multicriteria process. Indeed, at the start of the MACBETH process, they had a vague understanding of the process and did not think they would have enough time to build such a complex multicriteria model. By the end of the process, they had acquired new knowledge and were confident in the model they built.

Participants expressed their wish to learn more about the UrbanBEATS and M-MACBETH tools to be able to use them autonomously in the future. In the case of Trois-Rivières, for example, the decision-makers asked for a day's training in these tools to develop their autonomy for future improvement and update of the models. The presentations, publications, and conferences of the results prepared by the research team, participants, decision-makers and partners raised interest from other Canadian and French cities. They are interested in applying the MCDA-NBS method to their territory and thus be able to compare their results with other cities in similar contexts. In Melbourne's case, the method is intended to be applied to the other catchments to cover the greater Melbourne area.

Participants and decision-makers were also able to make links between current projects (e.g., the 100,000 trees project in Toulouse, and the Integrated Water Management Forums project in Melbourne) and the results of this research. As part of the project for planting 100,000 urban trees in Toulouse, the results will be used to validate the planting sectors or identify new areas.

4.3.5.2 Recommendations and future work

The case studies of Trois-Rivières, Toulouse and Melbourne demonstrated that the MCDA-NBS method could be implemented in different contexts. As expected, the multicriteria models were different, highlighting the importance of developing site-specific models. Even though some of the criteria use similar terms, the way they are expressed and evaluated are different. In addition, some criteria are specific to the context of the study and are not relevant in another context (e.g. NBS performance in a cold climate vs a warm climate). This demonstrates the importance of stakeholder participation to ensure the models' adaptation to the particular context.

One aspect not covered by the multicriteria evaluation in these three case studies is the economic aspect. In the context of an MCDA problem, taking into account the economic aspect comes to a portfolio problem of resource allocation and cost-benefit balance (Phillips & Bana e Costa, 2007). We addressed the issue by assuming that the more NBS proposed in a plan, the more expensive the alternative. However, this is a more complex question, as it requires taking into account the type of NBS and its life-cycle (i.e., the design, installation, maintenance and the possible replacement of the NBS). Recent existing studies on the costs of NBS could help integrate this aspect in the analysis as the work of Dr. Marie-Eve Jean during her thesis in partnership with INRS. In this project, however the aim was to concentrate on assessing the quality of NBS implementation alternatives proposed by UrbanBEATS. Developing a method for assessing costs and then carrying out a quality-cost analysis would be an interesting avenue for future research.

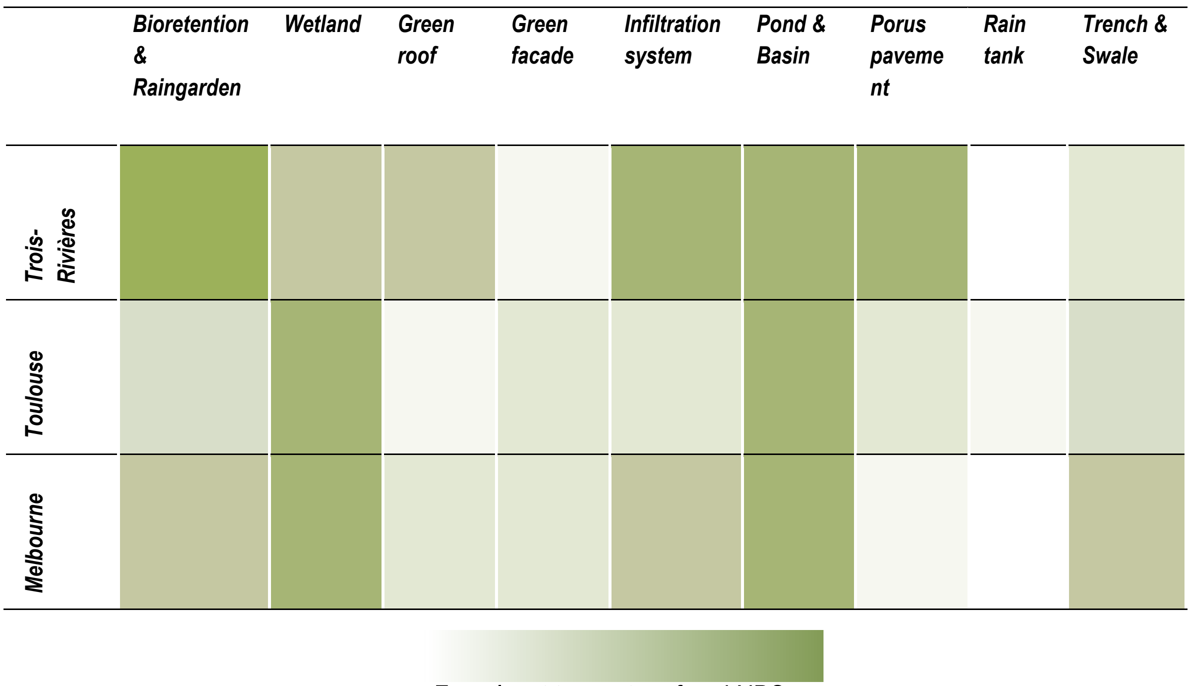
The proposed MCDA-NBS method can be adapted to other MCDA methods than MACBETH and other planning-support tools than UrbanBEATS to produce NBS planning alternatives. We must remain cautious as other methods and tools have not been tested and we cannot therefore state that they will produce reliable and satisfactory results. The tools chosen (UrbanBEATS and MACBETH) are well suited to our problem and we recommend applying the MCDA-NBS method with these tools. They were perceived positively by the participants of the three case studies as producing robust results. However, the alternatives to be evaluated by the multicriteria model do not necessarily need to be the output of a planning model, such as UrbanBEATS. They could also, for example, be created by the participants, based on their expertise.

Furthermore, other data can be integrated into UrbanBEATS for other simulations such as a biodiversity map or the groundwater table height map, which are recurring criteria in all three case studies. UrbanBEATS could also prioritise specific types of NBS according to participants' preferences. We could use some of the MCDA model results, especially the technical dimension (i.e., a score given to NBS types regarding their performance on a criterion). The sum of these scores could be calculated in order to get the overall performance of NBS type in the criteria models for Trois-Rivières, Toulouse and Melbourne (Table 13). This analysis showed that, in all three case studies, wetlands and ponds & basins performed well, unlike green facades and rain tanks. This means that participants prefer an alternative of NBS implementation which incorporates more wetlands and ponds & basins than other types of NBS. This work could help improve the UrbanBEATS model and the generation of the NBS planning alternatives as well as provide more adaptation to the stakeholders' preferences.

Once the 20 alternatives of NBS implementation have been evaluated and the highest ranking alternatives have been identified and validated by the participants, the next step consists in implementing the selected alternative in practice. However, it is not possible to install a high number of NBS in a short period of time. It would therefore be appropriate to develop methods that can identify in a given alternative the NBS that have the greatest impact on the strategy and prioritise their installation. This analysis could be carried out by overlaying the criteria data on GIS software and thus identify the NBS that perform best on the criteria, but it will require much time and effort. It can also be done by looking the economic aspect, expertise, space opportunity, etc. This work could lead to the production of a priority action plan for the implementation of NBS within a planning alternative.

A fundamental element underlying the MCDA-NBS method is the participative process with the stakeholders. The aim of this participatory process is to select a group of participants that represents different perspectives. It is therefore not necessary to have a large group of participants, but rather to have as many different types of expertise as possible to better represent the diversity of opinion. The Toulouse case study had a group of 8 participants with distinct profiles, unlike the Trois-Rivières and Melbourne studies, which included several participants with the same profiles, i.e. planning, engineering and research experts that could have lead to over-representation of a particular aspect.

Table 13 – Overall performance of NBS types on the criteria (i.e., sum of performance on each criterion) regarding participants' preference for Trois-Rivières, Toulouse and Melbourne



In our study, the political and governmental category was difficult to approach which explain why they were not often represented. They are the "fiduciary stakeholders", who rarely participate in the decision processes because they don't feel personally affected by the problem even if they have strong decision-making power. They have influence at a national level and, when it concerns regional planning at a more local scale, they delegate decision-making to the cities. We can then question the relevance of having these types of actors in an MCDA-NBS process. Furthermore, effort should be spent on including civil society representatives since they are participants who will be impacted by NBS implementation projects.

4.3.6 Conclusion

The research developed a new MCDA-NBS method that combines a planning-support model, UrbanBEATS, and a MCDA method, MACBETH, through workshop sessions with a group of participants selected by the decision-makers (i.e., municipality representatives). We applied this new method in three different cities on different continents to test its ability to adapt to various climatic, urban and sociocultural contexts. Our partnerships with Trois-Rivières, Toulouse and Melbourne brought together decision-makers, researchers, and stakeholders with diversified profiles in a transdisciplinary approach and a research-action process. Decision-makers in Trois-Rivières, Toulouse and Melbourne selected different types of stakeholders (i.e., different expertise) to be involved in the workshops. However, some profiles were missing in all case studies such as citizen representatives and economic experts, identified as "silent stakeholders" because they are rarely involved in decision-making processes. However, civil society is often seen as a key player by the scientific community in participatory processes that improve the social acceptance of projects and its therefore recommended to include them in future applications.

The UrbanBEATS tool produced several alternatives for NBS implementation using a Monte-Carlo method process. We evaluated the 20 best ones (according to the model) which raised the interest from decision-makers and participants. In future, the model could integrate other data (criteria) to provide more attractive NBS planning alternative for the participants. The MACBETH method allowed evaluating the performance of the alternatives on various criteria. The multicriteria models (i.e., criteria chosen, units of measurement, reference data, preferences linked to the types of NBS) constructed by the participants were different for every case study even if they shared some similarities (e.g., biodiversity or temperature dimensions). Indeed, the indicators, the value scales and the weights were different. This highlights the relevance of MCDA methods and participatory approaches to adequately adapt the evaluation of NBS planning alternatives to a particular context and in this way support decision-making.

Decision-makers and participants validated the results obtained and recognized the importance of multicriteria analysis in the process. They expressed the wish to use the results to support future decision-making and actions related to the implementation of NBS on their territories. Thus, a training day will be planned with Trois-Rivières to allow them to use the UrbanBEATS and MACBETH models autonomously. Several presentations are planned in other cities for potential future case studies to share best practice and feedback among cities.

Potential future work would be to integrate a cost-quality analysis into the multicriteria model and to develop a method to prioritise NBS to be implemented. In addition, this research could lead to further develop the UrbanBEATS model by adding new data inputs (e.g., biodiversity priority map, groundwater table heights) or to create NBS planning scenarios with participants. Finally, the integration of civil society into the group is an important issue and would allow considering their perception on multi-criteria models.

Conclusion

Overview of the research

This PhD study presented a new MCDA-NBS method which aims to improve the decision-making process for NBS planning. The development of this method is essentially based on the findings of a literature review carried out at the start of the research. This showed that scientific studies do not really consider the multicriteria nature of the NBS planning process, rarely involve participants in the process of constructing the multicriteria model and develop tools that are difficult to adapt to other contexts. Therefore, the proposed MCDA-NBS method uses five steps that combine the MACBETH method and the engineering-based planning-support model UrbanBEATS. MACBETH is an advanced MCDA method that helps stakeholders to build a multicriteria model representing the preferences of stakeholders. The multi-criteria model is obtained through workshop sessions with a group of participants selected by the decision-makers (i.e., municipalities). The M-MACBETH model supports the application of the method and automatically verifies judgement consistency which significantly decreases the risk of bias. UrbanBEATS generates spatial layouts of NBS planning alternatives. It suggests the type of NBS to be implemented in view of their performance in achieving stormwater management objectives. This research demonstrated how MCDA methods and approaches can be adapted for NBS planning and can be combined with existing water engineering tools to evaluate NBS planning alternatives.

We successfully applied this new method in three different cities worldwide to test its ability to adapt to different climatic, urban and socio-cultural contexts. Our partnerships with Trois-Rivières (Canada), Toulouse (France) and Melbourne (Australia) brought together decision-makers, researchers and stakeholders with various profiles in a transdisciplinary approach and a research-action process. Our partners played an important role in helping us to convince and unite participants around the research project. Decision-makers in Trois-Rivières, Toulouse and Melbourne selected different types of stakeholders (i.e. expertise) to be involved during workshop sessions. However, some profiles were missing for all case studies such as citizen representative and economic experts, identified as “silent stakeholders” because they are rarely involved in decision-making processes. Each case study contributed to the development of the MCDA-NBS method. The Trois-Rivières case study provided training in the MACBETH method and tested the MCDA-NBS method with employees of the municipality through online workshops. The Toulouse case study included more participants from outside the municipality and proposed a redesign of the face-to-face method to make it more time-efficient for each participant. Finally, the Melbourne case study confirmed the various steps of the method in an English-speaking context and again at a significantly larger scale.

The UrbanBEATS tool produced several alternatives for NBS implementation which received interest from decision-makers and stakeholders, but which required a more precise analysis by integrating the additional criteria compiled in the multi-criteria model in order to select the most relevant alternative. The multi-criteria models (i.e. criteria chosen, units of measurement, reference data, preferences linked to the types of NBS) constructed by the participants were different for all case studies. Even if some criteria may look quite similar (e.g., improving biodiversity, mitigating temperature), the reference data, value scale and weights were different. This makes the use of an MCDA method relevant to provide a better adaptation to a context and help decision-making while combining the multi-criteria model to evaluate the NBS planning alternatives produced by UrbanBEATS.

Decision-makers and stakeholders of the different case studies validated the results obtained and also recognized the importance of multi-criteria analysis in the process. They expressed the wish to use the results to support their decision-making and future actions relating to the implementation of NBS in their territories. Thus, a training day will be planned with Trois-Rivières to enable the use of the UrbanBEATS model and the MACBETH model, whereas several presentations are planned in other cities for potential future case studies and provide a benchmark for comparing cities with each other.

The application of the MCDA-NBS method in three different contexts demonstrated that the combination of MCDA and water engineering tools improves the results for NBS planning and is flexible enough to be adapted to other geographical, socio-political, and urban contexts.

Shortcomings & Recommendations

This research does have certain limitations and requires certain recommendations to be followed when interpreting the results.

The UrbanBEATS model is freely available in its first (current) version, unlike the other tools mentioned in the literature which are under a commercial licence or even not shared by their developers. As with most models, UrbanBEATS depends on data accessibility and quality, which can be an issue in some applications. Moreover, UrbanBEATS does not directly integrate MCDA models other than its simplified preference matrix for different NBS technologies, which means that the performance of each alternative must be calculated separately. Some independent GIS-based tools have been developed that integrate MCDA analysis, but this approach is inconsistent with a full MCDA process where the first step is the selection and definition of criteria, which depends on the context. Indeed, the choice of criteria, their evaluation and the objectives are not the same from one context to another and it is therefore difficult to generalise it within a model.

The MACBETH method relies on stakeholder involvement and is especially well-designed to foster discussion and consensus. A facilitator is needed to lead the different steps of the MCDA process and to bring together decision-makers, stakeholders, and researchers. The facilitator should have expertise in MCDA as well as in the software used. It also requires a time investment of the stakeholders for the workshops, 10 to 20 hours per person. The assessment of alternatives by the research team depends on the complexity of the criteria chosen, 50 to 80 hours were needed per person for the three case studies. The MACBETH method comes with the M-MACBETH software to support the method, which allows validation of the robustness of the model by analysing the consistency of stakeholder judgements, the influence of the criteria on the overall multi-criteria model or on the evaluation of the NBS alternatives. However, the tool is under a commercial licence (i.e., between 1,500$ and 15,000$ depending on the licence).

A fundamental element underlying the MCDA-NBS method is the participative process with the stakeholders. The aim of this participatory process is to assemble a group of stakeholders that represents different perspectives. It is therefore not necessary to have a large group of participants, but rather to have as many different types of expertise as possible. For example, the Toulouse case study had a group of 8 participants with distinct profiles, unlike the Trois-Rivières and Melbourne studies, which included several participants with thesame profiles i.e. planning, engineering and research experts. The presence of several similar participant profiles can lead to the over-representation of one or more aspects in the multicriteria model constructed. The facilitator made sure to separate participants into sub-groups according to their specialties, associating each sub-group with the criteria corresponding to their specialty. Moreover, it was possible to avoid certain group behavioural biases (e.g. one person having a dominant voice, group leader) by, for example, asking participants to think individually about the criteria to be taken into account for the study before sharing them with the other members of the group. The facilitator's role was to ensure that the debate was equally divided between all participants. Group behavioural biases were more difficult to avoid in the Trois-Rivières study, where the workshops were held online. In addition, the online workshops required more participation time than the face-to-face workshops, as it was more difficult for participants to concentrate for long periods online and the tasks required (e.g. grouping criteria) were more difficult to perform.

Beyond the final score, each step of the MCDA-NBS method is relevant as we obtained intermediate results along the process (e.g., value scales on criterion) which can be useful on their own. Care must be taken to ensure that these criteria are independent and that there are no interactions between them, which could lead to double counting and, ultimately, unsatisfactory results. Also, the criteria selected by the stakeholders should be measurable from available data or expressed on a qualitative scale.

One aspect not covered by the multi-criteria evaluation in these three case studies is the economic aspect. We addressed the issue by assuming that the more NBS proposed in a plan, the more expensive the alternative. However, this is a more complex question, as it requires taking into account the type of NBS and its life-cycle (i.e., the design, installation, maintenance and the possible replacement of the NBS). In this research, the aim was to concentrate on assessing the quality of the NBS implementation alternatives proposed by UrbanBEATS, whereas the financial dimension was considered secondary.

Perspectives & Future work

The proposed MCDA-NBS method could be adapted to other MCDA methods than MACBETH and other planning-support tools than UrbanBEATS to produce automatic NBS planning alternatives. However, replacing the MACBETH method by another MCDA method would affect the obtained multi-criteria model as other MCDA methods will not use the same algorithm. It will also affect the MCDA process itself as the workshop sessions follow the steps of the selected MCDA method. Thus, applying a different method to one of the three case studies could test the influence of the chosen MCDA method. The work of Hajkowicz (2007) analysed the influence of different methods on the same problem, and his method could be applied to NBS planning. Also, the choice of criteria depends on the workshop participants as there are individual and group behavioural biases identified in the research work of Montibeller & Von Winterfeldt (2018). It would be interesting to explore the variation of the multi-criteria model with different participants for the same issue.

The NBS planning alternatives to be evaluated by the multi-criteria model do not necessarily need to be the output of a planning model, such as UrbanBEATS. NBS planning alternatives can also come directly from decision-makers, based on scenarios developed internally, that could then be evaluated using the same multi-criteria model. However, automating the process of generating alternatives avoids having to evaluate alternatives that would be influenced by the people who developed them (e.g. greening certain neighborhoods would increase gentrification). To take this a step further, the alternative with the highest score using the multi-criteria model could be used to prioritize NBS implementation. Performance of each NBS could be analysed to identify which NBS brings the most benefits and is therefore the most interesting to prioritize for implementation. This can be done using a multi-criteria model which often integrates this aspect in the criteria evaluation. GIS software could be used to overlay the criteria data and the NBS planning alternative data to identify the NBS that perform best on a subset of criteria. This analysis can lead to the development of a priority map of the NBS with the highest impact. UrbanBEATS could then be expanded to integrate NBS preferences based on this analysis. The model could also integrate new NBS such as green roofs, green facades or porous pavements which are increasingly considered by decision-makers but are currently beyond the model's scope.

Regarding the use of the UrbanBEATS model, other data could be integrated for alternative simulations such as a biodiversity map or the groundwater table height map, which are recurring criteria in all three case studies. Moreover, in the current study, simulations were carried out using a selection of the 10 best alternatives (filtered from 1000 generated options). This selection could be larger (e.g., 100) and could lead to the development of an automatic algorithm based on the multi-criteria model for NBS alternative evaluation rather than be based on manual evaluation.

In its current state, the proposed MCDA-NBS method does not include costs because the research on this aspect is still in its infancy for NBS options. Recent research (e.g. carried out by CERIU (Centre d'Expertise et de Recherche en Infrastructures Urbaines)) is conducting interviews with experts in several countries to estimate the costs involved in implementing NBS. It would be interesting to integrate this recent work into the Trois-Rivières,Toulouse and Melbourne case studies and add a cost-benefit analysis to the results of the MCDA-NBS method. The return on investment is another relevant aspect to evaluate as it allows considering the time dimension in the decision of implementing NBS. Indeed, these infrastructures will last a few decades and their implementation can have impact over a couple of generations.

One should be reminded that the MCDA-NBS method is a participatory approach and must include representatives of civil society, researchers, and economic experts in future case studies to follow scientific recommendations. Further research integrating these type of stakeholders could assess their impacts and relevance on multicriteria models and decision-making.

Finally, the proposed MCDA-NBS method is the result of transdisciplinary research between the decision-making sciences and the biophysical sciences, and the obtained results can be useful in many fields (e.g., urban planning, water management, sustainable development) by providing new data on specific criteria.

References

Abi-Zeid, I., Marleau Donais, F., & Cerutti, J. (2023). Mutlicriteria Decision Aiding: Challenges in Real-Life Interventions. In M.-F. Norese, M. A. De Vicente y Oliva et I. Abi-Zeid (Ed). *Multicriteria Decision Aiding Interventions - Multiple Criteria Decision Making* (pp. 161-186). Springer. https://doi.org/10.1007/978-3-031-28465-6_6.

Ahammed, F., Hewa, G. A., & Argue, J. R. (2012). Applying multi-criteria decision analysis to select WSUD and LID technologies. *Water Supply*, *12*(6), 844-853. https://doi.org/10.2166/ws.2012.060

Alamanos, A., & Papaioannou, G. (2020). A GIS multi-criteria analysis tool for a low-cost, preliminary evaluation of wetland effectiveness for nutrient buffering at watershed scale: The case study of grand river, Ontario, Canada. *Water*, *12*(11), 3134. https://doi.org/10.3390/w12113134

Albert, C., Brillinger, M., Guerrero, P., Gottwald, S., Henze, J., Schmidt, S., Ott, E., & Schröter, B. (2021). Planning nature-based solutions: Principles, steps, and insights. *Ambio*, *50*(8), 1446-1461. https://doi.org/10.1007/s13280-020-01365-1

Allain, S., Plumecocq, G., & Leenhardt, D. (2017). How do multi-criteria assessments address landscape-level problems? A review of studies and practices. *Ecological Economics*, *136*, 282-295. https://doi.org/10.1016/j.ecolecon.2017.02.011

Alves, A., Gersonius, B., Sanchez, A., Vojinovic, Z., & Kapelan, Z. (2018). Multi-criteria approach for selection of green and grey infrastructure to reduce flood risk and increase co-benefits. *Water Resources Management*, *32*(7), 2505-2522. https://doi.org/10.1007/s11269-018-1943-3

Anderson, V., Suneja, M., & Dunjic, J. (2023). Sensing and measurement techniques for evaluation of nature-based solutions: A state-of-the-art review. *Land*, *12*(8), 1477. https://doi.org/10.3390/land12081477

Antognelli, S., & Vizzari, M. (2016). Ecosystem and urban services for landscape liveability: A model for quantification of stakeholders' perceived importance. *Land Use Policy, 50*, 277-292. https://doi.org/10.1016/j.landusepol.2015.09.023

Antognelli, S., & Vizzari, M. (2017a). Landscape liveability spatial assessment integrating ecosystem and urban services with their perceived importance by stakeholders. *Ecological Indicators*, *72*, 703-725. https://doi.org/10.1016/j.ecolind.2016.08.015

Antognelli, S., & Vizzari, M. (2017b). Landscape liveability spatial assessment integrating ecosystem and urban services with their perceived importance by stakeholders. *Ecological Indicators*, *72*, 703-725. https://doi.org/10.1016/j.ecolind.2016.08.015

Antognelli, S., & Vizzari, M. (2021). Assessing ecosystem and urban services for landscape suitability mapping. *Applied Sciences*, *11*(17), 8232. https://doi.org/10.3390/app11178232

Apud, A., Faggian, R., Sposito, V., & Martino, D. (2020). Suitability analysis and planning of green infrastructure in Montevideo, Uruguay. *Sustainability*, *12*(22), 9683. https://doi.org/10.3390/su12229683

Arciniegas, G., & Janssen, R. (2012). Spatial decision support for collaborative land use planning workshops. *Landscape and Urban Planning*, *107*(3), 332-342. https://doi.org/10.1016/j.landurbplan.2012.06.004

Arjomandi, A., Mortazavi, S. A., Khalilian, S., & Garizi, A. Z. (2021). Optimal land-use allocation using MCDM and SWAT for the Hablehroud Watershed, Iran. *Land Use Policy, 100*, 104930. https://doi.org/10.1016/j.landusepol.2020.104930

Atiqul Haq, S. Md., Islam, M. N., Siddhanta, A., Ahmed, K. J., & Chowdhury, M. T. A. (2021). Public perceptions of urban green spaces: Convergences and divergences. *Frontiers in Sustainable Cities*, *3*, 755313. https://doi.org/10.3389/frsc.2021.755313

Aubert, A. H., Esculier, F., & Lienert, J. (2020). Recommendations for online elicitation of swing weights from citizens in environmental decision-making. *Operations Research Perspectives*, *7*, 100156. https://doi.org/10.1016/j.orp.2020.100156

Aza, A., Riccioli, F., & Di Iacovo, F. (2021). Optimising payment for environmental services schemes by integrating strategies: The case of the Atlantic Forest, Brazil. *Forest Policy and Economics*, *125*, 102410. https://doi.org/10.1016/j.forpol.2021.102410

Bach, P. M. (2014). *UrbanBEATS: a virtual urban water system tool for exploring strategic planning scenarios*. Monash Water for Liveability. Thesis. Monash University, Melbourne, Australia.

Bach, P. M., Deletic, A., Urich, C., & McCarthy, D. T. (2018). Modelling characteristics of the urban form to support water systems planning. *Environmental Modelling & Software*, *104*, 249-269. https://doi.org/10.1016/j.envsoft.2018.02.012

Bach, P. M., Dotto, C. B. S., McCarthy, D. T., & Deletic, A. (2015). *Exploring multi-objective water sensitive urban design through integrated modeling*. 10th IWA International Urban Drainage Modelling Conference, Mont Saint-Anne, Québec, Canada.

Bach, P. M., Kuller, M., McCarthy, D. T., & Deletic, A. (2020). A spatial planning-support system for generating decentralised urban stormwater management schemes. *Science of The Total Environment*, *726*, 138282. https://doi.org/10.1016/j.scitotenv.2020.138282

Bach, P. M., Leitao, J. P., & Maurer, M. (2020). *'Roses are red, water is blue, multi-functional green spaces are for you' – An integrated model for strategic liveability planning*. 15th International Conference on Urban Drainage (15 ICUD), Melbourne, Australia.

Bach, P. M., Staalesen, S., McCarthy, D. T., & Deletic, A. (2015). Revisiting land use classification and spatial aggregation for modelling integrated urban water systems. *Landscape and Urban Planning*, *143*, 43-55. https://doi.org/10.1016/j.landurbplan.2015.05.012

Badura, T., Krkoška Lorencová, E., Ferrini, S., & Vačkářová, D. (2021). Public support for urban climate adaptation policy through nature-based solutions in Prague. *Landscape and Urban Planning*, *215*, 104215. https://doi.org/10.1016/j.landurbplan.2021.104215

Baskent, E. Z. (2018). A review of the development of the multiple use forest management planning concept. *International Forestry Review*, *20*(3), 296-313. https://doi.org/10.1505/146554818824063023

Baskent, E. Z. (2020). A framework for characterizing and regulating ecosystem services in a management planning context. *Forests*, *11*(1), 102. https://doi.org/10.3390/f11010102

Beardmore, L., Heagney, E., & Sullivan, C. A. (2019). Complementary land use in the Richmond River catchment: Evaluating economic and environmental benefits. *Land Use Policy*, *87*, 104070. https://doi.org/10.1016/j.landusepol.2019.104070

Belton, V., & Pictet, J. (1997). A framework for group decision using a MCDA model: Sharing, aggregating or comparing individual information? *Journal of Decision Systems*, *6*(3), 283-303. https://doi.org/10.1080/12460125.1997.10511726

Belton, V., & Stewart, T. J. (2002). *Multiple criteria decision analysis*. Springer, Heidelberg, Germany. https://doi.org/10.1007/978-1-4615-1495-4

Billaud, O., Soubeyrand, M., Luque, S., & Lenormand, M. (2020). Comprehensive decision-strategy space exploration for efficient territorial planning strategies. *Computers, Environment and Urban Systems*, *83*, 101516. https://doi.org/10.1016/j.compenvurbsys.2020.101516

Blattert, C., Lemm, R., Thees, O., Hansen, J., Lexer, M. J., & Hanewinkel, M. (2018). Segregated versus integrated biodiversity conservation: Value-based ecosystem service assessment under varying forest management strategies in a Swiss case study. *Ecological Indicators*, *95*, 751-764. https://doi.org/10.1016/j.ecolind.2018.08.016

Blattert, C., Lemm, R., Thees, O., Lexer, M. J., & Hanewinkel, M. (2017). Management of ecosystem services in mountain forests: Review of indicators and value functions for model based multi-criteria decision analysis. *Ecological Indicators*, *79*, 391-409. https://doi.org/10.1016/j.ecolind.2017.04.025

Boggia, A., Massei, G., Pace, E., Rocchi, L., Paolotti, L., & Attard, M. (2018). Spatial multicriteria analysis for sustainability assessment: A new model for decision making. *Land Use Policy*, *71*, 281-292. https://doi.org/10.1016/j.landusepol.2017.11.036

Borsuk, M. E., Mavrommati, G., Samal, N. R., Zuidema, S., Wollheim, W., Rogers, S. H., Thorn, A. M., Lutz, D., Mineau, M., Grimm, C., Wake, C. P., Howarth, R., & Gardner, K. (2019). Deliberative multiattribute valuation of ecosystem services across a range of regional land-use, socioeconomic, and climate scenarios for the upper Merrimack River watershed, New Hampshire, USA. *Ecology and Society*, *24*(2):11. https://doi.org/10.5751/ES-10806-240211

Bottero, M., Ferretti, V., Figueira, J. R., Greco, S., & Roy, B. (2015). Dealing with a multiple criteria environmental problem with interaction effects between criteria through an extension of the Electre III method. *European Journal of Operational Research*, *245*(3), 837-850. https://doi.org/10.1016/j.ejor.2015.04.005

Bourne, A., Holness, S., Holden, P., Scorgie, S., Donatti, C. I., & Midgley, G. (2016). A socio-ecological approach for identifying and contextualising Spatial ecosystem-based adaptation priorities at the sub-national level. *PLOS ONE*, *11*(5), e0155235. https://doi.org/10.1371/journal.pone.0155235

Bousquet, M. (2020). *Application d'un outil d'aide à la planification intégrant une gestion de l'eau plus durable en milieu urbain dans un contexte en climat froid (Québec, Canada)* (p. 31) Rapport de stage de fin d'études. Institut National des Sciences Appliquées (INSA), Toulouse, France.

Brasil, J., Macedo, M., Lago, C., Oliveira, T., Júnior, M., Oliveira, T., & Mendiondo, E. (2021). Nature-based solutions and real-Time control: Challenges and opportunities. *Water*, *13*(5), 651. https://doi.org/10.3390/w13050651

Brillinger, M., Scheuer, S., & Albert, C. (2022). Deliberating options for nature-based river development: Insights from a participatory multi-criteria evaluation. *Journal of Environmental Management*, *317*, 115350. https://doi.org/10.1016/j.jenvman.2022.115350

Brink, E., Aalders, T., Ádám, D., Feller, R., Henselek, Y., Hoffmann, A., Ibe, K., Matthey-Doret, A., Meyer, M., Negrut, N. L., Rau, A.-L., Riewerts, B., von Schuckmann, L., Törnros, S., von Wehrden, H., Abson, D. J., & Wamsler, C. (2016). Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, *36*, 111-123. https://doi.org/10.1016/j.gloenvcha.2015.11.003

Bush, E., Lemmen, D. S., Canada, & Environment and Climate Change Canada. (2019). *Canada's changing climate report*. http://publications.gc.ca/collections/collection_2019/eccc/En4-368-2019-eng.pdf

Caglayan, İ., Yeşil, A., Kabak, Ö., & Bettinger, P. (2021). A decision making approach for assignment of ecosystem services to forest management units : A case study in northwest Turkey. *Ecological Indicators*, *121*, 107056. https://doi.org/10.1016/j.ecolind.2020.107056

Campos, P., Caparrós, A., Cerdá, E., Díaz-Balteiro, L., Herruzo, C., Huntsinger, L., Martín-Barroso, D., Martínez-Jauregui, M., Ovando, P., Oviedo, J. L., Pasalodos-Tato, M., Romero, C., Soliño, M., & Standiford, R. B. (2017). Multifunctional natural forest silviculture economics revised : Challenges in meeting landowners' and society's wants. A review. *Forest Systems*, *26*(2), eR01S. https://doi.org/10.5424/fs/2017262-10505

Cao, Q., Zhang, X., Lei, D., Guo, L., Sun, X., Kong, F., & Wu, J. (2019). Multi-scenario simulation of landscape ecological risk probability to facilitate different decision-making preferences. *Journal of Cleaner Production*, *227*, 325-335. https://doi.org/10.1016/j.jclepro.2019.03.125

Cecílio, R., Oliveira-Ravani, L., Zanetti, S., & Mendes, H. (2021). Method for classifying sites to Atlantic Rainforest restoration aiming to increase basin's streamflows. *iForest - Biogeosciences and Forestry*, *14*(1), 86-94. https://doi.org/10.3832/ifor3658-013

Census Profile, 2016 Census. (2017, février 8). [Governmental]. Statistics Canada. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E

Cerreta, M., Mele, R., & Poli, G. (2020). Urban ecosystem services (UES) assessment within a 3D virtual environment : A methodological approach for the larger urban zones (LUZ) of Naples, Italy. *Applied Sciences*, *10*(18), 6205. https://doi.org/10.3390/app10186205

Cervelli, E., Pindozzi, S., Capolupo, A., Okello, C., Rigillo, M., & Boccia, L. (2016). Ecosystem services and bioremediation of polluted areas. *Ecological Engineering*, *87*, 139-149. https://doi.org/10.1016/j.ecoleng.2015.09.045

Cervelli, E., Pindozzi, S., Sacchi, M., Capolupo, A., Cialdea, D., Rigillo, M., & Boccia, L. (2017). Supporting land use change assessment through ecosystem services and wildlife indexes. *Land Use Policy*, *65*, 249-265. https://doi.org/10.1016/j.landusepol.2017.04.011

Cervelli, E., Scotto Di Perta, E., & Pindozzi, S. (2020). Identification of marginal landscapes as support for sustainable development : GIS-based analysis and landscape metrics assessment in southern Italy areas. *Sustainability*, *12*(13), 5400. https://doi.org/10.3390/su12135400

Chatzinikolaou, P., Viaggi, D., & Raggi, M. (2018). Review of multicriteria methodologies and tools for the evaluation of the provision of ecosystem services. In J. Berbel, T. Bournaris, B. Manos, N. Matsatsinis, & D. Viaggi (Éds.), *Multicriteria Analysis in Agriculture* (p. 43-68). Springer International Publishing, Heidelberg, Germany. https://doi.org/10.1007/978-3-319-76929-5_2

Checkland, P. (2000). Soft systems methodology: A thirty year retrospective. *John Wiley & Sons*, New-York, NY, USA. https://doi.org/10.1002/1099-1743(200011)17:1+<::AID-SRES374>3.0.CO;2-O

Choi, B. C. K., & Pak, A. W. P. (2007). Multidisciplinarity, interdisciplinarity, and transdisciplinarity in health research, services, education and policy: 2. Promotors, barriers, and strategies of enhancement. *Clinical & Investigative Medicine*, *30*(6), 224. https://doi.org/10.25011/cim.v30i6.2950

Chopin, P., Bergkvist, G., & Hossard, L. (2019). Modelling biodiversity change in agricultural landscape scenarios—A review and prospects for future research. *Biological Conservation, 235*, 1-17. https://doi.org/10.1016/j.biocon.2019.03.046

Cimon-Morin, J., & Poulin, M. (2018). Setting conservation priorities in cities: Approaches, targets and planning units adapted to wetland biodiversity and ecosystem services. *Landscape Ecology*, *33*(11), 1975-1995. https://doi.org/10.1007/s10980-018-0707-z

Cinelli, M., Kadziński, M., Miebs, G., Gonzalez, M., & Słowiński, R. (2022). Recommending multiple criteria decision analysis methods with a new taxonomy-based decision support system. *European Journal of Operational Research*, *302*(2), 633-651. https://doi.org/10.1016/j.ejor.2022.01.011

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Éds.). (2016). *Nature-based solutions to address global societal challenges*. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2016.13.en

Comino, E., Bottero, M., Pomarico, S., & Rosso, M. (2014). Exploring the environmental value of ecosystem services for a river basin through a spatial multicriteria analysis. *Land Use Policy*, *36*, 381-395. https://doi.org/10.1016/j.landusepol.2013.09.006

Cook, D., Fazeli, R., & Davíðsdóttir, B. (2019). The need for integrated valuation tools to support decision-making – The case of cultural ecosystem services sourced from geothermal areas. *Ecosystem Services*, *37*, 100923. https://doi.org/10.1016/j.ecoser.2019.100923

Cortinovis, C., Geneletti, D., & Hedlund, K. (2021). Synthesizing multiple ecosystem service assessments for urban planning: A review of approaches, and recommendations. *Landscape and Urban Planning*, *213*, 104129. https://doi.org/10.1016/j.landurbplan.2021.104129

Costa, C. A. B. e. (2012). *Readings in multiple criteria decision aid*. Springer Science & Business Media, Heidelberg, Germany.

Bana e Costa, Carlos & De Corte, Jean-Marie & Vansnick, Jean-Claude. (2003). MACBETH. (Overview of MACBETH multicriteria decision analysis approach). International Journal of Information Technology and Decision Making. 11. 359-387.

Costa, C. A. B. e, Ensslin, L., Cornêa, É. C., & Vansnick, J.-C. (1999). Decision Support Systems in action: Integrated application in a multicriteria decision aid process. *European Journal of Operational Research*, *113*(2), 315-335. https://doi.org/10.1016/S0377-2217(98)00219-7

Costa, C. A. B. e, Vieira, A. C. L., Nóbrega, M., Quintino, A., Oliveira, M. D., & Costa, J. B. e. (2019). Collaborative Value Modelling in corporate contexts with MACBETH. *Procedia Computer Science*, *162*, 786-794. https://doi.org/10.1016/j.procs.2019.12.051

Croeser, T., Garrard, G., Sharma, R., Ossola, A., & Bekessy, S. (2021). Choosing the right nature-based solutions to meet diverse urban challenges. *Urban Forestry & Urban Greening*, *65*, 127337. https://doi.org/10.1016/j.ufug.2021.127337

Crossman, N. D., Bryan, B. A., & King, D. (2009). *Integration of landscape-scale and site-scale metrics for prioritising investments in natural capital*. https://api.semanticscholar.org/CorpusID:56437890

Da Cunha, A., & Thomas, I. (2017). *La ville résiliente : Comment la construire?* https://login.proxy.bib.uottawa.ca/login?url=http://deslibris.ca/ID/479176

Dagenais, D., Thomas, I., & Paquette, S. (2017). Siting green stormwater infrastructure in a neighbourhood to maximise secondary benefits: Lessons learned from a pilot project. *Landscape Research*, *42*(2), 195-210. https://doi.org/10.1080/01426397.2016.1228861

Dall’Ara, E., Maino, E., Gatta, G., Torreggiani, D., & Tassinari, P. (2019). Green Mobility Infrastructures. A landscape approach for roundabouts’ gardens applied to an Italian case study. *Urban Forestry & Urban Greening*, *37*, 109-125. https://doi.org/10.1016/j.ufug.2018.03.011

Dandy, G. C., Di Matteo, M., & Maier, H. R. (2019). Optimization of WSUD Systems. In *Approaches to Water Sensitive Urban Design* (p. 303-328). Elsevier, Amsterdam, The Netherlands. https://doi.org/10.1016/B978-0-12-812843-5.00015-0

D'Auria, A., De Toro, P., Fierro, N., & Montone, E. (2018). Integration between GIS and multi-criteria analysis for ecosystem services assessment: A methodological proposal for the national park of Cilento, Vallo di Diano and Alburni (Italy). *Sustainability*, *10*(9), 3329. https://doi.org/10.3390/su10093329

De Castro Pardo, M., Martínez, P. F., Martínez, J. M. G., & Martín, J. M. M. (2020). Modelling natural capital : A proposal for a mixed multi-criteria approach to assign management priorities to ecosystem services. *Contemporary Economics*, *14*(1), 22-37. https://doi.org/10.5709/ce.1897-9254.330

De Toro, P., & Iodice, S. (2017). La valutazione nella pianificazione urbanistica : Un approccio multicriterio per la scelta di Piani Operativi alternativi a Cava De' Tirreni. *Aestimum*, 93-112 Pages. https://doi.org/10.13128/AESTIMUM-20450 (in Italian)

Deng, X., Li, Z., & Gibson, J. (2016). A review on trade-off analysis of ecosystem services for sustainable land-use management. *Journal of Geographical Sciences*, *26*(7), 953-968. https://doi.org/10.1007/s11442-016-1309-9

Di Matteo, M., Maier, H. R., & Dandy, G. C. (2019). Many-objective portfolio optimization approach for stormwater management project selection encouraging decision maker buy-in. *Environmental Modelling & Software*, *111*, 340-355. https://doi.org/10.1016/j.envsoft.2018.09.008

Dick, J., Miller, J. D., Carruthers-Jones, J., Dobel, A. J., Carver, S., Garbutt, A., Hester, A., Hails, R., Magreehan, V., & Quinn, M. (2019). How are nature based solutions contributing to priority societal challenges surrounding human well-being in the United Kingdom: A systematic map protocol. *Environmental Evidence, 8*(1), 37. https://doi.org/10.1186/s13750-019-0180-4

Donais M., F., Abi-Zeid, I., Waygood, E. O. D., & Lavoie, R. (2019). Assessing and ranking the potential of a street to be redesigned as a complete Street: A multi-criteria decision aiding approach. *Transportation Research Part A: Policy and Practice*, *124*, 1-19. https://doi.org/10.1016/j.tra.2019.02.006

Dorst, H., van der Jagt, A., Raven, R., & Runhaar, H. (2019). Urban greening through nature-based solutions – Key characteristics of an emerging concept. *Sustainable Cities and Society*, *49*, 101620. https://doi.org/10.1016/j.scs.2019.101620

Drenning, P., Chowdhury, S., Volchko, Y., Rosén, L., Andersson-Sköld, Y., & Norrman, J. (2022). A risk management framework for Gentle Remediation Options (GRO). *Science of The Total Environment*, *802*, 149880. https://doi.org/10.1016/j.scitotenv.2021.149880

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A review. *Science of The Total Environment*, *607-608*, 413-432. https://doi.org/10.1016/j.scitotenv.2017.06.254

Eden, C. (1988). Cognitive mapping. *European Journal of Operational Research*, *36*(1), 1-13. https://doi.org/10.1016/0377-2217(88)90002-1

Engström, R., Howells, M., Mörtberg, U., & Destouni, G. (2018). Multi-functionality of nature-based and other urban sustainability solutions: New York City study. *Land Degradation & Development*, *29*(10), 3653-3662. https://doi.org/10.1002/ldr.3113

Epelde, L., Mendizabal, M., Gutiérrez, L., Artetxe, A., Garbisu, C., & Feliu, E. (2022). Quantification of the environmental effectiveness of nature-based solutions for increasing the resilience of cities under climate change. *Urban Forestry & Urban Greening*, *67*, 127433. https://doi.org/10.1016/j.ufug.2021.127433

Escobar-Camacho, D., Rosero, P., Castrejón, M., Mena, C. F., & Cuesta, F. (2021). Oceanic islands and climate: Using a multi-criteria model of drivers of change to select key conservation areas in Galapagos. *Regional Environmental Change*, *21*(2), 47. https://doi.org/10.1007/s10113-021-01768-0

Estrella, R., Cattrysse, D., & Van Orshoven, J. (2016). An integer programming model to determine land use trajectories for optimizing regionally integrated ecosystem services delivery. *Forests*, *7*(2), 33. https://doi.org/10.3390/f7020033

Ezquerro, M., Pardos, M., & Diaz-Balteiro, L. (2016). Operational research techniques used for addressing biodiversity objectives into forest management : An overview. *Forests*, *7*(12), 229. https://doi.org/10.3390/f7100229

Ezquerro, M., Pardos, M., & Diaz-Balteiro, L. (2019). Integrating variable retention systems into strategic forest management to deal with conservation biodiversity objectives. *Forest Ecology and Management*, *433*, 585-593. https://doi.org/10.1016/j.foreco.2018.11.003

Ferrans, P., Torres, M. N., Temprano, J., & Rodríguez Sánchez, J. P. (2022). Sustainable Urban Drainage System (SUDS) modeling supporting decision-making : A systematic quantitative review. *Science of The Total Environment*, *806*, 150447. https://doi.org/10.1016/j.scitotenv.2021.150447

Ferreira, J. C., Monteiro, R., & Silva, V. R. (2021). Planning a green infrastructure network from theory to practice: The case study of Setúbal, Portugal. *Sustainability*, *13*(15), 8432. https://doi.org/10.3390/su13158432

Ferretti, V., & Montibeller, G. (2016). Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems. *Decision Support Systems*, *84*, 41-52. https://doi.org/10.1016/j.dss.2016.01.005

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, *12*(7), 525-542. https://doi.org/10.1080/1573062X.2014.916314

Fontana, V., Radtke, A., Bossi Fedrigotti, V., Tappeiner, U., Tasser, E., Zerbe, S., & Buchholz, T. (2013). Comparing land-use alternatives: Using the ecosystem services concept to define a multi-criteria decision analysis. *Ecological Economics, 93*, 128-136. https://doi.org/10.1016/j.ecolecon.2013.05.007

Franco, L. A., & Montibeller, G. (2010). Facilitated modelling in operational research. *European Journal of Operational Research, 205*(3), 489-500. https://doi.org/10.1016/j.ejor.2009.09.030

Friend, J. (2011). The strategic choice approach. In J. J. Cochran, L. A. Cox, P. Keskinocak, J. P. Kharoufeh, & J. C. Smith, *Wiley Encyclopedia of Operations Research and Management Science* (p. eorms0971). John Wiley & Sons, New-York, NY, USA. https://doi.org/10.1002/9780470400531.eorms0971

Galychyn, O., Buonocore, E., & Franzese, P. P. (2020). Exploring the global scientific literature on urban metabolism. *Ecological Questions*, *31*(4), 1. https://doi.org/10.12775/EQ.2020.031

García De Jalón, S., Iglesias, A., Cunningham, R., & Pérez Díaz, J. I. (2014). Building resilience to water scarcity in southern Spain: A case study of rice farming in Doñana protected wetlands. *Regional Environmental Change*, *14*(3), 1229-1242. https://doi.org/10.1007/s10113-013-0569-5

Gebre, S. L., Cattrysse, D., Alemayehu, E., & Van Orshoven, J. (2021). Multi-criteria decision making methods to address rural land allocation problems: A systematic review. *International Soil and Water Conservation Research, 9*(4), 490-501. https://doi.org/10.1016/j.iswcr.2021.04.005

Gielczewski, M., Stelmaszczyk, M., Piniewski, M., & Okruszko, T. (2011). How can we involve stakeholders in the development of water scenarios? Narew River Basin case study. *Journal of Water and Climate Change*, *2*(2-3), 166-179. https://doi.org/10.2166/wcc.2011.027

Gomes, E., Inácio, M., Bogdzevič, K., Kalinauskas, M., Karnauskaitė, D., & Pereira, P. (2021). Future land-use changes and its impacts on terrestrial ecosystem services: A review. *Science of The Total Environment*, *781*, 146716. https://doi.org/10.1016/j.scitotenv.2021.146716

Gómez, A., & Carnero, M. C. (2016). Decision support system for maintenance policy optimization in medicinal gases subsystems. *IFAC-PapersOnLine*, *49*(28), 268-273. https://doi.org/10.1016/j.ifacol.2016.11.046

Gonzalez, A., & Enríquez-de-Salamanca, Á. (2018). Spatial multi-criteria analysis in environmental assessment: A review and reflection on benefits and limitations. *Journal of Environmental Assessment Policy and Management*, *20*(03), 1840001. https://doi.org/10.1142/S146433321840001X

Goodspeed, R., Liu, R., Gounaridis, D., Lizundia, C., & Newell, J. (2022). A regional spatial planning model for multifunctional green infrastructure. *Environment and Planning B: Urban Analytics and City Science*, *49*(3), 815-833. https://doi.org/10.1177/23998083211033610

Graça, M., Cruz, S., Monteiro, A., & Neset, T.-S. (2022). Designing urban green spaces for climate adaptation: A critical review of research outputs. *Urban Climate*, *42*, 101126. https://doi.org/10.1016/j.uclim.2022.101126

Gray, E., Ozment, S., Altamirano, J. C., Feltran-Barbieri, R., & Morales, G. (2019). *Green-gray assessment: How to assess the costs and benefits of green infrastructure for water supply systems*. World Resource Institute. https://doi.org/10.13140/RG.2.2.26788.01923

Grêt-Regamey, A., Altwegg, J., Sirén, E. A., Van Strien, M. J., & Weibel, B. (2017). Integrating ecosystem services into spatial planning—A spatial decision support tool. *Landscape and Urban Planning*, *165*, 206-219. https://doi.org/10.1016/j.landurbplan.2016.05.003

Griffith, T. L., Fuller, M. A., & Northcraft, G. B. (1998). Facilitator influence in group support systems: Intended and unintended effects. *Information Systems Research*, *9*(1), 20-36. https://doi.org/10.1287/isre.9.1.20

Grima, N., Singh, S. J., & Smetschka, B. (2018). Improving payments for ecosystem services (PES) outcomes through the use of Multi-Criteria Evaluation (MCE) and the software OPTamos. *Ecosystem Services*, *29*, 47-55. https://doi.org/10.1016/j.ecoser.2017.11.019

Groot, J. C. J., & Rossing, W. A. H. (2011). Model-aided learning for adaptive management of natural resources: An evolutionary design perspective: *Model-aided learning for adaptive NRM*. *Methods in Ecology and Evolution*, *2*(6), 643-650. https://doi.org/10.1111/j.2041-210X.2011.00114.x

Haag, F., Reichert, P., Maurer, M., & Lienert, J. (2019). Integrating uncertainty of preferences and predictions in decision models: An application to regional wastewater planning. *Journal of Environmental Management*, *252*, 109652. https://doi.org/10.1016/j.jenvman.2019.109652

Haase, D., Haase, A., & Rink, D. (2014). Conceptualizing the nexus between urban shrinkage and ecosystem services. *Landscape and Urban Planning*, *132*, 159-169. https://doi.org/10.1016/j.landurbplan.2014.09.003

Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., Gomez-Baggethun, E., Gren, Å., Hamstead, Z., Hansen, R., Kabisch, N., Kremer, P., Langemeyer, J., Rall, E. L., McPhearson, T., Pauleit, S., Qureshi, S., Schwarz, N., Voigt, A., … Elmqvist, T. (2014). A quantitative review of urban ecosystem service assessments : Concepts, models, and implementation. *AMBIO*, *43*(4), 413-433. https://doi.org/10.1007/s13280-014-0504-0

Haile, G., & Suryabhagavan, K. V. (2019). GIS-based approach for identification of potential rainwater harvesting sites in Arsi Zone, Central Ethiopia. *Modeling Earth Systems and Environment*, *5*(1), 353-367. https://doi.org/10.1007/s40808-018-0537-7

Haines-Young, R. (2011). Exploring ecosystem service issues across diverse knowledge domains using Bayesian Belief Networks. *Progress in Physical Geography: Earth and Environment*, *35*(5), 681-699. https://doi.org/10.1177/0309133311422977

Hajkowicz, S. (2007). A comparison of multiple criteria analysis and unaided approaches to environmental decision making. *Environmental Science & Policy*, *10*(3), 177-184. https://doi.org/10.1016/j.envsci.2006.09.003

Hamouz, V., Møller-Pedersen, P., & Muthanna, T. M. (2020). Modelling runoff reduction through implementation of green and grey roofs in urban catchments using PCSWMM. *Urban Water Journal*, *17*(9), 813-826. https://doi.org/10.1080/1573062X.2020.1828500

Hanna, E., & Comín, F. A. (2021). Urban green infrastructure and sustainable development : A review. *Sustainability*, *13*(20), 11498. https://doi.org/10.3390/su132011498

Heathcote, I. W. (2009). *Integrated Watershed Management: Principles and Practice* (2nd ed). John Wiley & Sons, New-York, NY, USA.

Hébert, S., & Belley, J. (2005). *Direction du suivi de l'état de l'environnement : Le Saint Laurent-La qualité des eaux du fleuve 1990-2003* (ENV/2005/0095; QE/156). Ministry of Environment of Québec, Québec, QC, Canada.

Hernández-Romero, G., Álvarez-Martínez, J. M., Pérez-Silos, I., Silió-Calzada, A., Vieites, D. R., & Barquín, J. (2022). From forest dynamics to wetland siltation in mountainous landscapes: A RS-based framework for enhancing erosion control. *Remote Sensing*, *14*(8), 1864. https://doi.org/10.3390/rs14081864

Islam, A., Hassini, S., & El-Dakhakhni, W. (2021). A systematic bibliometric review of optimization and resilience within low impact development stormwater management practices. *Journal of Hydrology*, *599*, 126457. https://doi.org/10.1016/j.jhydrol.2021.126457

Jackson, B., Pagella, T., Sinclair, F., Orellana, B., Henshaw, A., Reynolds, B., Mcintyre, N., Wheater, H., & Eycott, A. (2013). Polyscape : A GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. *Landscape and Urban Planning*, *112*, 74-88. https://doi.org/10.1016/j.landurbplan.2012.12.014

Jato-Espino, D., Rodriguez-Hernandez, J., Andrés-Valeri, V. C., & Ballester-Muñoz, F. (2014). A fuzzy stochastic multi-criteria model for the selection of urban pervious pavements. *Expert Systems with Applications*, *41*(15), 6807-6817. https://doi.org/10.1016/j.eswa.2014.05.008

Jayasooriya, V. M., Muthukumaran, S., Ng, A. W. M., & Perera, B. J. C. (2018). Multi criteria decision making in selecting stormwater management green infrastructure for industrial areas part 2: A case study with TOPSIS. *Water Resources Management*, *32*(13), 4297-4312. https://doi.org/10.1007/s11269-018-2052-z

Jayasooriya, V. M., Ng, A. W. M., Muthukumaran, S., & Perera, B. J. C. (2019). Multi criteria decision making in selecting stormwater management green infrastructure for industrial areas part 1: Stakeholder preference elicitation. *Water Resources Management*, *33*(2), 627-639. https://doi.org/10.1007/s11269-018-2123-1

Jelokhani-Niaraki, M. (2021). Collaborative spatial multicriteria evaluation: A review and directions for future research. *International Journal of Geographical Information Science*, *35*(1), 9-42. https://doi.org/10.1080/13658816.2020.1776870

Johnson, J. A., Jones, S. K., Wood, S. L. R., Chaplin-Kramer, R., Hawthorne, P. L., Mulligan, M., Pennington, D., & DeClerck, F. A. (2019). Mapping ecosystem services to human well-being: A toolkit to support integrated landscape management for the SDGs. *Ecological Applications*, *29*(8), e01985. https://doi.org/10.1002/eap.1985

Joyce, J., Chang, N.-B., Harji, R., & Ruppert, T. (2018). Coupling infrastructure resilience and flood risk assessment via copulas analyses for a coastal green-grey-blue drainage system under extreme weather events. *Environmental Modelling & Software*, *100*, 82-103. https://doi.org/10.1016/j.envsoft.2017.11.008

Kamal, A. (2016). *Expanding Boundaries - Campus sustainability retrofits: A multi-criteria site selection model for Low Impact Development (LID) – A. Kamal*. vdf Hochschulverlag AG an der ETH Zürich. https://doi.org/10.3218/3774-6_41

Kaner, S. (2014). *Facilitator's guide to participatory decision-making* (3. ed). Jossey-Bass. John Wiley & Sons, New-York, NY, USA.

Karacapilidis, N., & Tzagarakis, M. (2007). Web-based collaboration and decision making support: A multi-disciplinary approach. *International Journal of Web-Based Learning and Teaching Technologies*, *2*(4), 12-23. https://doi.org/10.4018/jwltt.2007100102

Kaykhosravi, S., Khan, U. T., & Jadidi, M. A. (2022). A simplified geospatial model to rank LID solutions for urban runoff management. *Science of The Total Environment*, *831*, 154937. https://doi.org/10.1016/j.scitotenv.2022.154937

Keeney, R. L. (2004). Making better decision makers. *Institute for Operations Research and the Management Sciences*, *4, Making Better Decision Makers. Decision Analysis 1*. https://doi.org/10.1287/ deca.1040.0009

Keller, A. A., Fournier, E., & Fox, J. (2015). Minimizing impacts of land use change on ecosystem services using multi-criteria heuristic analysis. *Journal of Environmental Management*, *156*, 23-30. https://doi.org/10.1016/j.jenvman.2015.03.017

Kiker, G. A., Bridges, T. S., Varghese, A., Seager, T. P., & Linkov, I. (2005). Application of multicriteria decision analysis in environmental decision making. *Integrated Environmental Assessment and Management*, *1*(2), 95-108. https://doi.org/10.1897/IEAM_2004a-015.1

Koc, K., Ekmekcioğlu, Ö., & Özger, M. (2021). An integrated framework for the comprehensive evaluation of low impact development strategies. *Journal of Environmental Management*, *294*, 113023. https://doi.org/10.1016/j.jenvman.2021.113023

Kordrostami, F., Attarod, P., Abbaspour, K. C., Ludwig, R., Etemad, V., Alilou, H., & Bozorg-Haddad, O. (2021). Identification of optimum afforestation areas considering sustainable management of natural resources, using geo-environmental criteria. *Ecological Engineering*, *168*, 106259. https://doi.org/10.1016/j.ecoleng.2021.106259

Koschke, L., Fürst, C., Frank, S., & Makeschin, F. (2012). A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. *Ecological Indicators*, *21*, 54-66. https://doi.org/10.1016/j.ecolind.2011.12.010

Kremer, P., Hamstead, Z. A., & McPhearson, T. (2016). The value of urban ecosystem services in New York City : A spatially explicit multicriteria analysis of landscape scale valuation scenarios. *Environmental Science & Policy*, *62*, 57-68. https://doi.org/10.1016/j.envsci.2016.04.012

Kuller, M., Bach, P. M., Ramirez-Lovering, D., & Deletic, A. (2017). Framing water sensitive urban design as part of the urban form : A critical review of tools for best planning practice. *Environmental Modelling & Software*, *96*, 265-282. https://doi.org/10.1016/j.envsoft.2017.07.003

Kuller, M., Bach, P. M., Ramirez-Lovering, D., & Deletic, A. (2018). What drives the location choice for water sensitive infrastructure in Melbourne, Australia? *Landscape and Urban Planning*, *175*, 92-101. https://doi.org/10.1016/j.landurbplan.2018.03.018

Kuller, M., Bach, P. M., Roberts, S., Browne, D., & Deletic, A. (2019). A planning-support tool for spatial suitability assessment of green urban stormwater infrastructure. *Science of The Total Environment*, *686*, 856-868. https://doi.org/10.1016/j.scitotenv.2019.06.051

Kuller, M., Farrelly, M., Deletic, A., & Bach, P. M. (2018). Building effective planning support systems for green urban water infrastructure—Practitioners' perceptions. *Environmental Science & Policy*, *89*, 153-162. https://doi.org/10.1016/j.envsci.2018.06.011

Kuller, M., Farrelly, M., Marthanty, D. R., Deletic, A., & Bach, P. M. (2022). Planning support systems for strategic implementation of nature-based solutions in the global south : Current role and future potential in Indonesia. *Cities*, *126*, 103693. https://doi.org/10.1016/j.cities.2022.103693

Kuller, M., Reid, D. J., & Prodanovic, V. (2021). Are we planning blue-green infrastructure opportunistically or strategically? Insights from Sydney, Australia. *Blue-Green Systems*, *3*(1), 267-280. https://doi.org/10.2166/bgs.2021.023

Labib, S. M. (2019). Investigation of the likelihood of green infrastructure (GI) enhancement along linear waterways or on derelict sites (DS) using machine learning. *Environmental Modelling & Software*, *118*, 146-165. https://doi.org/10.1016/j.envsoft.2019.05.006

Labiosa, W. B., Forney, W. M., Esnard, A.-M., Mitsova-Boneva, D., Bernknopf, R., Hearn, P., Hogan, D., Pearlstine, L., Strong, D., Gladwin, H., & Swain, E. (2013). An integrated multi-criteria scenario evaluation web tool for participatory land-use planning in urbanized areas : The Ecosystem Portfolio Model. *Environmental Modelling & Software*, *41*, 210-222. https://doi.org/10.1016/j.envsoft.2012.10.012

Lagroue III, H. J. (2008). Supporting structured group decision making through system-directed user guidance : An experimental study. *International Journal of Intelligent Information Technologies*, *4*(2), 57-74. https://doi.org/10.4018/jiit.2008040104

Landry, M. (1995). A note on the concept of « problem ». *Organization Studies*, *16*(2), 315-343. https://doi.org/10.1177/017084069501600206

Langemeyer, J., Gómez-Baggethun, E., Haase, D., Scheuer, S., & Elmqvist, T. (2016). Bridging the gap between ecosystem service assessments and land-use planning through multi-criteria decision analysis (MCDA). *Environmental Science & Policy*, *62*, 45-56. https://doi.org/10.1016/j.envsci.2016.02.013

Latifi, M., Rakhshandehroo, G., Nikoo, M. R., & Sadegh, M. (2019). A game theoretical low impact development optimization model for urban storm water management. *Journal of Cleaner Production*, *241*, 118323. https://doi.org/10.1016/j.jclepro.2019.118323

Lavoie, R., Deslandes, J., & Proulx, F. (2016). Assessing the ecological value of wetlands using the MACBETH approach in Quebec City. *Journal for Nature Conservation*, *30*, 67-75. https://doi.org/10.1016/j.jnc.2016.01.007

Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L., & Lai, F. (2012). A watershed-scale design optimization model for stormwater best management practices.

Environmental Modelling & Software, *37*, 6-18. https://doi.org/10.1016/j.envsoft.2012.04.011

Legesse Gebre, S., Cattrysse, D., Alemayehu, E., & Van Orshoven, J. (2021). Multi-criteria decision making methods to address rural land allocation problems : A systematic review. *International Soil and Water Conservation Research*, *9*(4), 490-501. https://doi.org/10.1016/j.iswcr.2021.04.005

Leng, L., Mao, X., Jia, H., Xu, T., Chen, A. S., Yin, D., & Fu, G. (2020). Performance assessment of coupled green-grey-blue systems for Sponge City construction. *Science of The Total Environment*, *728*, 138608. https://doi.org/10.1016/j.scitotenv.2020.138608

Lerer, S., Arnbjerg-Nielsen, K., & Mikkelsen, P. (2015). A mapping of tools for informing water sensitive urban design planning decisions—Questions, aspects and context sensitivity. *Water*, *7*(12), 993-1012. https://doi.org/10.3390/w7030993

Li, F., Guo, S., Li, D., Li, X., Li, J., & Xie, S. (2020). A multi-criteria spatial approach for mapping urban ecosystem services demand. *Ecological Indicators*, *112*, 106119. https://doi.org/10.1016/j.ecolind.2020.106119

Li, L., Uyttenhove, P., & Van Eetvelde, V. (2020). Planning green infrastructure to mitigate urban surface water flooding risk – A methodology to identify priority areas applied in the city of Ghent. *Landscape and Urban Planning*, *194*, 103703. https://doi.org/10.1016/j.landurbplan.2019.103703

Li, N., Xie, L., Du, P., & Huang, X. (2018). Multi-criteria evaluation for china low-impact development based on principal component analysis. *Water, 10*(11), 1547. https://doi.org/10.3390/w10111547

Li, Z., Zhang, X., Ma, Y., Feng, C., & Hajiyev, A. (2019). A multi-criteria decision making method for urban flood resilience evaluation with hybrid uncertainties. *International Journal of Disaster Risk Reduction*, *36*, 101140. https://doi.org/10.1016/j.ijdrr.2019.101140

Liang, C., Zhang, X., Xu, J., Pan, G., & Wang, Y. (2020). An integrated framework to select resilient and sustainable sponge city design schemes for robust decision making. *Ecological Indicators*, *119*, 106810. https://doi.org/10.1016/j.ecolind.2020.106810

Lienert, J., Scholten, L., Egger, C., & Maurer, M. (2015). Structured decision-making for sustainable water infrastructure planning and four future scenarios. *EURO Journal on Decision Processes*, *3*(1-2), 107-140. https://doi.org/10.1007/s40070-014-0030-0

Lima, C. A. S., Heck, H. A. D., Almeida, A. K., Marques, L. D. S., De Souza, R. S., & De Almeida, I. K. (2022). Multicriteria analysis for identification of flood control mechanisms : Application to extreme events in cities of different Brazilian regions. *International Journal of Disaster Risk Reduction*, *71*, 102769. https://doi.org/10.1016/j.ijdrr.2021.102769

Liquete, C., Udias, A., Conte, G., Grizzetti, B., & Masi, F. (2016). Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. *Ecosystem Services*, *22*, 392-401. https://doi.org/10.1016/j.ecoser.2016.09.011

Liu, R., Zhang, K., Zhang, Z., & Borthwick, A. G. L. (2014). Land-use suitability analysis for urban development in Beijing. *Journal of Environmental Management*, *145*, 170-179. https://doi.org/10.1016/j.jenvman.2014.06.020

Liu, S., Crossman, N. D., Nolan, M., & Ghirmay, H. (2013). Bringing ecosystem services into integrated water resources management. *Journal of Environmental Management*, *129*, 92-102. https://doi.org/10.1016/j.jenvman.2013.06.047

Lourdes, K. T., Hamel, P., Gibbins, C. N., Sanusi, R., Azhar, B., & Lechner, A. M. (2022). Planning for green infrastructure using multiple urban ecosystem service models and multicriteria analysis. *Landscape and Urban Planning*, *226*, 104500. https://doi.org/10.1016/j.landurbplan.2022.104500

Luan, B., Yin, R., Xu, P., Wang, X., Yang, X., Zhang, L., & Tang, X. (2019). Evaluating Green Stormwater Infrastructure strategies efficiencies in a rapidly urbanizing catchment using

SWMM-based TOPSIS. *Journal of Cleaner Production*, *223*, 680-691. https://doi.org/10.1016/j.jclepro.2019.03.028

Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science*, *20*(7), 703-726. https://doi.org/10.1080/13658810600661508

MAMH. (2023). *Rapport annuel de gestion (RAG) 2022-2023* (p. 92). Ministère des Affaires municipales et de l’Habitation (MAMH). https://cdn-contenu.quebec.ca/cdn-contenu/adm/min/affaires-municipales/publications-adm/documents/ministere/RAG_2022_2023.pdf

Mani, M., Bozorg-Haddad, O., & Loáiciga, H. A. (2019). A new framework for the optimal management of urban runoff with low-impact development stormwater control measures considering service-performance reduction. *Journal of Hydroinformatics*, *21*(5), 727-744. https://doi.org/10.2166/hydro.2019.126

Marais, A. E., & Abi-Zeid, I. (2021). *A method to identify, characterize and engage relevant stakeholders in decision processes*. Document de travail. Université Laval, Québec, QC.

Marleau Donais, F., Abi-Zeid, I., Waygood, E. O. D., & Lavoie, R. (2019). Assessing and ranking the potential of a street to be redesigned as a complete street : A multi-criteria decision aiding approach. *Transportation Research Part A: Policy and Practice*, *124*, 1-19. https://doi.org/10.1016/j.tra.2019.02.006

Marques, M., Reynolds, K. M., Marques, S., Marto, M., Paplanus, S., & Borges, J. G. (2021). A participatory and spatial multicriteria decision approach to prioritize the allocation of ecosystem services to management units. *Land*, *10*(7), 747. https://doi.org/10.3390/land10070747

Martínez-López, J., Bagstad, K. J., Balbi, S., Magrach, A., Voigt, B., Athanasiadis, I., Pascual, M., Willcock, S., & Villa, F. (2019). Towards globally customizable ecosystem service models.

Science of The Total Environment, *650*, 2325-2336. https://doi.org/10.1016/j.scitotenv.2018.09.371

Marto, M., Reynolds, K., Borges, J., Bushenkov, V., & Marques, S. (2018). Combining decision support approaches for optimizing the selection of bundles of ecosystem services. *Forests*, *9*(7), 438. https://doi.org/10.3390/f9070438

Marto, M., Reynolds, K., Borges, J., Bushenkov, V., Marques, S., Marques, M., Barreiro, S., Botequim, B., & Tomé, M. (2019). Web-based forest resources management decision support system. *Forests*, *10*(12), 1079. https://doi.org/10.3390/f10121079

Marttunen, M., Lienert, J., & Belton, V. (2017). Structuring problems for multi-criteria decision analysis in practice : A literature review of method combinations. *European Journal of Operational Research*, *263*(1), 1-17. https://doi.org/10.1016/j.ejor.2017.04.041

Masson-Delmotte, V., Zhai, P., Portner, H. O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. IPCC.

McInnes, R., Smith, G., Greaves, J., Watson, D., Wood, N., & Everard, M. (2016). Multicriteria decision analysis for the evaluation of water quality improvement and ecosystem service provision. *Water and Environment Journal*, *30*(3-4), 298-309. https://doi.org/10.1111/wej.12195

Medland, S. J., Shaker, R. R., Forsythe, K. W., Mackay, B. R., & Rybarczyk, G. (2020). A multi-criteria wetland suitability index for restoration across Ontario’s mixedwood plains. *Sustainability*, *12*(23), 9953. https://doi.org/10.3390/su12239953

Meerow, S. (2019). A green infrastructure spatial planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities. *Environmental Research Letters*, *14*(12), 125011. https://doi.org/10.1088/1748-9326/ab502c

Meerow, S. (2020). The politics of multifunctional green infrastructure planning in New York City. *Cities*, *100*, 102621. https://doi.org/10.1016/j.cities.2020.102621

Meerow, S., & Newell, J. P. (2017). Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landscape and Urban Planning*, *159*, 62-75. https://doi.org/10.1016/j.landurbplan.2016.10.005

Melbourne Water. (2022). *Melbourne water annual report—2021-22* (p. 192). Melbourne Water, Australia. https://www.melbournewater.com.au/about/what-we-do/annual-report

Mele, R., & Poli, G. (2017). The effectiveness of geographical data in multi-criteria evaluation of landscape services. *Data*, *2*(1), 9. https://doi.org/10.3390/data2010009

Membele, G. M., Naidu, M., & Mutanga, O. (2022). Examining flood vulnerability mapping approaches in developing countries : A scoping review. *International Journal of Disaster Risk Reduction*, *69*, 102766. https://doi.org/10.1016/j.ijdrr.2021.102766

Mendonça, R., Roebeling, P., Fidélis, T., & Saraiva, M. (2021). Policy instruments to encourage the adoption of nature-based solutions in urban landscapes. *Resources*, *10*(8), 81. https://doi.org/10.3390/resources10080081

Mendoza, G. A., & Martins, H. (2006). Multi-criteria decision analysis in natural resource management : A critical review of methods and new modelling paradigms. *Forest Ecology and Management*, *230*(1-3), 1-22. https://doi.org/10.1016/j.foreco.2006.03.023

Mingers, J. (2011). Soft OR comes of age—But not everywhere! *Omega*, *39*(6), 729-741. https://doi.org/10.1016/j.omega.2011.01.005

Mingers, J., & Rosenhead, J. (Éds.). (2001). *Rational analysis for a problematic world revisited: Problem structuring methods for complexity, uncertainty and conflict* (2nd ed). John Wiley and Sons, New-York, NY, USA.

Mitsova, D., Shuster, W., & Wang, X. (2011). A cellular automata model of land cover change to integrate urban growth with open space conservation. *Landscape and Urban Planning*, *99*(2), 141-153. https://doi.org/10.1016/j.landurbplan.2010.10.001

Mittleman, D. D., Briggs, R. O., & Nunamaker, J. F. (2000). *Best practices in facilitating virtual meetings: Some notes from initial experiences*. Group Facilitation: A research and applications journal. 2. 5-14.

Moglia, M., Sharma, A. K., & Maheepala, S. (2012). Multi-criteria decision assessments using subjective logic: Methodology and the case of urban water strategies. *Journal of Hydrology*, *452-453*, 180-189. https://doi.org/10.1016/j.jhydrol.2012.05.049

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA Statement. *Annals of Internal Medicine*, *151*(4), 264. https://doi.org/10.7326/0003-4819-151-4-200908180-00135

Monteiro, R., Ferreira, J., & Antunes, P. (2020). Green infrastructure planning principles: An integrated literature review. *Land*, *9*(12), 525. https://doi.org/10.3390/land9120525

Montibeller, G., & Von Winterfeldt, D. (2018). Individual and group biases in value and uncertainty judgments. In L. C. Dias, A. Morton, & J. Quigley (Éds.), *Elicitation* (Vol. 261, p. 377-392). Springer International Publishing. https://doi.org/10.1007/978-3-319-65052-4_15

Moores, J. P., Yalden, S., Gadd, J. B., & Semadeni-Davies, A. (2017). Evaluation of a new method for assessing resilience in urban aquatic social-ecological systems. *Ecology and Society*, *22*(4), art15. https://doi.org/10.5751/ES-09727-220415

Mubeen, A., Ruangpan, L., Vojinovic, Z., Sanchez Torrez, A., & Plavšić, J. (2021). Planning and suitability assessment of large-scale nature-based solutions for flood-risk reduction. *Water Resources Management*, *35*(10), 3063-3081. https://doi.org/10.1007/s11269-021-02848-w

Munier, N., & Hontoria, E. (2021). *Uses and limitations of the AHP method: A non-mathematical and rational analysis*. Springer International Publishing, Heidelberg, Germany. https://doi.org/10.1007/978-3-030-60392-2

Mustajoki, J., & Marttunen, M. (2017). Comparison of multi-criteria decision analytical software for supporting environmental planning processes. *Environmental Modelling & Software*, *93*, 78-91. https://doi.org/10.1016/j.envsoft.2017.02.026

Németh, B., Molnár, A., Bozóki, S., Wijaya, K., Inotai, A., Campbell, J. D., & Kaló, Z. (2019). Comparison of weighting methods used in multicriteria decision analysis frameworks in healthcare with focus on low- and middle-income countries. *Journal of Comparative Effectiveness Research*, *8*(4), 195-204. https://doi.org/10.2217/cer-2018-0102

Nesticò, A., Guarini, M. R., Morano, P., & Sica, F. (2019). An economic analysis algorithm for urban forestry projects. *Sustainability*, *11*(2), 314. https://doi.org/10.3390/su11020314

Neuenschwander, N., Hayek, U. W., & Gret-Regamey, A. (2012). *Integrated multi-criteria modeling and 3D visualization for informed trade-off decision making on urban development options*. PLUS - Planning of Landscape and Urban Systems, Switzerland. 203-211. https://doi.org/10.52842/conf.ecaade.2012.1.x.j7k

Neumann, V. A., & Hack, J. (2019). A methodology of policy assessment at the municipal level: Costa Rica´s readiness for the implementation of nature-based-solutions for urban stormwater management. *Sustainability*, *12*(1), 230. https://doi.org/10.3390/su12010230

Newton, A. C., Hodder, K., Cantarello, E., Perrella, L., Birch, J. C., Robins, J., Douglas, S., Moody, C., & Cordingley, J. (2012). Cost-benefit analysis of ecological networks assessed through spatial analysis of ecosystem services: *Cost-benefit analysis of ecological networks*. *Journal of Applied Ecology*, *49*(3), 571-580. https://doi.org/10.1111/j.1365-2664.2012.02140.x

Nguyen, T. T., Bach, P. M., & Pahlow, M. (2022). Multi-scale stormwater harvesting to enhance urban resilience to climate change impacts and natural disasters. *Blue-Green Systems*, *4*(1), 58-74. https://doi.org/10.2166/bgs.2022.008

Nguyen, T. T., Ngo, H. H., Guo, W., Wang, X. C., Ren, N., Li, G., Ding, J., & Liang, H. (2019). Implementation of a specific urban water management—Sponge City. *Science of The Total Environment*, *652*, 147-162. https://doi.org/10.1016/j.scitotenv.2018.10.168

Nin, M., Soutullo, A., Rodríguez-Gallego, L., & Di Minin, E. (2016). Ecosystem services-based land planning for environmental impact avoidance. *Ecosystem Services*, *17*, 172-184. https://doi.org/10.1016/j.ecoser.2015.12.009

Nutt, P. C. (1999). Surprising but true: Half the decisions in organizations fail. *Academy of Management*, *13*(4). https://www.jstor.org/stable/4165588

O'Donnell, E., Thorne, C., Ahilan, S., Arthur, S., Birkinshaw, S., Butler, D., Dawson, D., Everett, G., Fenner, R., Glenis, V., Kapetas, L., Kilsby, C., Krivtsov, V., Lamond, J., Maskrey, S., O'Donnell, G., Potter, K., Vercruysse, K., Vilcan, T., & Wright, N. (2020). The blue-green path to urban flood resilience. *Blue-Green Systems*, *2*(1), 28-45. https://doi.org/10.2166/bgs.2019.199

Oral, H. V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., Hullebusch, E. D. van, Kazak, J. K., Exposito, A., Cipolletta, G., Andersen, T. R., Finger, D. C., Simperler, L., Regelsberger, M., Rous, V., Radinja, M., Buttiglieri, G., Krzeminski, P., Rizzo, A., Dehghanian, K., … Zimmermann, M. (2020). A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature. *Blue-Green Systems*, *2*(1), 112-136. https://doi.org/10.2166/bgs.2020.932

Padró, R., La Rota-Aguilera, M. J., Giocoli, A., Cirera, J., Coll, F., Pons, M., Pino, J., Pili, S., Serrano, T., Villalba, G., & Marull, J. (2020). Assessing the sustainability of contrasting land use scenarios through the Socioecological Integrated Analysis (SIA) of the metropolitan green infrastructure in Barcelona. *Landscape and Urban Planning*, *203*, 103905. https://doi.org/10.1016/j.landurbplan.2020.103905

Paillé, P., & Mucchielli, A. (2016). *L'analyse qualitative en sciences humaines et sociales* (Vol. 4). Armand Colin Éditions, France.

Panczyk, M., Woynarowska-Sołdan, M., Belowska, J., Zarzeka, A., & Gotlib, J. (2015). Bibliometric evaluation of scientific literature in the area of research in education using incites™ database of thomson reuters. *INTED2015 Proceedings*, 487-496.

Park, Y., Lee, S.-W., & Lee, J. (2020). Comparison of fuzzy AHP and AHP in multicriteria inventory classification while planning green infrastructure for resilient stream ecosystems. *Sustainability*, *12*(21), 9035. https://doi.org/10.3390/su12219035

Pauleen, D. J., & Yoong, P. (2001). Facilitating virtual team relationships via Internet and conventional communication channels. *Internet Research*, *11*(3), 190-202. https://doi.org/10.1108/10662240110396450

Pearson, L. J., Park, S., Harman, B., & Heyenga, S. (2010). Sustainable land use scenario framework: Framework and outcomes from peri-urban South-East Queensland, Australia. *Landscape and Urban Planning*, *96*(2), 88-97. https://doi.org/10.1016/j.landurbplan.2010.02.006

Pelenc, J., & Etxano, I. (2021). Capabilities, ecosystem services, and strong sustainability through SMCE : The case of Haren (Belgium). *Ecological Economics*, *182*, 106876. https://doi.org/10.1016/j.ecolecon.2020.106876

Peñacoba-Antona, L., Gómez-Delgado, M., & Esteve-Núñez, A. (2021). Multi-criteria evaluation and sensitivity analysis for the optimal location of constructed wetlands (METland) at oceanic and mediterranean areas. *International Journal of Environmental Research and Public Health*, *18*(10), 5415. https://doi.org/10.3390/ijerph18105415

Perosa, F., Seitz, L. F., Zingraff-Hamed, A., & Disse, M. (2022). Flood risk management along German rivers – A review of multi-criteria analysis methods and decision-support systems. *Environmental Science & Policy*, *135*, 191-206. https://doi.org/10.1016/j.envsci.2022.05.004

Phillips, L. D. (2008). Decision conferencing/Facilitated workshops. In E. L. Melnick & B. S. Everitt (Éds.), *Encyclopedia of Quantitative Risk Analysis and Assessment* (p. risk0522).

John Wiley & Sons, New-Uork, NY, USA. https://doi.org/10.1002/9780470061596.risk0522

Phillips, L. D., & Bana e Costa, C. A. (2007). Transparent prioritisation, budgeting and resource allocation with multi-criteria decision analysis and decision conferencing. *Annals of Operations Research*, *154*(1), 51-68. https://doi.org/10.1007/s10479-007-0183-3

Pittman, S. J., Stamoulis, K. A., Antonopoulou, M., Das, H. S., Shahid, M., Delevaux, J. M. S., Wedding, L. M., & Mateos-Molina, D. (2022). Rapid site selection to prioritize coastal seascapes for nature-based solutions with multiple benefits. *Frontiers in Marine Science*, *9*, 832480. https://doi.org/10.3389/fmars.2022.832480

Puchol-Salort, P., O'Keeffe, J., van Reeuwijk, M., & Mijic, A. (2020). An urban planning sustainability framework: Systems approach to blue green urban design. *Sustainable Cities and Society*, 102677. https://doi.org/10.1016/j.scs.2020.102677

Qiu, L., Dong, Y., & Liu, H. (2022). Integrating ecosystem services into planning practice: Situation, challenges and inspirations. *Land*, *11*(4), 545. https://doi.org/10.3390/land11040545

Qureshi, A. M., & Rachid, A. (2021). Review and comparative study of decision support tools for the mitigation of urban heat stress. *Climate*, *9*(6), 102. https://doi.org/10.3390/cli9060102

Radinja, M., Comas, J., Corominas, L., & Atanasova, N. (2019a). Assessing stormwater control measures using modelling and a multi-criteria approach. *Journal of Environmental Management*, *243*, 257-268. https://doi.org/10.1016/j.jenvman.2019.04.102

Radinja, M., Comas, J., Corominas, L., & Atanasova, N. (2019b). Multi-criteria evaluation of sustainable urban drainage systems. In G. Mannina (Éd.), *New Trends in Urban Drainage Modelling* (p. 269-274). Springer International Publishing, Heidelberg, Germany. https://doi.org/10.1007/978-3-319-99867-1_45

Rayfield, B., Dupras, J., Francoeur, X., Dumitru, M., Dagenais, D., Vachon, J., Paquette, A., Lechowicz, M., Messier, C., Gonzalez, A., & David Suzuki Foundation. (2016). *Les* *infrastructures vertes : Un outil d'adaptation aux changements climatiques pour le grand Montréal*. Bibliothèque numérique canadienne. Ottawa, Ontario. http://www.deslibris.ca/ID/248812

Razmak, J., & Aouni, B. (2015). Decision support system and multi-criteria decision aid: A state of the art and perspectives: DSS-MCDA. *Journal of Multi-Criteria Decision Analysis*, *22*(1-2), 101-117. https://doi.org/10.1002/mcda.1530

Rędzińska, K., & Piotrkowska, M. (2020). Urban planning and design for building neighborhood resilience to climate change. *Land*, *9*(10), 387. https://doi.org/10.3390/land9100387

Rizzo, A., Conte, G., & Masi, F. (2021). Adjusted unit value transfer as a tool for raising awareness on ecosystem services provided by constructed wetlands for water pollution control : An Italian case study. *International Journal of Environmental Research and Public Health*, *18*(4), 1531. https://doi.org/10.3390/ijerph18041531

Rodríguez-Espinosa, V. M., Aguilera-Benavente, F., & Gómez-Delgado, M. (2020). Green infrastructure design using GIS and spatial analysis : A proposal for the Henares Corridor (Madrid-Guadalajara, Spain). *Landscape Research*, *45*(1), 26-43. https://doi.org/10.1080/01426397.2019.1569221

Roy, B. (2010). Robustness in operational research and decision aiding : A multi-faceted issue. *European Journal of Operational Research*, *200*(3), 629-638. https://doi.org/10.1016/j.ejor.2008.12.036

Ruangpan, L., Vojinovic, Z., Plavšić, J., Doong, D.-J., Bahlmann, T., Alves, A., Tseng, L.-H., Randelović, A., Todorović, A., Kocic, Z., Beljinac, V., Wu, M.-H., Lo, W.-C., Perez-Lapeña, B., & Franca, M. J. (2021). Incorporating stakeholders' preferences into a multi-criteria framework for planning large-scale Nature-Based Solutions. *Ambio*, *50*(8), 1514-1531. https://doi.org/10.1007/s13280-020-01419-4

Sanches, P. M., & Mesquita Pellegrino, P. R. (2016). Greening potential of derelict and vacant lands in urban areas. *Urban Forestry & Urban Greening*, *19*, 128-139. https://doi.org/10.1016/j.ufug.2016.07.002

Sarabi, Han, Romme, Vries, & Wendling. (2019). Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: A review. *Resources*, *8*(3), 121. https://doi.org/10.3390/resources8030121

Schein, E. H. (2017). *Organizational culture and leadership* (Fifth Edition). John Wiley and Sons, New-Yok, NY, USA.

Scionti, F., Miguez, M. G., Barbaro, G., De Sousa, M. M., Foti, G., & Canale, C. (2018). Integrated methodology for urban flood risk mitigation in Cittanova, Italy. *Journal of Water Resources Planning and Management*, *144*(10), 05018013. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000985

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Segura, M., Maroto, C., Belton, V., & Ginestar, C. (2015). A new collaborative methodology for assessment and management of ecosystem services. *Forests*, *6*(12), 1696-1720. https://doi.org/10.3390/f6051696

Sheikh, V., & Izanloo, R. (2021). Assessment of low impact development stormwater management alternatives in the city of Bojnord, Iran. *Urban Water Journal*, *18*(6), 449-464. https://doi.org/10.1080/1573062X.2021.1893364

Shojaeizadeh, Geza, McCray, & Hogue. (2019). Site-scale integrated decision support tool (i-DSTss) for stormwater management. *Water*, *11*(10), 2022. https://doi.org/10.3390/w11102022

Silva, C. N. (Éd.). (2010). *Handbook of Research on E-Planning: ICTs for urban development and monitoring*. IGI Global. https://doi.org/10.4018/978-1-61520-929-3

Simon, M., & Tryby, M. (2018). *Open source SWMM: Community-based software development for storm water management modeling*. Environmental Protection Agency, Washington, DC, USA.

Skrydstrup, J., Madsen, H. M., Löwe, R., Gregersen, I. B., Pedersen, A. N., & Arnbjerg-Nielsen, K. (2020). Incorporating objectives of stakeholders in strategic planning of urban water management. *Urban Water Journal*, *17*(2), 87-99. https://doi.org/10.1080/1573062X.2020.1748204

Smyth, E. R. B., & Drake, D. A. R. (2022). A classification framework for interspecific trade-offs in aquatic ecology. *Conservation Biology*, *36*(1), e13762. https://doi.org/10.1111/cobi.13762

Soares Dal Poz, M. E., De Arruda Ignácio, P. S., Azevedo, A., Francisco, E. C., Piolli, A. L., Gheorghiu Da Silva, G., & Pereira Ribeiro, T. (2022). Food, energy and water nexus: An urban living laboratory development for sustainable systems transition. *Sustainability*, *14*(12), 7163. https://doi.org/10.3390/su14127163

Song, J., & Chung, E.-S. (2017). A multi-criteria decision analysis system for prioritizing sites and types of low impact development practices: Case of Korea. *Water*, *9*(4), 291. https://doi.org/10.3390/w9040291

Soulé, E., Michonneau, P., Michel, N., & Bockstaller, C. (2021). Environmental sustainability assessment in agricultural systems: A conceptual and methodological review. *Journal of Cleaner Production*, *325*, 129291. https://doi.org/10.1016/j.jclepro.2021.129291

Steis T., J., Miller, C. J., & Treemore-Spears, L. (2020). The role of green stormwater infrastructure in flood mitigation (Detroit, MI USA) – Case study. *Urban Water Journal*, *17*(9), 838-846. https://doi.org/10.1080/1573062X.2020.1823429

Sturiale, L., & Scuderi, A. (2018b). The evaluation of green investments in urban areas: A proposal of an eco-social-green model of the city. *Sustainability*, *10*(12), 4541. https://doi.org/10.3390/su10124541

Sturiale, L., Scuderi, A., & Timpanaro, G. (2022). A multicriteria decision-making approach of “tree” meaning in the new urban context. *Sustainability*, *14*(5), 2902. https://doi.org/10.3390/su14052902

Sturiale & Scuderi. (2019). The role of green infrastructures in urban planning for climate change adaptation. *Climate*, *7*(10), 119. https://doi.org/10.3390/cli7100119

Teotónio, I., Cabral, M., Cruz, C. O., & Silva, C. M. (2020). Decision support system for green roofs investments in residential buildings. *Journal of Cleaner Production*, *249*, 119365. https://doi.org/10.1016/j.jclepro.2019.119365

Tezer, A., Turkay, Z., Uzun, O., Terzi, F., Koylu, P., Karacor, E., Okay, N., & Kaya, M. (2020). Ecosystem services-based multi-criteria assessment for ecologically sensitive watershed management. *Environment, Development and Sustainability*, *22*(3), 2431-2450. https://doi.org/10.1007/s10668-018-00300-5

Therond, O., Duru, M., Roger-Estrade, J., & Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. A review. *Agronomy for Sustainable Development*, *37*(3), 21. https://doi.org/10.1007/s13593-017-0429-7

Thorpe, R., Gold, J., & Lawler, J. (2011). Locating distributed leadership. *International Journal of Management Reviews*, *13*(3), 239-250. https://doi.org/10.1111/j.1468-2370.2011.00303.x

Thorpe, S. (2016). *Online facilitator competencies for group facilitators*. 77-90. IAF, International Association of Facilitators.

Torres, V. A., Tiwari, C., & Atkinson, S. F. (2021). Progress in ecosystem services research : A guide for scholars and practitioners. *Ecosystem Services*, *49*, 101267. https://doi.org/10.1016/j.ecoser.2021.101267

Toulouse Metropole. (2022). *Toulouse Metropole en chiffres 2022*. Observatoire de Toulouse Metropole. https://metropole.toulouse.fr/sites/toulouse-fr/files/2023-01/les_chiffres_cles_2022_de_toulouse_metropole.pdf

Trois-Rivières. (2022). *Rapport annuel de gestion 2022* (p. 49). https://www.v3r.net/wp-content/uploads/2023/05/Rapport-annuel-17x11_2022-1.pdf

Uhde, B., Andreas Hahn, W., Griess, V. C., & Knoke, T. (2015). Hybrid MCDA methods to integrate multiple ecosystem services in forest management planning: A critical review. *Environmental Management*, *56*(2), 373-388. https://doi.org/10.1007/s00267-015-0503-3

United Nations. (2019). How certain are the United Nations global population projections? *Population Division of the United Nations Department of Economic and Social Affairs*, *2019/6*, 4.

United Nations. (2022). *UN Biodiversity Conference (COP 15)*. Montréal, QC, Canada.

United Nations. (2015). *World urbanization prospects - The 2014 revision*. Department of Economic and Social Affairs. https://population.un.org/wup/publications/files/wup2014-report.pdf

Urich, C., Bach, P. M., Sitzenfrei, R., Kleidorfer, M., McCarthy, D. T., Deletic, A., & Rauch, W. (2013). Modelling cities and water infrastructure dynamics. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, *166*(5), 301-308. https://doi.org/10.1680/ensu.12.00037

Urich, C., & Rauch, W. (2014). Exploring critical pathways for urban water management to identify robust strategies under deep uncertainties. *Water Research*, *66*, 374-389. https://doi.org/10.1016/j.watres.2014.08.020

Urrutiaguer, M., Lloyd, S., & Lamshed, S. (2010). Determining water sensitive urban design project benefits using a multi-criteria assessment tool. *Water Science and Technology*, *61*(9), 2333-2341. https://doi.org/10.2166/wst.2010.045

Ustaoglu, E., & Aydınoglu, A. C. (2020). Suitability evaluation of urban construction land in Pendik district of Istanbul, Turkey. *Land Use Policy*, *99*, 104783. https://doi.org/10.1016/j.landusepol.2020.104783

Van Oijstaeijen, W., Van Passel, S., & Cools, J. (2020). Urban green infrastructure: A review on valuation toolkits from an urban planning perspective. *Journal of Environmental Management*, *267*, 110603. https://doi.org/10.1016/j.jenvman.2020.110603

Van Ostrand, A., Wolfe, S., Arredondo, A., Skinner, A. M., Visaiz, R., Jones, M., & Jenkins, J. J. (2016). Creating virtual communities that work : Best practices for users and developers of e-collaboration software. *International Journal of E-Collaboration*, *12*(4), 41-60. https://doi.org/10.4018/IJeC.2016100104

Vennix, J. A. M. (1996). *Group model building: Facilitating team learning using system dynamics*. Johm Wiley and Sons, New-York, NY, USA.

Venter, Z. S., Barton, D. N., Martinez-Izquierdo, L., Langemeyer, J., Baró, F., & McPhearson, T. (2021). Interactive spatial planning of urban green infrastructure – Retrofitting green roofs where ecosystem services are most needed in Oslo. *Ecosystem Services*, *50*, 101314. https://doi.org/10.1016/j.ecoser.2021.101314

Vidal Pastrana, C., Mejia Ávila, D., & Soto Barrera, V. C. (2021). Mathematical model for the definition and integration of buffer zones for terrestrial tropical protected areas. *Ecological Engineering*, *163*, 106193. https://doi.org/10.1016/j.ecoleng.2021.106193

Vogdrup-Schmidt, M., Olsen, S. B., Dubgaard, A., Kristensen, I. T., Jørgensen, L. B., Normander, B., Ege, C., & Dalgaard, T. (2019). Using spatial multi-criteria decision analysis to develop new and sustainable directions for the future use of agricultural land in Denmark. *Ecological Indicators*, *103*, 34-42. https://doi.org/10.1016/j.ecolind.2019.03.056

Vogdrup-Schmidt, M., Strange, N., Olsen, S. B., & Thorsen, B. J. (2017). Trade-off analysis of ecosystem service provision in nature networks. *Ecosystem Services*, *23*, 165-173. https://doi.org/10.1016/j.ecoser.2016.12.011

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders☆. *Environmental Modelling & Software*, *25*(11), 1268-1281. https://doi.org/10.1016/j.envsoft.2010.03.007

Voskamp, I. M., de Luca, C., Polo-Ballinas, M. B., Hulsman, H., & Brolsma, R. (2021). Nature-based solutions tools for planning urban climate adaptation: State of the art. *Sustainability*, *13*(11), 6381. https://doi.org/10.3390/su13116381

Vulbeau, A. (2014). La maîtrise d'usage, entre ingénierie participative et travail avec autrui. *Recherche sociale*, *209*(1), 62. https://doi.org/10.3917/recsoc.209.0062

Wang, M., Sun, C., & Zhang, D. (2023). Opportunities and challenges in green stormwater infrastructure (GSI) : A comprehensive and bibliometric review of ecosystem services from 2000 to 2021. *Environmental Research*, *236*, 116701. https://doi.org/10.1016/j.envres.2023.116701

Webber, J. L., & Kuller, M. (2021). Enhancing the visibility of SuDS in strategic planning using preliminary regional opportunity screening. *ISPRS International Journal of Geo-Information*, *10*(11), 726. https://doi.org/10.3390/ijgi10110726

Wu, T., Song, H., Wang, J., & Friedler, E. (2020). Framework, procedure, and tools for comprehensive evaluation of sustainable stormwater management: A review. *Water*, *12*(5), 1231. https://doi.org/10.3390/w12051231

Yang, Jing & Liu, Yongxue & Wang, Songhui. (2007). *An overview of the methods of GIS-based land-use suitability analysis.* Proceedings of SPIE - The International Society for Optical Engineering. 6754. https://doi.org/10.1117/12.765488

Yang, W., & Zhang, J. (2021). Assessing the performance of gray and green strategies for sustainable urban drainage system development: A multi-criteria decision-making analysis. *Journal of Cleaner Production*, *293*, 126191. https://doi.org/10.1016/j.jclepro.2021.126191

Yeo, O. T. S., Mohd Yusof, M. J., Maruthaveeran, S., Mohd Shafri, H. Z., Saito, K., & Yeo, L. B. (2022). ABC of green infrastructure analysis and planning: The basic ideas and methodological guidance based on landscape ecological principle. *Urban Forestry & Urban Greening, 73*, 127600. https://doi.org/10.1016/j.ufug.2022.127600

Zagonari, F. (2016). Using ecosystem services in decision-making to support sustainable development: Critiques, model development, a case study, and perspectives. *Science of The Total Environment*, *548-549*, 25-32. https://doi.org/10.1016/j.scitotenv.2016.01.021

Zhang, X., Chen, L., Zhang, M., & Shen, Z. (2021). Prioritizing sponge city sites in rapidly urbanizing watersheds using multi-criteria decision model. *Environmental Science and Pollution Research*, *28*(44), 63377-63390. https://doi.org/10.1007/s11356-021-14952-w

Zotarelli, L., Dukes, M. D., Romero, C. C., Migliaccio, K. W., & Morgan, K. T. (2015). *Step by step calculation of the Penman-Monteith evapotranspiration (FAO-56 Method)*. Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Florida, USA.

Zwierzchowska, I., & Stępniewska, M. (2022). Green infrastructure and social perception of its ecosystem services within spatial structure of the city – Examples from Poznań, Poland. In I. Misiune, D. Depellegrin, & L. Egarter Vigl (Éds.), *Human-Nature Interactions* (p. 221-234). Springer International Publishing, Heidelberg, Germany. https://doi.org/10.1007/978-3-031-01980-7_18

Annex A – Equations of Penman-Monteith

The following steps of the Penman-Monteith method come from the paper of Zotarelli *et al.* (2010). It aims to calculate the evapotranspiration data.

Step 1-Mean daily temperature:

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

Where, Tmean = mean daily air temperature, ºC;

Tmax = maximum daily air temperature, ºC;

Tmin = minimum daily air temperature, ºC

Step 2-Mean daily solar radiation (R_s):

$$Rs_{(MJ\ m^{-2}\ day^{-1})} = Rs_{(W\ m^{-2}\ day^{-1})} * 0.0864$$

Step 3-Wind speed (u_2):

$$u_2 = u_h \frac{4.87}{\ln(67.8h - 5.42)}$$

Where, u_2 = wind speed 2 m above the ground surface, m s^{-1};

U_h = measured wind speed at h m above the ground surface, m s^{-1}

Step 4-Slope of saturation vapor pressure curve (î):

$$\Delta = \frac{4098\left[0.6108\, exp\left(\frac{17.27 * T_{mean}}{T_{mean} + 237.3}\right)\right]}{(T_{mean} + 237.3)^2}$$

Where, T_{mean} = mean daily air temperature, ºC;

exp = 2.7183 (base of natural logarithm)

Step 5-Atmospheric Pressure (P):

$$P = 101.3\left[\frac{293 - 0.0065z}{293}\right]^{5.26}$$

Where, z = elevation above sea level, m

Step 6-Psychrometric constant (³):

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = 0.000665\, P$$

Where, ³ = psychrometric constant, kPa °C^{-1};

P = atmospheric pressure, kPa;

ε= latent heat of vaporization, 2.45 MJ kg^{-1};

Cp = specific heat at constant pressure, 1.013 10^{-3} MJ kg^{-1} $°C^{-1}$;

λ= ratio molecular weight of water vapour/dry air = 0.622.

Step 7-Delta Term (DT) (auxiliary calculation for Radiation Term):

$$DT = \frac{\Delta}{\Delta + \gamma(1 + 0.34\, u_2)}$$

Step 8-Psi Term (PT) (auxiliary calculation for Wind Term):

$$PT = \frac{\gamma}{\Delta + \gamma(1 + 0.34\, u_2)}$$

Step 9-Temperature Term (PT) (auxiliary calculation for Temperature Term):

$$TT = \left[\frac{900}{T_{mean} + 273}\right] * u_2$$

Step 10-Mean saturation vapor pressure derived from air temperature (e):

$$e_{(T_{max})} = 0.6108\, exp\left[\frac{17.27\, T_{max}}{T_{max} + 237.3}\right]$$

and

$$e_{(T_{min})} = 0.6108\, exp\left[\frac{17.27\, T_{min}}{T_{min} + 237.3}\right]$$

Where, $e_{(T)}$ = saturation vapor pressure at the air temperature T, kPa

T = air temperature, ºC.

Then,

$$e_s = \frac{e_{(T_{max})} + e_{(T_{min})}}{2}$$

Step 11-Actual vapor pressure (e_a) derived from relative humidity:

$$e_a = \frac{e_{(T_{min})}\left[\frac{RH_{max}}{100}\right] + e_{(T_{max})}\left[\frac{RH_{min}}{100}\right]}{2}$$

or

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e_{(T_{min})} + e_{(T_{max})}}{2}\right]$$

Where, e_a = actual vapour pressure, kPa;

$e_{(Tmin)}$ = saturation vapour pressure at daily minimum temperature, kPa;

$e_{(Tmax)}$ = saturation vapour pressure at daily maximum temperature, kPa;

RH_{max} = maximum relative humidity, %;

RH_{min} = minimum relative humidity, %.

Step 12-The inverse relative distance Earth-Sun (dr) and solar declination (δ):

$$d_r = 1 + 0.033 \cos\left[\frac{2\pi}{365}J\right]$$

and

$$\delta = 0.409 \sin\left[\frac{2\pi}{365}J - 1.39\right]$$

Where, J = number of the day in the year between 1 (1 January) and 365 or 366 (31 December)

Step 13-Conversion of latitude (φ) in degrees to radians:

$$\varphi\ [radians] = \frac{\pi}{180}\varphi[decimal\ degrees]$$

Step 14-Sunset hour angle (ω_s):

$$\omega_s = \arccos[-\tan\varphi\ \tan\delta]$$

Step 15-Extraterrestrial radiation (Ra):

$$R_a = \frac{24(60)}{\pi}\ G_{sc}\ d_r\ [(\omega_s\ \sin\varphi\ \sin\delta) + (\cos\varphi\ \cos\delta\ \sin\omega_s)]$$

Where, Ra = extraterrestrial radiation, MJ m^{-2} day^{-1};

Gsc = solar constant = 0.0820 MJ m^{-2} min^{-1}

Step 16-Clear sky solar radiation (Rso):

$$R_{so} = (0.75 + 2E10^{-5}z)R_a$$

Where, z = elevation above sea level, m

Step 17-Net solar or net shortwave radiation (Rns):

$$R_{ns} = (1 - a)R_s$$

Where, Rns = net solar or shortwave radiation, MJ m^{-2} day^{-1}

Step 18-Net outgoing long wave solar radiation (Rnl):

$$R_{nl} = \sigma\left[\frac{(T_{max} + 273.16)^4 + (T_{min} + 273.16)^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left[1.35\frac{R_s}{R_{so}} - 0.35\right]$$

Where, Rnl = net outgoing longwave radiation, MJ m^{-2} day^{-1};

σ = Stefan-Boltzmann constant 4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1};

T_{max} = K maximum absolute temperature during the 24-hour period [K = °C + 273.16];

T_{min} = K minimum absolute temperature during the 24- hour period [K = °C + 273.16]

Step 19-Net radiation (Rn):

$R_n = R_{ns} - R_{nl}$

To express the net radiation (Rn) in equivalent of evaporation (mm) (Rng):

$R_{ng} = 0.408\, R_n$

Step 20-Overall ET_o equation:

$ET_{rad} = DT\, R_{ng}$

Where, ET_{rad} radiation term, mm d^{-1}

And

$ET_{wind} = PT\, TT\, (e_s - e_a)$

Where, ETwind = wind term, mm d^{-1}

Then

$ET_o = ET_{wind} + ET_{rad}$

Where, ETo = reference evapotranspiration, mm d^{-1}

Annex B – Criteria measurement for Trois-Rivières

Aspects	Criterion	Measure	Data (spatial)	Data (technical)
Biodiversity	Encouraging green corridor	Fraction (%) of the territory within a 100m or less distance from a green corridor (ZGC) Neutral level: 10% in PU and 100m from ZGC Good level: 25% in PU and 100m from ZGC	Green corridor map (ZGC) Urban area (PU)	
Aesthetic	Increasing green cover	Distribution (%) of NBS regarding NBS type preference Neutral level: 50% F1,2 ; 50% F3 Good level: 60% F1,2 ; 40% F3		F1: Pond & Basin, Wetland, Bioretention & Raingarden, Green facade, Green roof F2: Retention basin, Porous pavement F3: Infiltration system, Tank, Trench & Swale
Recreativity	Maximizing multi-functional potential	Distribution (%) of NBS regarding NBS type preference Neutral level: 50% F1,2,3 ; 50% F4 Good level: 40% F1,2 ; 30% F3 ; 30% F4		F1 : Porous pavement, Retention basin F2: Bioretention & raingardens, Wetland, Pond & Basin F3: Green facade, Green roof F4: Infiltration systems, Tank, Trench & Swale
Water management	Encouraging infiltration	Distribution (%) of NBS in sectors ZGw and ZW and regarding NBS type preference Neutral level: 85% F1,2 in ZGw and ZW Good level: 90% F1,2 in ZGw and ZW	Groundwater table levels (limit: 5mfrom soil level) (ZGw) Well protection zone (ZW)	F1: Bioretention & Raingarden, Wetland, Infiltration system, Pond & Basin, Porous pavement F2: Trench & Swale F3: Tank, Green facade, Green roof, Retention basin
	Encouraging implementation in overflow areas	Distribution (%) of NBS in sectors ZO and ZR and regarding NBS type preference Neutral level: 100% F2 in ZD and ZR Good level: 25% F1 in ZD and ZR	Overflow Zone (ZO) Restricted areas (ZR)	F1: Bioretention & Raingarden, Wetland, Infiltration system, Pond & Basin, Porous pavement, Tank, Green roof F2: Green facade, Trench & Swale, Bioretention & Raingarden, Green roof, Infiltration system, Porous pavement
Users	Minimizing user impacts (perception)	Distribution (%) of NBS regarding NBS type preference Neutral level: 50% F1,2 ; 50% F3,4 Good level:		F1: Infiltration system, Tank, Green facade, Green roof F2: Porous pavement F3: Retention basin, Bioretention & Raingarden F4: Trench & Swale, Pond & Basin, Wetland

		60% F1,2 ; 20% F3 ; 20% F4		
Performance	Adopting NBS for cold climate	Distribution (%) of NBS regarding NBS type preference Neutral level: 40% F1,2 ; 60% F3,4,5 Good level: 60% F1,2,3 ; 40% F4,5		F1: Wetland, Pond & Basin, Infiltration system F2: Trench & Swale, Retention basin F3: Bioretention & Raingarden, Porous pavement F4: Green roof F5: Green facade, Tank
Other	Minimizing skill needs for construction and maintenance	Distribution (%) of NBS regarding NBS type preference Neutral level: 90% F1,2,3,4 ; 10% F5 Good level: 30% F1 ; 20% F2 ; 20% F3 ; 20% F4 ; 10% F5		F1: Trench & Swale F2: Tank, Retention basin F3: Infiltration system, Porous pavement F4: Bioretention & Raingarden, Pond & Basin, Wetland F5: Green facade, Green roof
	Encouraging implementation on public lands	Distribution (%) of NBS in sectors ZP and ZPI Neutral level: 35% ZP ; 25% ZPI Good level: 50% ZP ; 30% ZPI	Public Zone (ZP) Industrial Public Zone (ZPI)	
	Minimizing footprint	Distribution (%) of NBS in sector PU Neutral level: 80% F1,2,3 ; 20% F4,5,6 in PU Good level: 80% F1,2 ; 10% F3 ; 10% F4 in PU	Urban area (PU)	F1: Green facade, Green roof F2: Infiltration system, Tank, Porous pavement F3: Bioretention & Raingarden F4: Trench & Swale F5: Pond & Basin, Retention basin F6: Wetland

Annex C – Criteria measurement for Toulouse

Aspects	Criterion	Measure	Data (spatial)	Data (technical)
Biodiversity	Creating biodiversity	Distribution (%) of NBS regarding NBS type preference Neutral level: 20% F1, 20% F2, 60% F3 Good level: 40% F1, 40% F2, 20% F3		F1: Pond & Basin, Wetland, Bioretention & Raingarden F2: Green facade, Trench & Swale F3: Porous pavement, Infiltration system, Green roof
	Protecting biodiversity	Distribution (%) of NBS in sectors ZP1, ZP2 and ZC Neutral level: 0% ZP1, 10% ZP2, 20% ZC Good level: 0% ZP1, 0% ZP2, 20% ZC	Zones protégées 1 (ZP1) (APPB, zones humides SAGE) Zone protégées 2 (ZP2) (Natura 2000) Zone de connaissance (ZC) (ZNIEFF, ZICO)	
Recreativity	Improving multi-functionality	Distribution (%) of NBS regarding NBS type preference Neutral level: 40% F1, 30% F2, 30% F3 Good level: 50% F1, 40% F2, 10% F3		F1: Wetland, Pond & Basin F2: Trench & Swale, Porous pavement, Bioretention & Raingarden F3: Tank, Infiltration system, Green facade, Green roof
Water management	Improving water quality	Distribution (%) of NBS in sectors ZTF, ZF, ZR and ZE Neutral level: 20% F1 ZR, 80% F1 ZF Good level: 100% F1 ZF	Hauteur de la nappe (zone à exclure ZE, zone à risque ZR, zone favorable ZF, zone très favorable ZTF)	F1: Bioretention & Raingarden, Wetland, Infiltration system, Porous pavement, Trench & Swale, Pond & Basin F2: Green roof, Green facade, Tank
	Preventing flooding risk	Distribution (%) of NBS in sectors ZD and ZDP regarding NBS type preference Neutral level: 75% F1-ZPD, 50% F2-ZD Good level: 80% F1-ZPD, 60% F2-ZD	Carte PPRI (ZP) Carte schéma directeur des zones à débordements (ZD) ZDP = ZP + ZD	F1: Pond & Basin, Wetland F2: Trench & Swale, Porous pavement, Infiltration system, Bioretention & Raingarden F3: Green facade, Green roof, Tank
Temperature	Mitigating urban heat island	Distribution (%) of NBS in sectors ZF and ZNN regarding NBS type preference Neutral level: 40% F1 Good level: 20% F1	Carte des ilots de chaleur (zones fortes ZF, zones non négligeables ZNN, zones négligeables ZN)	F1: Bioretention & Raingarden, Wetland, Green facade F2: Pond & Basin, Green roof, Trench & Swale, Porous pavement F3: Tank, Infiltration system
Users	Managing user waste	Distribution (%) of NBS within 500m or less from fast food regarding NBS type preference	Carte des services de restauration rapide	F1: Trench & Swale, Pond & Basin, Wetland, Bioretention & Raingarden

		Neutral level: 50% F1,2 ; 50% F3,4 Good level: 60% F1,2 ; 20% F3 ; 20% F4		F2: Green facade, Green roof, Tank, Infiltration system, Porous pavement
Performance	Balancing water/energy/waste	Distribution (%) of NBS regarding NBS type preference Neutral level: 10% F1, 30% F2, 50% F3, 10% F4 Good level: 10% F1, 50% F2, 30% F3, 10% F4		F1: Wetland F2: Bioretention & Raingarden, Trench & Swale F3: Infiltration system, Porous pavement F4: Green roof, Green facade, Tank
Other	Adopting a planning strategy	Fraction (%) of the territory within a 1km or less distance from green spaces in sectors ZUD and ZP Neutral level: 50% ZUD, 20% ZP Good level: 80% ZUD, 50% ZP	Zone urbaine dense (ZUD) Zone pavillonnaire (ZP)	
	Adapting to historic context	Distribution (%) of NBS in sectors ARC, CLA and POL regarding NBS type preference Neutral level: 70% FARC-ARC ; 50% FCLA-CLA ; 70% FPOL-POL Good level: 80% FARC-ARC ; 70% FCLA-CLA ; 80% FPOL-POL	Zone d'archéologie préventive (sous-sol) (ARC) Zone bâtiments classés (CLA) Zone des sols pollués (POL)	Farc: Porous pavement, Infiltration system, Green facade, Green roof Fcla: Bioretention & Raingarden, Wetland, Infiltration system, Pond & Basin, Porous pavement, Tank, Trench & Swale Fpol: Tank, Trench & Swale, Green roof, Green façade
	Reducing design costs	Distribution (%) of NBS regarding NBS type preference Neutral level: 60% F1, 20% F2, 20% F3 Good level: 80% F1, 10% F2, 10% F3		F1: Trench & Swale F2: Infiltration system, Bioretention & Raingarden, Green roof, Green facade, Pond & Basin F3: Tank, Porous pavement, Wetland

Annex D – Criteria measurement for Melbourne

Aspects	Criterion	Measure	Data (spatial)	Data (technical)
Biodiversity	Creating connectiveness, quality and quantity biodiversity	Fraction (%) of the territory within a 100m or less distance from a green corridor (ZGC) Neutral level: 10% in PU and 100m from ZGC Good level: 25% in PU and 100m from ZGC	Green corridor map (ZGC) Urban area (PU)	
Aesthetic	Increasing green cover	Distribution (%) of NBS regarding NBS type preference Neutral level: 20% Good level: 40%		F1: Pond & Basin, Wetland, Bioretention, Trench & Swale, Infiltration system (+1) F2: Green roof, Green facade, Porous pavement, Tank (+0)
Recreativity	Improving recreation and accessibility	Distribution (%) of NBS in ZG regarding NBS type preference Neutral level: 20% ZG Good level: 60% ZG	ZG: Priority green area	F1: Pond & Basin, Wetland (+2) F2: Green roof, Bioretention, Trench & Swale, Infiltration system (+1) F3: Green facade, Tank, Porous pavement (+0)
Water management	Reducing catchment and local flooding	Distribution (%) of NBS in sectors ZUp and ZDn regarding NBS type preference Neutral level: 50% ZB 1km Good level: 50% ZB 100m	ZUp: Flooding risk area + upstream area ZDn: Downstream catchment area	F1: Pond & Basin, Wetland (+3) F2: Bioretention & Raingarden, Infiltration system (+2) F3: Green roof, Green facade, Trench & Swale, Porous pavement (+1)
	Recharging base flow	Distribution (%) of NBS in ZI regarding NBS type preference Neutral level: 20% ZG Good level: 25 60% ZG	ZI: infiltration priority map (proximity to waterways + low groundwater table zones)	F1: Bioretention, Infiltration system, Trench & Swale, Pervious pavement (+2) F2: Pond & Basin, Wetland (+1) F3: Green roof, Green facade, Tank (+0)
Temperature	Reducing extreme heat	Distribution (%) of NBS in sectors ZHH and ZLH regarding NBS type preference Neutral level: 30% HH Good level: 75% HH	Urban heat island area (High heat - HH and Low heat - LH)	F1: Pond & Basin, Wetland (+2) F2: Green facade, Green roof, Bioretention, Trench & Swale, Infiltration system (+1) F3: Tank, Porous pavement (+0)
Other	Improving carbon sequestration	Distribution (%) of NBS regarding NBS type preference Neutral level:		F1: Wetland (+3) F2: Pond & Basin, Green roof, Green facade, Bioretention (+2)

		15% F1,2 ; 5% F3 Good level: 50% F1 ; 50% F2,3		F3: Infiltration system, Trench & Swale (+1) F4: Tank, Porous pavement (+0)

Annex E – Supplementary Material of the article “A critical review of MCDA practices in planning of urban green spaces and NBS” (Chapter 1.3)

Research formula in Web of Science

Keywords	1st iteration	2nd iteration	3rd iteration	4th iteration
green spaces and infrastructure ("green infrastructure*" or GI or "nature-based solutions" or NBS or "ecosystem service*" or ES or WSUD or "water sensitive urban design" or SUDS or "sustainable urban drainage system*" or "LID" or "low impact development" or "sponge cit*" or BGI or "blue green infrastructure*" or "blue-green infrastructure*")	✓	✓	✓	✓
MCDA ("multi criteria" or "multi-criteria" or MCDA or multicriteria) and (tool* or model*)	✓	✓	✓	✓
application domain (planning, urban planning)	✓			
all elements (tool, method, model, system)	✓	✓		
some elements (tool, method)			✓	✓
Number of papers	285	701	477	474 (peer-reviewed)

Abstract screening

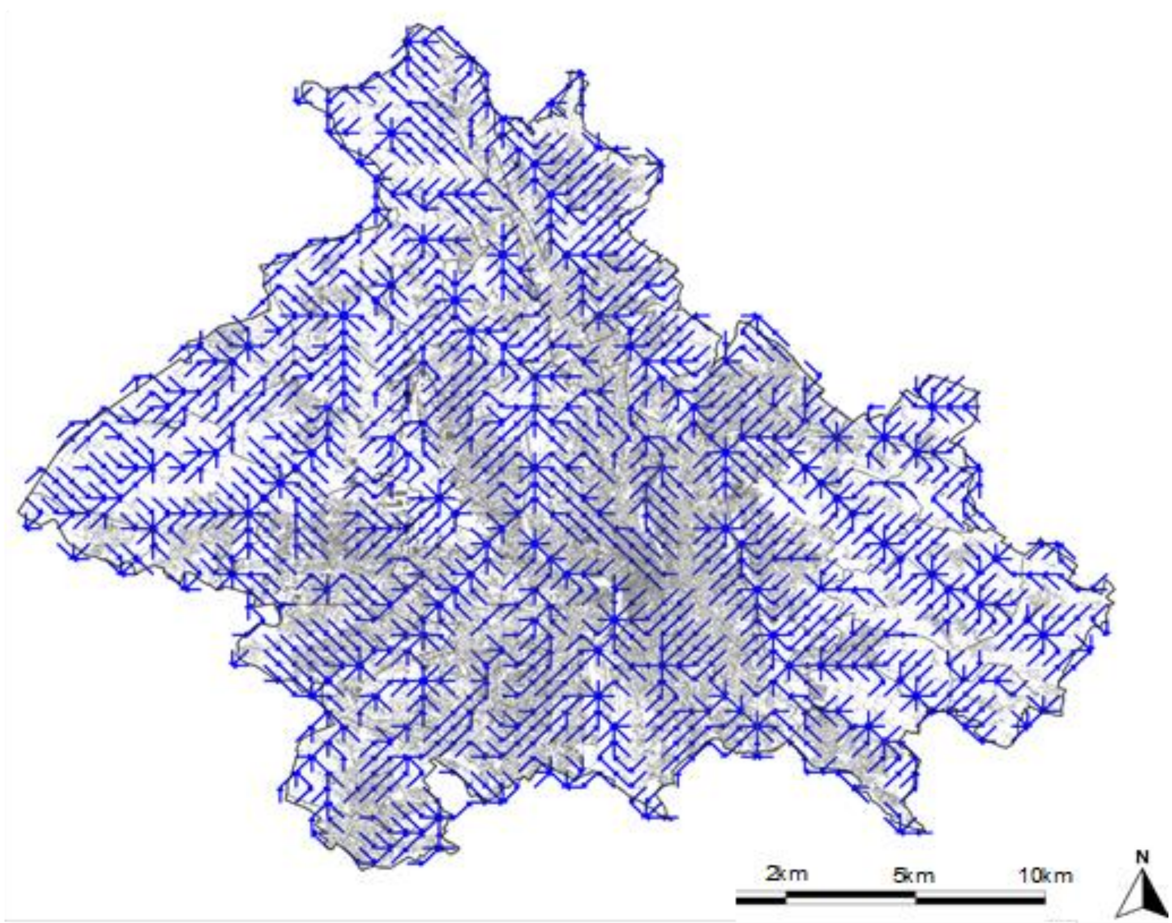
Legend	Justification	Number		Total	
urban planning		127	include	187	187
urban planning?		60	include		
literature review	approaches for urban planning/landscape management, ES evaluation tools/methods/approaches, GIS urban planning tools, ES education, risks evaluation, etc.	28	Different analysis (introduction)	28	287
evaluation	existing NBS, GI, ES, etc.	87	exclude	259	
identification	protection areas, land cover change	17	exclude		
off topic	agriculture, forest/land management, health, energy, soil erosion	149	exclude		
Other	conference paper, not in English, report	6	exclude		
Total		474		474	

Article screening

Number after abstract screening	187
keep	124
don't keep (total)	63
framework	4
no MCDA	22
SDG planning	3
evaluation of existing ES	8
off topic (hydrological power, agriculture, NBS law, river management, land change, environment protection, forest management, landfill, economic assessment)	24
experience feedbacks	1
not in English	1

Annex F – Supplementary Material of the article "MCDA-NBS: combining rigorous multi-criteria decision analysis and engineering tools for nature-based solutions planning" (Chapter 4.1)

Water flow network of the Toulouse Metropole area (Source: UrbanBEATS)



Annex G – Supplementary Material of the article "Applying multi-criteria decision analysis for nature-based solutions planning: findings from three different countries and continents" (Chapter 4.3)

Data used for the case studies of Trois-Rivières, Toulouse and Melbourne

	Name	Type	format	Use	Source
Trois-Rivières	Boundaries	spatial	.txt (GIS)	UrbanBEATS	Trois-Rivières municipality
	Elevation	spatial	.txt (GIS)	UrbanBEATS	Trois-Rivières municipality
	Land use	spatial	.txt (GIS)	UrbanBEATS	Trois-Rivières municipality
	Soil category	spatial	.txt (GIS)	UrbanBEATS	Trois-Rivières municipality
	Population	spatial	.txt (GIS)	UrbanBEATS	Trois-Rivières municipality
	Precipitation	climate	.cvs	UrbanBEATS	Hourly climate data for precipitation taken at the Trois-Rivières station over the period 2009-2018
	Evapotranspiration	climate	.cvs	UrbanBEATS	Climate data for evapotranspiration, calculated using the Penman-Monteith method and the NASA database, for the period 2009-2018 on each day.
	NBS design matrix	curves	.cvs	UrbanBEATS	City of Toronto Design Criteria for Green Infrastructure in the Right-of-Way manual; Constructed Wetlands—Wetlands restoration—US EPA Technical and Regulatory Guidance Document for Constructed Treatment Wetlands—US Interstate Technology & Regulatory Council (ITRC); Guidelines for Residential Rainwater Harvesting Systems, Handbook, Canada Mortgage and Housing Corporation, 2012
	Public Zone	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality
	Industrial Public Zone	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality
	Groundwater table levels	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality
	Well protection zone	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality
	Overflow Zone	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality
	Restricted areas	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality
	Green corridor map	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality
	Urban area	spatial	.txt (GIS)	MCDA	Trois-Rivières municipality

	Name	Type	format	Use	Source
Toulouse	Boundaries	spatial	.txt (GIS)	UrbanBEATS	data.gouv
	Elevation	spatial	.txt (GIS)	UrbanBEATS	Institut National de Geographie (IGN)
	Land use	spatial	.txt (GIS)	UrbanBEATS	Institut National de Geographie (IGN)
	Soil category	spatial	.txt (GIS)	UrbanBEATS	Institut National de la Recherche Agronomique (INRA)
	Population	spatial	.txt (GIS)	UrbanBEATS	Institut National de la Statistique et des Études Économiques (INSEE)
	Precipitation	climate	.cvs	UrbanBEATS	MeteoFrance (Hourly climate data for precipitation taken at the Trois-Rivières station over the period 2009-2018)
	Evapotranspiration	climate	.cvs	UrbanBEATS	MeteoFrance (Climate data for evapotranspiration, calculated using the Penman-Monteith method and the NASA database, for the period 2010-2020 on each day.)
	NBS design matrix	curves	.cvs	UrbanBEATS	https://www.gesteau.fr/sites/default/files/brochure-symasol_isbn_web.pdf
	Zones protégées (APPB, zones humides SAGE, Natura 2000)	spatial	.txt (GIS)	MCDA	Organisme National des Forêts (ONF), Office Français de la Biodiversité (OFB), Ministère de la transition écologique
	Zone de connaissance (ZNIEFF, ZICO)	spatial	.txt (GIS)	MCDA	data.gouv
	Hauteur de la nappe	spatial	.txt (GIS)	MCDA	Bureau de Recherche Biologique et Minière (BRGM)
	Zone urbaine dense	spatial	.txt (GIS)	MCDA	data.gouv
	Zone pavillonnaire	spatial	.txt (GIS)	MCDA	data.gouv
	Carte des ilots de chaleur	spatial	.txt (GIS)	MCDA	Toulouse metropole
	Carte PPRI	spatial	.txt (GIS)	MCDA	data.gouv
	Carte schéma directeur des zones à débordements	spatial	.txt (GIS)	MCDA	Toulouse metropole
	Carte des services de restauration rapide	spatial	.txt (GIS)	MCDA	research team, google map
	Zone d'archéologie préventive (sous-sol)	spatial	.txt (GIS)	MCDA	Institut National de Geographie (IGN)
	Zone bâtiments classés	spatial	.txt (GIS)	MCDA	Toulouse metropole
	Zone des sols pollués	spatial	.txt (GIS)	MCDA	Toulouse metropole

	Name	Type	format	Use	Source
Melbourne	Boundaries	spatial	.txt (GIS)	UrbanBEATS	vic.gov
	Elevation	spatial	.txt (GIS)	UrbanBEATS	vic.gov
	Land use	spatial	.txt (GIS)	UrbanBEATS	vic.gov
	Soil category	spatial	.txt (GIS)	UrbanBEATS	vic.gov
	Population	spatial	.txt (GIS)	UrbanBEATS	vic.gov
	Precipitation	climate	.cvs	UrbanBEATS	bom.gov
	Evapotranspiration	climate	.cvs	UrbanBEATS	bom.gov
	NBS design matrix	curves	.cvs	UrbanBEATS	Melbourne water
	Flooding risk area + upstream area	spatial	.txt (GIS)	MCDA	Melbourne water
	Downstream catchment area	spatial	.txt (GIS)	MCDA	Melbourne water
	Biodiversity area	spatial	.txt (GIS)	MCDA	Melbourne water
	Urban heat island area	spatial	.txt (GIS)	MCDA	vic.gov
	Priority green area	spatial	.txt (GIS)	MCDA	Melbourne water
	Infiltration priority map	spatial	.txt (GIS)	MCDA	Melbourne water

UrbanBEATS NBS planning alternatives for the case studies of Trois-Rivières, Toulouse and Melbourne

The values presented in this table represent the number of NBS for each alternative.

Alternative	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Trois-Rivières																				
Bioretention	235	283	233	239	189	153	69	119	83	120	73	122	108	95	134	119	73	98	144	126
Wetand	157	162	113	145	125	105	78	88	87	102	78	111	126	93	99	86	135	147	109	116
Pond & Basin	209	201	170	190	171	152	75	111	129	140	82	163	185	114	96	83	105	94	122	137
Trench & Swale	12	25	8	14	23	34	11	62	18	27	46	53	36	28	23	13	45	17	9	14
Infiltration system	3	11	24	9	15	7	27	12	32	13	28	16	5	9	28	8	6	19	14	17
Total	**616**	**682**	**548**	**597**	**523**	**451**	**260**	**392**	**349**	**402**	**307**	**465**	**460**	**339**	**380**	**309**	**364**	**375**	**398**	**410**
Toulouse																				
Bioretention	438	413	371	390	382	307	297	310	272	231	338	286	254	231	407	352	374	419	222	275
Wetand	85	81	69	62	64	69	51	53	42	64	58	102	68	55	82	67	73	84	117	95
Pond & Basin	139	137	152	142	123	132	114	154	153	108	139	145	130	114	107	128	149	103	110	123
Trench & Swale	234	219	197	185	196	153	175	293	125	112	120	182	186	123	149	174	130	144	168	157
Infiltration system	2	7	0	12	0	3	6	5	13	4	3	0	4	0	1	8	0	0	2	5
Total	**898**	**857**	**789**	**791**	**765**	**664**	**643**	**815**	**605**	**519**	**658**	**715**	**642**	**523**	**746**	**729**	**726**	**750**	**619**	**655**
Melbourne																				
Bioretention	612	546	404	349	298	290	250	211	191	134	307	169	386	468	397	274	432	572	510	535
Wetand	95	88	75	67	66	69	50	44	46	30	72	57	77	55	94	69	70	104	115	84
Pond & Basin	341	275	226	221	171	182	163	147	107	95	160	234	284	194	189	317	225	306	246	275
Trench & Swale	226	135	145	127	101	100	80	75	67	62	107	179	95	165	142	68	122	83	127	190
Infiltration system	270	223	175	162	142	130	113	149	110	210	139	111	253	284	171	195	148	272	220	273
Total	**1544**	**1267**	**1025**	**926**	**778**	**771**	**656**	**626**	**521**	**531**	**785**	**750**	**1095**	**1166**	**993**	**923**	**997**	**1337**	**1218**	**1357**

NBS planning alternatives assessment with the MACBETH model for the case studies of Trois-Rivières, Toulouse and Melbourne

The values presented in this table represent the weighted values obtained for each of the alternatives for each criterion and the overall score for each alternative (weighted sum of the weighted values for each criterion).

Alternative	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Trois-Rivières																				
Maximising multi-functional potential	280	12	203	280	204	280	234	177	280	-50	280	280	133	136	-67	286	280	31	280	280
Increasing green cover	109	-39	217	217	-55	178	217	72	164	217	217	-57	217	146	217	69	217	217	217	105
Minimising user impacts (perception)	220	220	220	144	220	191	220	65	220	220	220	137	95	193	55	-76	220	205	-72	108
Encouraging implementation on public lands	15	166	166	-45	166	-49	166	166	166	-69	166	22	-85	166	166	166	28	152	142	166
Encouraging infiltration	134	191	330	381	151	104	378	22	288	218	-18	219	394	197	122	179	45	-55	-22	222
Encouraging implementation in overflow areas	275	259	-31	80	222	275	275	275	275	275	244	275	58	258	275	165	186	55	105	275
Encouraging green corridor links	-45	185	190	190	303	305	70	237	-64	312	182	31	-97	225	-91	278	61	363	130	-21
Minimizing footprint	38	133	-33	80	133	133	133	133	133	-33	133	133	82	133	133	133	-33	-33	75	133
Adopting NBS for cold climate	-49	-24	207	257	85	225	257	57	254	194	207	60	257	83	62	257	-74	103	198	228
Minimising skill needs for construction and maintenance	167	-55	120	167	-55	97	-55	148	167	167	167	18	167	167	167	167	-55	100	167	35
Total	**1144**	**1048**	**1589**	**1751**	**1374**	**1739**	**1895**	**1352**	**1883**	**1451**	**1798**	**1118**	**1221**	**1704**	**1039**	**1624**	**875**	**1138**	**1220**	**1531**
Toulouse																				
Protecting biodiversity	54	137	-41	200	183	92	200	37	200	-28	-125	138	58	111	57	245	95	-14	-94	89
Creating biodiversity	185	185	108	-70	183	-70	-70	-7	-70	-10	60	-31	-70	83	185	-70	185	-40	105	11
Improving water quality	230	-46	-130	-57	201	86	-131	90	230	-41	-23	262	106	230	168	-134	225	230	27	139
Adopting a planning strategy	-45	100	100	69	74	100	100	100	100	-45	100	-45	100	100	100	59	-45	11	-45	245
Mitigating urban heat island	150	119	-19	147	-133	240	79	23	92	136	-142	42	-93	146	160	262	114	-50	179	92
Preventing flooding risk	-106	115	-49	-130	-105	61	-14	175	123	147	-130	95	99	-101	163	201	139	18	-104	55
Improving multifunctionnality	170	83	131	-30	143	-45	69	170	-30	66	94	66	170	170	109	-30	88	-30	89	188
Managing user waste	42	-58	94	150	4	-35	-130	130	132	36	13	-117	19	159	-102	172	102	143	-33	148
Adapting to historic constraints	-7	200	43	-71	-62	-75	168	-75	-75	139	-25	-31	92	200	-75	-75	90	-75	200	-112
Balancing water/energy/waste	-41	144	214	-38	26	-59	131	-106	131	-80	-58	-128	152	143	-133	207	-46	268	153	112
Reducing design costs	198	-75	-51	125	-75	104	160	9	-6	57	-20	-69	250	0	-75	-75	-7	-27	40	-87
Total	**830**	**904**	**400**	**295**	**439**	**399**	**562**	**546**	**827**	**377**	**-256**	**182**	**883**	**1241**	**557**	**762**	**940**	**434**	**517**	**880**
Melbourne																				
Reducing catchment and local flooding	-31	59	200	68	109	107	200	77	37	16	200	99	200	200	130	78	-38	200	182	161
Creating connectiveness, quality and quantity biodiversity	150	147	80	150	150	150	150	150	150	150	150	91	150	150	84	150	150	150	-18	237
Reducing extreme heat	150	150	150	-26	150	58	36	82	150	-16	68	90	83	138	81	42	29	33	150	150
Increasing green cover	74	100	91	99	100	96	100	100	100	88	86	90	100	100	100	12	100	77	100	40
Improving recreation and accessibility	90	130	130	130	130	88	57	53	130	115	130	116	115	130	130	130	130	130	47	433
Recharging Base Flow	130	-13	118	130	130	130	11	130	130	130	130	31	130	130	130	130	90	80	130	130
Improving carbon sequestration	25	200	269	131	200	200	169	32	107	23	200	39	200	11	120	148	191	90	200	142
Total	**588**	**773**	**1038**	**682**	**969**	**829**	**723**	**624**	**804**	**506**	**964**	**556**	**978**	**859**	**775**	**690**	**652**	**760**	**791**	**1293**