SSANTO

Planning Support for Water Sensitive Urban Design

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Abstract

Distributed and green stormwater management infrastructure, known as Water Sensitive Urban Design (WSUD), is increasingly implemented around the world to mitigate the negative impacts of increased urbanisation and climate change on surface water quality and quantity. As an integral part of the urban landscape, a reciprocal relationship exists between WSUD and the urban biophysical, socio-economic and governance context. Considering this context, while capturing the diverse ecological and amenity benefits derived from WSUD calls for spatially explicit strategic planning approaches. Current practice is lacking planning support tools and models that consider the full complexity of spatial suitability for WSUD implementation.

This thesis aimed to support WSUD planning through the development of a tool, called **S**patial **S**uitability **AN**alysis **TO**ol (SSANTO). SSANTO allows rapid and rigorous spatial suitability analysis by applying advanced Geo Information Science (GIS) based Multi-Criteria Decision Analysis (MCDA) techniques on a comprehensive set of criteria. This core functionality combined with a simple, stepwise process and intuitive, visual output maps enable deeper understanding of WSUD planning contexts as well as promoting collaborative modelling. Three steps preceded the development of SSANTO: (i) development of a WSUD suitability framework, (ii) spatial analysis of WSUD distribution in Melbourne, Australia, and (iii) structured qualitative study of planning practice in a developed (Australia) and developing (Indonesia) context.

Spatial suitability for WSUD was defined from two angles: *WSUD needs a place* (Opportunities), referring to the physical and non-physical aspects of the urban context that WSUD systems need to function well; and *A place needs WSUD* (Needs), capturing the locations where the benefits derived from WSUD are needed. A WSUD suitability framework was developed by combining these angles. *WSUD needs a place* was divided into three categories of criteria: (1) biophysical, (2) socio-economic and (3) planning & governance. *A place needs WSUD* brings knowledge from ecosystem services into the framework following the four categories of criteria as adopted by the United Nations framework: (1) provisioning, (2) regulating, (3) cultural and (4) habitat. Each of the seven categories in the WSUD suitability framework contain criteria that are coupled with measurable spatial indicators.

To assess the strategic level of current WSUD placement, the spatial distribution of WSUD systems existing in Melbourne was compared to indicators from the suitability framework. A unique spatial

database containing all geo-located WSUD asset records was analysed using a mix of statistical methods including exploratory spatial regression and principal component analysis. While biophysical and urban form factors were found to strongly drive WSUD locations, socio-economic factors appeared to be overlooked. The most important driver for WSUD occurrence was the distance to the city centre, with more WSUD found further away from the centre. These findings suggested opportunistic and ad-hoc planning practices. Such practices may lead to poorly functioning systems and failure to capitalise on the full suite of potential benefits derived from WSUD.

Structured engagement with practitioners in Melbourne confirmed the opportunistic character of planning. Interviews were conducted with stakeholders involved in WSUD planning from local- and state government, the water authority, consultants and a water utility. It was found that urban planning could benefit from improved collaboration, clear local water strategies and legislation as well as building business cases for WSUD. The uptake of planning support systems was moderate. Respondents indicated that user-friendliness, simplicity, visual outputs and industry conventions all impacted on their decision to adopt a tool or model.

The above findings guided SSANTO's development, which was informed by the Australian and Indonesian planning context. Its algorithms follow a four-step procedure to operationalise the WSUD suitability framework: (1) compiling a geodatabase, (2) masking constrained areas, (3) value scaling (translating raw data into suitability values), and (4) combining, offering a mix of techniques for criteria weighting and overlaying. SSANTO applies value scales of a piecewise linear form. It provides the user the option of hierarchical- and non-hierarchical manual weighting, entropy-based weighting or a mix of these. Suitability is represented through a unitless scale from low to high (0-100) and visualised on raster-based maps for both suitability angles (Opportunities and Needs), which can be combined to create an overall suitability map. SSANTO was tested for a developed and developing context.

Testing SSANTO in a developed context was accomplished for the municipality of Darebin in Melbourne, using the outcomes of a prioritisation study conducted by a consultancy firm. The algorithms of SSANTO were validated by comparing its outputs to the results of suitability mapping from the consultancy. Further testing compared the tool's output to a map of priority sites produced by the consultant. It was found that SSANTO was able to reflect the selection of these priority sites by calculating above-average suitability in these locations. These findings were consistent across configurations with varying criteria selection and weight assignment.

SSANTO was tested in the developing context of Bogor, Indonesia. Data limitations rendered quantitative model testing impossible. Therefore, SSANTO was tested qualitatively through structured engagement with planning practitioners in interviews and tool demonstration workshops. Indonesian planning practice was found to be highly receptive to planning support offered by SSANTO. The tool could help diminish the reported lack of capacity from governmental agencies. Practitioners, including planning consultancies which do the bulk of urban planning in Indonesia, were found to be very willing to adopt novel and innovative tools and methods. Most important barrier for uptake was limited availability of data.

SSANTO's ability to rapidly reproduce strategic planning outcomes while reflecting user preferences and expertise using automated GIS-MCDA capabilities facilitates urban planners to significantly improve the outcomes of WSUD implementation. Continuous trialling and testing have provided ample avenues for refinement, further development, and coupling with other models and tools to enhance its capacities. Originally conceived to aid WSUD planning, opportunities for SSANTO's application extend beyond sustainable urban water management to any type of spatial planning and location selection. This is a PhD thesis with published work. It comprises five journal articles of which three have already been published and one more has been submitted.

Acknowledgements

A PhD is never smooth sailing, and neither was this one. A huge thank you to my supervisors, Professor Ana Deletic, Dr. Peter Bach and Professor Diego Ramirez, who have done everything to make sure I came through it mostly unscathed. Your insightfulness, creativity and support until the end have helped make the journey worthwhile and the result one I am truly proud of.

I extend my gratitude to all my co-authors: Megan Farrelly, Simon Roberts and Dale Browne. Your help has been an indispensable addition to my thesis, and your enthusiasm and encouragement a real inspiration. Your advice and reviews have significantly improved the quality of my articles and motivated me to broaden my work. I gratefully thank all the people from Melbourne's municipal councils, water utility, state government, water authority and engineering consultancies, for sharing your data, knowledge, experience with WSUD and planning, particularly Melbourne Water, E2DesignLab and the City of Darebin.

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Writing a doctoral thesis can be a lonely experience. I was incredibly fortunate to be part of a PhD cohort of 12 other candidates. Going through every stage of the process at the same time made it so much more fun! Thank-you to them for their friendship, support and chit-chat around the office. It really would not have been the same without you. Special thank you to Natalie, for all the laughs and lifts; and to my office neighbour Behzad for his patience with my programming questions and watering my plants.

To all the friends I have made since I moved to Australia. Your banter, drinks, coffees, dinners, parties, festivals, camping trips, tennis matches and 'deep-and-meaningfuls' have made my life awesome, kept me sane and are the reason I feel truly at home in Melbourne. Special thanks to Dave, who’s accurate, inside advice about academia I never took, but who still patiently put up with my complaints about it.

Last but not least, thank you so much to my friends and family back home in The Netherlands and around the world. You have always there for me, even when I’m so far away. Your endless love, support and interest in my life have kept me going. To Mum, I hope I have inherited some of your perseverance, organisational skills and passion for new adventures. To Dad, I hope I have inherited some of your critical thinking and passion for the environment. To my sister, who always keeps me open to other perspectives and reminds me of the things that really matter in life. I love you!

List of publications

This is a thesis with published work. A total of five first-authored journal articles resulted from the research and form the core of this thesis. Three articles have already been published and one has been submitted. Furthermore, the work has been presented at four international academic conferences, which has resulted in a number of first- and second authored conference articles.

Peer-reviewed journal articles

Lead-authored articles

1. **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 and strategies for best planning practice." Environmental Modelling and Software 96, 265-282, https://doi.org/10.1016/j.envsoft.2017.07.003

2. **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

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

4. **Kuller, M.**, Bach, P.M., Roberts, S., Browne, D., D., Deletic, A, submitted. "A planning-support tool for spatial suitability assessment of green urban stormwater infrastructure" To be submitted to the Journal of Water Resources Planning and Management

5. **Kuller, M.**, Farrelly, M., Deletic, A.., Bach, P.M., in preparation. "Planning support for Green Infrastructure in a developing context: the case of Indonesia" To be submitted to Cities

Co-authored articles

1. Barron, N., **Kuller, M.**, …, Deletic, A., 2017. "Towards Water Sensitive Cities in Asia: An Interdisciplinary Journey" Water Science and Technology, https://doi.org/10.2166/wst.2017.287

Conference articles

Lead-authored articles

1. **Kuller, M.**, Bach, P.M., Ramirez-Lovering, D., Deletic, A., 2016. "The location choice of Water Sensitive Urban Design within a city: A case study of Melbourne." IWA World Water Congress and Exhibition, At Brisbane, Australia.

2. **Kuller, M.**, Farrelly, M., Deletic, A.., Bach, P.M., 2017. "Building effective planning support systems for green urban water infrastructure – practitioners' viewpoints and perceptions" 4th Water Research Conference, Waterloo, Canada

3. **Kuller, M.**, Bach, P.M., Ramirez-Lovering, D., Deletic, A., 2017. "Getting the locations right: a GIS-based Planning Support System for Water Sensitive Urban Design" 14th International Conference on Urban Drainage, At Prague, Czech Republic

4. **Kuller, M.**, Farrelly, M., Deletic, A.., Bach, P.M., 2017. "Building effective planning support systems for green urban water infrastructure – practitioners' viewpoints and perceptions" 14th International Conference on Urban Drainage, At Prague, Czech Republic

5. **Kuller, M.**, Bach, P.M., Roberts, S., Browne, D., D., Deletic, A, 2018. "Supporting the needs and necessity for urban green stormwater infrastructure – a novel planning-support system." 11th International Conference on Urban Drainage Modelling, Palermo, Italy

Co-authored articles

1. Barron, N.J., **Kuller, M.**, et al., 2016. "Towards Water Sensitive Cities in Asia: An Interdisciplinary Journey. " *IWA World Water Congress and Exhibition, At Brisbane, Australia.*

2. A. Deletic, K. Zhang, B. Jamali, A. Charette-Castonguay, **M. Kuller**, V. Prodanovic, P.M. Bach, 2018. "Modelling to support the planning of sustainable urban water systems." *11th International Conference on Urban Drainage Modelling, Palermo, Italy*

Declaration of thesis including published works

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes three original articles published in peer reviewed journals, one submitted article and one drafter article. The core theme of the thesis is planning support for water sensitive urban design. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the candidate, working within the Department of Civil Engineering under the supervision of Prof. Ana Deletic, Dr. Peter M. Bach and Prof. Diego Ramirez-Lovering. The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research.

In the case of Chapters 2-5 my contribution to the work involved the following:

Thesis Chapter	Publication Title	Status	Nature and % of candidate's contribution	Co-author name(s) Nature of Co-author's contribution*	Co-author Monash student
2	Framing Water Sensitive Urban Design as part of the urban form: a critical review of tools and strategies for best planning practice	Published	65%. Initiation of ideas, conducting literature review, conceptualising and developing suitability framework, leading of write-up and revision	1) Peter M. Bach, initiation, provision of key literature, ideas and reviewing 2) Diego Ramirez, ideas and reviewing 3) Ana Deletic, initiation, provision of key literature, ideas and reviewing	No No No
3	What drives the location choice for water sensitive infrastructure in Melbourne, Australia?	Published	75% Initiation of ideas, leading data gathering, data analysis and interpretation, leading of write-up and revision	1) Peter M. Bach, initiation, ideas and reviewing 2) Diego Ramirez, initiation, ideas and reviewing 3) Ana Deletic, initiation, ideas and reviewing	No No No
4	Building effective Planning Support Systems for green urban water infrastructure—Practitioners' perceptions	Published	80% Initiation of ideas, data gathering, data analysis and interpretation, leading of write-up and revision	1) Megan Farrelly, initiation, ideas and reviewing 2) Ana Deletic, initiation, ideas and reviewing 3) Peter M. Bach, initiation, ideas and reviewing	No No No

I have not renumbered sections of submitted or published articles.

Candidate's signature: **Date:** 14 Sept. 2018

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the candidate's and co-authors' contributions to this work. In instances where I am not the responsible author I have consulted with the responsible author to agree on the respective contributions of the authors.

Main Supervisor signature: **Date:** 14 Sept. 2018

Preface

This thesis presents the research and development of a new planning support tool for the implementation of green urban stormwater infrastructure in the form of five lead-authored journal articles. Three of these have been published, one has been submitted for review and one has been written. The journal articles are accompanied by an introduction and conclusion chapter.

The introduction provides the research background, rationale, aim, scope and research context. The first article (*Framing Water Sensitive Urban Design as part of the urban form: a critical review of tools and strategies for best planning practice*) presents the literature review and includes a critical review and typology of current planning support tools for WSUD planning. It further presents the WSUD suitability framework used for the development of the tool. The remainder of the chapter presents the research objectives, research questions and hypotheses. The second article (*What drives the location choice for water sensitive infrastructure in Melbourne, Australia?*) examines the spatial relationships between some important factors from the WSUD suitability framework and the locations of WSUD infrastructure in the Melbourne metropolitan area. The third paper (*Building effective Planning Support Systems for green urban water infrastructure—Practitioners' perceptions*) investigates the Australian WSUD planning practice and the role of tools and models. The fourth paper (*A planning-support tool for spatial suitability assessment of green urban stormwater infrastructure*) presents the development and testing of the tool. The fifth paper (*Planning support for distributed green stormwater infrastructure in a developing context: the case of Indonesia*) investigates the Indonesian (WSUD) planning practice, the role of tools and models, and tests the applicability of the tool in an Indonesian context. Finally, practical implications of the research are discussed, concluding remarks are given and avenues for further work are suggested.

In addition to the five journal articles in this thesis, one co-authored journal article is provided as an Appendix. The candidate also produced seven conference articles (five of which are lead-authored). These are not included in the thesis, but were presented at four major international conferences across the world.

Contents

List of abbreviations

ABS	Australian Bureau of Statistics
AHP	Analytical Hierarchy Process
AIC	Australia-Indonesia Centre
BAPPEDA	BAdan Perencana PEmbangunan DAerah
BAPPENAS	BAdan Perencanaan PEmbangunan NASional
BMP	Best Management Practice
CBA	Cost-Benefit Analysis
CBD	Central Business District
CSO	Combined Sewer Overflow
DCI	Directly Connected Imperviousness
DELWP	Department of Environment, Land, Water and Planning
DEM	Digital Elevation Model
ELECTRE	ELimination Et Choix Traduisant la REalité
EPA	Environmental Protection Authority
ETH	Eidgenössische Technische Hochschule
FOSMA	Feasibility Of Stormwater Management Actions
GI	Green Infrastructure
GIS	Geo Information Systems/Science
H	Hypothesis
IER	Index of Economic Resources
IRSAD	Index of Relative Socio-economic Advantage and Disadvantage
IUWM	Integrated Urban Water Management
IWA	International Water Association
LID	Low Impact Development
MCA	Multi-Criteria Assessment
MCDA	Multi-Criteria Decision Analysis
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
PCA	Principle Component Analysis

POI	Points Of Interest
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PSS	Planning Support Systems
PST	Planning Support Tool
RQ	Research Question
RW	Relative WSUD
SSANTO	Spatial Suitability ANalysis TOol
SUDS	Sustainable Urban Drainage Systems
SUWM	Sustainable Urban Water Management
SWMM	Storm Water Management Model
UI	User Interface
UK	United Kingdom
UN	United Nations
UrbanBEATS	Urban Biophysical Environments And Technologies Simulator
US	United States
USA	United States of America
VIC	Victoria
WLC	Weighted Linear Combination
WSUD	Water Sensitive Urban Design

CHAPTER 1
INTRODUCTION

Veel beekjes maken een groot water

“Many streams make a great river”

1.1 RESEARCH BACKGROUND

1.1.1 The rise of urban water management

Advances in urban water management have been driven by a sequence of societal and natural drivers throughout the history of human settlement (Brown et al. 2008, Burian et al. 1999, Lofrano and Brown 2010). The basic human need for safe and clean water supply for consumption and other purposes was one of the primary drivers behind the location of human settlement and early water supply systems like the ancient Greek and Roman aqueducts (Koutsoyiannis et al. 2008). Concerns for public health related to the disposal of human waste in cities drove the development of a water-based sanitation system combined with urban wastewater conveyance systems.

As cities grew in size and number, their impact on the natural water cycle was exacerbated through the increased area of impervious surfaces. Resulting increase in urban stormwater runoff triggered the development of urban drainage systems, aimed at quick and safe conveyance of stormwater out of the city and protection against flooding. Although water supply, wastewater conveyance and urban drainage satisfied the basic human needs of city dwellers, they severely impacted the health of receiving natural water bodies. Concerns for the ecological health of natural waterways as well as their indirect impact on the safety of water supply and other human uses of surface waters (recreation, fishing etc.) led to the introduction of wastewater and stormwater treatment systems. Thus, urban water systems grew more and more complex over time (Geldof 2002).

Traditionally, the urban water infrastructure (supply, sanitation and drainage) implemented as a response to these drivers can be characterised as highly engineered and centralised, both in their physical layout as well as their management (Bertrand-Krajewski 2005, Ferguson et al. 2013, Sitzenfrei et al. 2013). Although these systems are highly efficient in delivering the service they were designed for, a number of limitations and shortcomings have recently been recognised: (1) their capital intensive nature and long design life time leads to rigidity of the management paradigm (lock-in), (2) aging assets require very high investment for repair and replacement, (3) their centralised nature is associated with low resilience and adaptability, (4) low public awareness and appreciation because they are out of sight, (5) degradation of receiving waterways, (6) increased probability of flooding and drought conditions (Rogers and Defee Ii 2005, Segaran et al. 2014).

The increased severity and frequency of extreme weather events associated with global climate change have driven many of these centralised systems to their limit. Prolonged periods of dry weather have been jeopardising water supply while intense rainfall events have flooded the overburdened drainage systems (UNW DPAC 2010). Human societies are continuing to become more urbanised, with consistently high rates of urbanisation in the western world and rapidly increasing urbanisation of the global south. More than half of the world's 7 billion people currently live in cities while share of urban population is projected to increase to 66% in 2050 (United Nations 2012) Although many western cities are still growing, the majority of this growth is driven by Asian countries (UN HABITAT 2013).

1.1.2 Water Sensitive Urban Design as the way forward?

Alternative paradigms of urban water management have emerged around the world in the past decades, in response to the abovementioned shortcomings of centralised practices. Such paradigms, known as Integrated Urban Water Management (IUWM) or Sustainable Urban Water Management (SUWM), move away from separated systems for water supply, wastewater management and stormwater conveyance (Larsen and Gujer 1997, Mitchell 2006). Instead, they take a holistic approach to water management through the application of a mix of centralised, decentralised and integrated forms of infrastructure. While IUWM and SUWM are umbrella terms for a diverse pallet of novel and innovative approaches and technologies, they share the goal to increasing resilience, sustainability and liveability of urban landscapes and urban communities.

With the emergence of IUWM and SUWM, urban stormwater management approaches have also started to change. New practices have emerged, which align with the principles of IUWM and SUWM. Depending on geography, these practices are known as Water Sensitive Urban Design (WSUD), Sustainable Urban Water Systems (SUDS), Low Impact Development (LID), Best Management Practices (BMP), Green Infrastructure (GI), Nature-based solutions or Sponge City (Fletcher et al. 2014). Their underpinning philosophy is to restore the natural hydrological cycle through the "activation of natural processes" (Fryd et al. 2012). This is achieved through the implementation of distributed and, often, vegetated technologies such as rain gardens, green roofs and constructed wetlands. Development of such technologies has received considerable attention in the academic scholarship of the past two decades (Argue 1994, Armitage et al. 2013, Melbourne Water 2005, Woods Ballard et al. 2007).

In the pursuit of WSUD, equally important to advancements in novel stormwater technologies are corresponding advancements in planning practices. Faced with uncertain future climate and urban development combined with the complexity of decentralised management of technology, urban planning for WSUD can be classified as a 'wicked problem' (Klosterman 1997, Makropoulos et al. 2008, Rittel and Webber 1973). To meet the multiple objectives associated with WSUD, interdisciplinary, collaborative and adaptable planning practices are called for. Indeed, the success and performance of technologies rely on their strategic integration in the urban landscape, sensitive to the reciprocal interactions between urban design, technology and the natural, cultural and socio-economic context (Ellis et al. 2008). Unfortunately, this aspect of WSUD remains relatively underexposed in the scholarship and proves challenging in practice. The lack of advancement in WSUD planning may thus limit the potential benefits derived from the growing uptake of WSUD technologies.

1.1.3 Planning support for WSUD

Wicked problems are not unique to urban water management and planning (Klosterman 1997). The need for strategic approaches in spatial planning have prompted the development of Planning Support Systems (PSS) and Decision Support Systems (DSS) (Geertman and Stillwell 2004, 2012). Such PSS, which include models, tools and frameworks, have great potential to improve planning processes and outcomes (Klosterman 1997). Current day planning greatly benefits from their capacity to deal with the growing complexity of urban planning tasks through visualisation (often using Geo Information Systems - GIS) and conceptualisation of spatial and temporal changes. PSS have also been adopted in urban water management and planning, reflected in a growing body of both grey and academic literature (e.g. Lerer et al. 2015). However, their potential benefit to the planning process has not been fully capitalised, as uptake of novel PSS remains relatively low (te Brömmelstroet et al. 2014, Vonk et al. 2005). This underutilisation despite recognised benefits has been referred to as the "implementation gap" (Brömmelstroet and Schrijnen 2010). Causes to this implementation gap are commonly hypothesised to be related to their lack of user-friendliness, too high levels of complexity, high data-demands and lack of relevance to real-world processes (Lee Jr 1973, Vonk et al. 2005). Increased levels of engagement between PSS development and planning practice are instrumental to overcome such problems.

1.2 RESEARCH AIM AND SCOPE

The aim of the PhD is to ***add robustness to, as well as streamline the process of decision making for urban planning of WSUD through explicit consideration of location-specific context, represented by relevant biophysical, socio-economic and planning related factors as well as local needs***.

This thesis outlines the preparation, development and testing of a novel PSS for automated GIS-based Multi-Criteria Decision Analysis (GIS-MCDA), called **S**patial **S**uitabilitiy **AN**alysis **TO**ol (SSANTO). While the methods, tool and underlying suitability framework are easily transferable to other types of (green) urban infrastructure, this PhD research focus primarily on planning support for WSUD, including the following technologies: bioretention & rain gardens, green roofs, infiltration systems, ponds & lakes, swales, rainwater tanks and constructed wetlands. Although greenfield development can greatly benefit from, and readily utilise the outputs of this work, the tool developed during this PhD is initially targeted at infill development. SSANTO's purpose is to guide the location planning of WSUD through visual exploration of diverse spatially explicit data related to the feasibility and benefits related to WSUD. Its purpose is not to perform optimisation or provide 'objective' or deterministic measure of suitability. Through SSANTO, we seek to guide the *process* of knowledge gathering to understand the spatial context within which to implement WSUD, rather than to provide an solution, or description of the desired *outcome* of planning.

This interdisciplinary work draws on methods from a diverse set of academic fields. These include civil engineering, environmental science, urban planning, social science and computer software development. The research, tool development and testing are based in the developed context of Australian urban landscapes (using Melbourne as our specific case study city), where experiences with WSUD implementation are relatively long and extensive. However, the Indonesian context has informed this process throughout the PhD, and the resulting tool was tested for transferability in an Indonesian city. The choice of Indonesia is also attributed to the broader research context of this work.

1.3 RESEARCH CONTEXT

This PhD was conducted as part of a Monash University doctoral cohort known as the Graduate Research Interdisciplinary Program (GRIP). This inaugural GRIP with the overarching theme *Water and Sustainability in Asia* initially involved 14 students from 12 different countries and four continents. Students were divided over two faculties (Engineering and Arts) and supervised by a team of academics from three faculties (including Architecture). Research focussed on several Asian countries. For more information on the GRIP approach, refer to Barron et al. (2017), which can be found in Appendix I.

This PhD research was part of, and partly funded by, the Australia-Indonesia Centre's (AIC) Urban Water Cluster project. This collaborative research initiative brought together academics from three Australian and three Indonesian universities from cities across Java. The Urban Water Cluster consisted of 5 research streams called 'sub-projects': (1) benchmarking, (2) Governance, (3) Modelling, (4) Technologies and (5) Design and Demonstration. This PhD was part of the 5^{th} research stream on Design and Demonstration. The work in Indonesia, that was part of this PhD, was conducted primarily in Bogor in collaboration with the Bogor Agricultural University (IPB), but also in Surabaya with the Sepuluh Nopember Institute of Technology (ITS).

1.4 THESIS STRUCTURE

This is a PhD thesis with published work. A total of five first-authored journal articles resulted from the research and shape the core of the thesis. The work was conducted in four stages (Figure 1-1):

1. **Setting the scene**; where the aim, background and research questions are presented;

2. **Informing SSANTO**; where the rationale is developed, conceptual- and methodological information is gathered, and content scope was defined;

3. **Building SSANTO**; where the spatial suitability analysis methodology is developed and translated into a simple GIS-based computer tool; and

4. **Testing SSANTO**; where the concept, methodology and algorithms are tested in the context of Melbourne (Australia) and Bogor (Indonesia), and the overall findings of the PhD are synthesised.

'Setting the scene' starts with **Chapter 1: Introduction**, which provides background to the problems addressed in this thesis, defines the aim of the work, discusses the research context and outlines the structure of the thesis. In the first part of **Chapter 2: Literature review and suitability framework**, relevant WSUD planning and PSS literature are critically reviewed and existing tools and models for urban water management are organised in a descriptive framework. This results in the definition of research gaps.

Chapter 2 continues in 'Informing SSANTO', with the definition of a suitability framework that forms the basis for spatial suitability analysis in later chapters. The suitability framework is used in **Chapter 3: Spatial analysis of WSUD distribution,** to analyse the current distribution of WSUD systems across Melbourne. This analysis of spatial planning outcomes is followed by an analysis of planning practices that lead to these outcomes, and the role that tools and models play in them (**Chapter 4: WSUD planning practice**).

In 'Building SSANTO', the suitability framework from Chapter 2 is operationalised through the development of an automated GIS-MCDA methodology. The outcomes of Chapter 4 inform the development of a computer tool based on the aforementioned methodology, as reported in **Chapter 5: SSANTO; development and testing**.

Chapter 5 continues into 'Testing SSANTO', with the application in a case-study in Melbourne. Using existing strategic planning exercises, we compare the operation of algorithms and the outcomes of the tool to the equivalent manual, human decision-making process. The usefulness and applicability are further tested for an Indonesian context in **Chapter 6: SSANTO in the Indonesian planning context**. The thesis ends with the implications to practice, a summary of key findings and conclusions, a discussion of strengths and weaknesses in the evidence and recommendations for future research in **Chapter 7: Conclusions**.

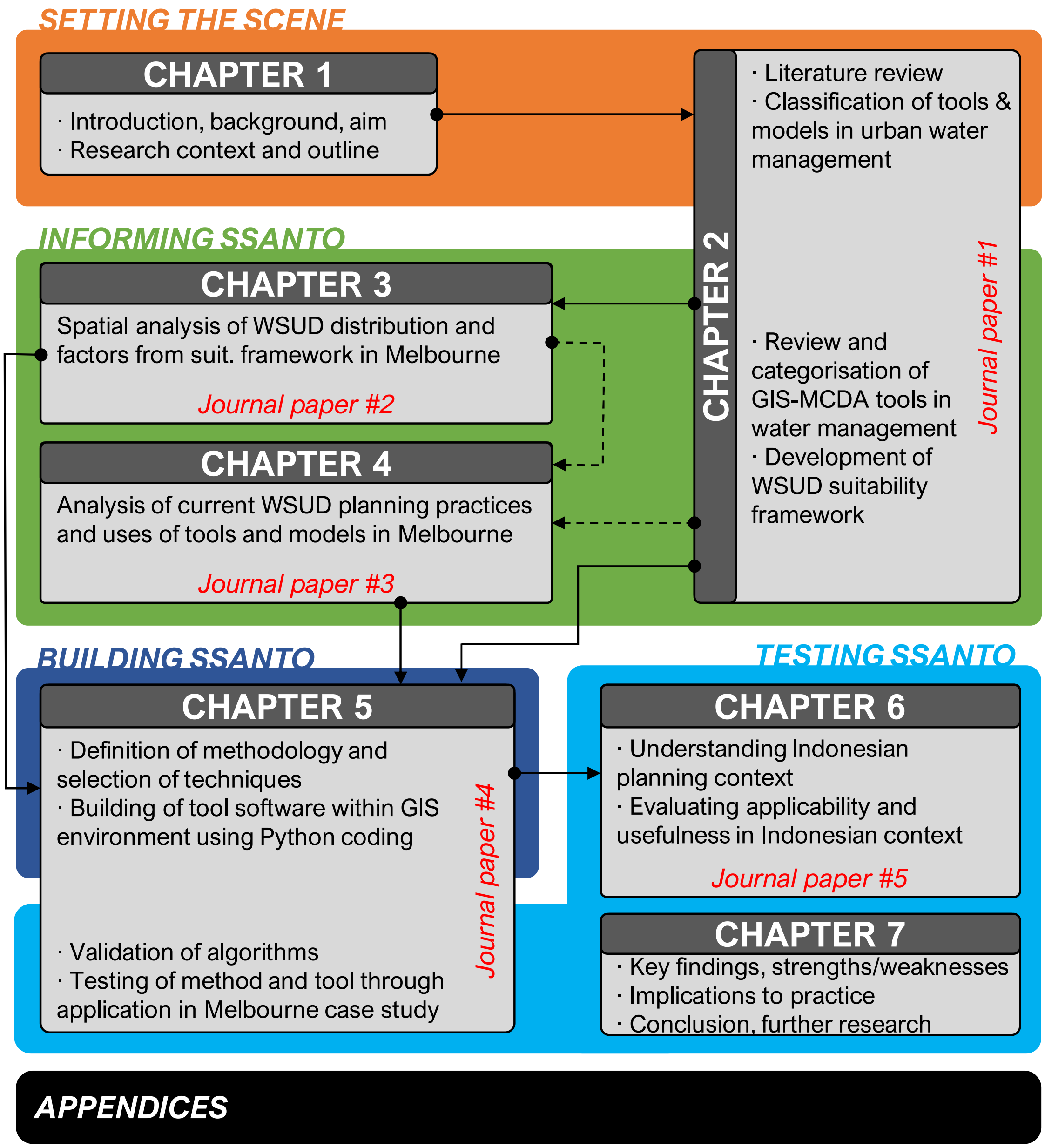

Figure 1-1 Overview of the thesis structure

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CHAPTER 2

LITERATURE REVIEW & SUITABILITY FRAMEWORK

Stille wateren hebben diepe gronden

"Still waters run deep"

2.1 INTRODUCTION

The purpose of this chapter is twofold; (1) critically review literature on WSUD planning support and (2) gather knowledge about the factors impacting on spatial suitability for WSUD to create a suitability framework for WSUD planning. For the former, a broad set of tools, models and frameworks intended to support any stage of the planning and management of urban water systems was reviewed and organised into a typology. For the latter, literature on strategic WSUD planning, technical literature on WSUD systems and ecosystem services literature were systematically reviewed to build the suitability framework. This entire study has been published in *Environmental Modelling & Software* and is included in section 2.2.

The second part of this work, the development of the suitability framework, responds to the first objective of this PhD (section 2.4): **"Create a structured and comprehensive definition of spatial suitability for WSUD placement"**. To this end, this section seeks to answer research question RQ1: *How can we define spatial suitability for WSUD, i.e. which are the relevant spatial contextual factors and the reciprocal relationship that these green systems have with the urban landscape they sit in?*

To answer this research question, the following hypothesis was tested:
H1: Spatial suitability goes beyond traditionally used biophysical factors to include aspects related factors such as to economical, ecological, social and planning factors.

Section 2.3 extracts the main conclusions from the critical review and list the key research gaps that resulted from it. These findings shape the research design of this thesis, which is presented in section 2.4. This critical review covers the core literature of the fields related to the work in this PhD. In addition to this critical review, each chapter separately engages with relevant literature for the associated part of the research. For example, the critical review doesn't specifically discuss the developing context, which is discussed separately in the introduction of the article that forms the core of chapter 6.

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2.2 LITERATURE REVIEW AND SUITABILITY FRAMEWORK

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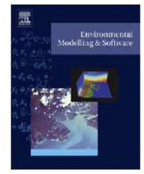

Framing water sensitive urban design as part of the urban form: A critical review of tools for best planning practice

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A B S T R A C T

Spatial planning for green stormwater treatment technologies, known as Water Sensitive Urban Design (WSUD), is a 'wicked' problem which can greatly benefit from the application of Planning Support Systems (PSS). Our review of currently existing WSUD-PSS shows that WSUD is approached from three perspectives: hydrological, urban planning and water governance. As a form of best (urban) planning practice, WSUD requires PSS that regard these technologies as an integral part of the urban form. We argue that suitability of location for WSUD has two sides: 'WSUD needs a place' and 'a place needs WSUD'. No framework or PSS exists that frames WSUD from both sides of suitability. We propose such a suitability framework, building on evidence from literature. Our review found no comprehensive tool or strategy incorporating all relevant factors for suitability analysis. Our proposed framework addresses this gap, and serves as the basis for rigorous WSUD-PSS.

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1. Introduction

Integrated Urban Water Management (IUWM) and Sustainable Urban Water Management (SUWM) principles have emerged in the past decades (Larsen and Gujer, 1997; Mitchell, 2006; Pahl-Wostl et al., 2008; Vlachos and Braga, 2001). Focusing on the urban drainage aspect, numerous similar urban planning and design approaches for distributed, 'green systems' have emerged around the world (Fletcher et al., 2014). These include: Sustainable Urban Drainage Systems (SUDS) (Woods-Ballard et al., 2007), Low Impact Development (LID) (US EPA, 2000), Green Infrastructure (GI) (Benedict and McMahon, 2006), and Best Management Practice (BMP) (US EPA, 2011), Water Sensitive Urban Design (WSUD) (Wong and Ashley, 2006) and Sponge City (MUHORD, 2014). Although there are differences in scope and context between these concepts, their main philosophy is the same: instead of ignoring the natural hydrological cycle, they rely on the "activation of natural processes" (Fryd et al., 2012). Judging from the exponential growth of academic as well as grey literature on this topic, IUWM and SUWM paradigms are gaining momentum, both in academia and practice (Fletcher et al., 2014). This can be explained on two levels: firstly the persistent pressures that continuing urbanisation and climate change exert on our urban systems; secondly - and on a lower level - demonstration of best practice, policy compliance, environmental protection and, to a lesser extent, service constraints of existing infrastructure (Sharma et al., 2012). The latter drives local governments to adopt SUWM practices, as prominently evident in the Singapore example (Tortajada et al., 2013).

WSUD, as an example of a SUWM strategy, is described by Lloyd et al. (2002b) as an approach to urban planning and design that integrates the urban water cycle with the aim to minimise hydrological impact of urban development on its surrounding environment. It is practiced through both structural (green infrastructure systems e.g. raingardens, wetlands) and non-structural measures (i.e. policies aimed at improving efficiency of water use) (Beecham, 2003; Butler and Memon, 2006; Taylor and Wong, 2002). WSUD is associated with the integration of multiple objectives that have traditionally been addressed separately: water security, public health, flood protection, waterway health, amenity, economic vitality, equity and long-term sustainability (Ashley et al., 2004; Fryd et al., 2012; Martin et al., 2007; Wong et al., 2013; Wong and Brown, 2009; Woods-Ballard et al., 2007). Lloyd et al. (2002a, b) outline two fundamental aspects to WSUD: *best management practice* and *best planning practice*. While the former refers to these structural and non-structural measures, the latter refers to urban planning aspects of the implementation of green, distributed systems.

Best planning practice for SUWM as a multi-objective, interdisciplinary and multi-stakeholder problem requires integrative, inclusive and interactive practices in urban planning (Brown et al., 2015; Coutts et al., 2013; Malmquist, 2006; Pahl-Wostl et al., 2008; Van der Brugge et al., 2005). As such, the quality of planning processes ultimately determines the success of distributed systems. This highlights the need to approach WSUD as an urban planning challenge. However, the majority of research focuses on best management practice, such as refining WSUD philosophy, simulating and analysing the performance and potential of green systems and optimising technology engineering (e.g. Beck et al., 2011; Hijosa-Valsero et al., 2010; Payne et al., 2014; Zinger et al., 2013). As a result, we may be confronted with technologically optimised systems that fail to deliver to their potential in practice due to ad-hoc planning and implementation.

This raises the question why the "planning side" of urban water management remains underexposed? The answer may be found in the fact that we are faced with a highly complex planning problem that is beyond conventional infrastructure engineering (Ashley et al., 2004; Cross, 1989; Jin et al., 2006; Makropoulos et al., 2008; Rahman et al., 2012; Rijke et al., 2008; Sakellari et al., 2005). Such problems, characterised by a lack of understanding and lack of agreement both in terms of their causes and solutions, have been called "wicked" problems (Cross, 1989; Klosterman, 1997; Rittel and Webber, 1973).

If we are serious about employing best planning practice for the implementation of green systems, we need frameworks and tools that: (i) consider both primary function and additional benefits of green systems, (ii) conceptualise green systems in terms of their relevant planning aspects, (iii) explicitly link these benefits and planning aspects to a complete set of measurable indicators and (iv) allow for spatially explicit analysis on variable scales. Essentially, there is a need to consider WSUD planning as a *location choice*.

This review aims to improve understanding and promote *best planning practice* for WSUD through the development of a comprehensive planning framework, targeted towards advancements in WSUD planning support (in this paper, WSUD is narrowed to implementation of green stormwater treatment technologies within the urban form). The key objectives of the review are to:

- Organise the diversity approaches to WSUD planning in a typology of tools and models;
- Assess the extent to which WSUD planning is currently approached as a *location choice*;
- Review the use of GIS and MCDA techniques in urban water management, an emerging sub-class of tools designed to support planning processes;
- Rigorously define the 'location suitability' for the implementation of WSUD assets through the development of a suitability framework.

2. Spatial planning of WSUD infrastructure

The integration in the urban landscape causes a multi-faceted reciprocal sensitivity between WSUD systems and their urban surroundings (Rijke et al., 2008): while the WSUD systems' location affect its functioning, the system impacts the function and quality of its surroundings as well. Thus, we define a location's *suitability* for the implementation of WSUD measures to have two sides: (1) the needs of WSUD, answering the question "what do technologies need for optimal functioning?" (in short: ***'WSUD needs a place'***) and (2) the needs for WSUD, answering the question "where is the need for the benefits of WSUD highest?" (***'A place needs WSUD'***). In order for systems to perform optimally, and for the full potential of extra benefits to be exploited, urban planning needs to appreciate and consider the full range of aspects related to WSUD.

2.1. Linking urban planning with WSUD

The high level of complexity in contemporary planning problems causes current planning practices to be reactive and focussed on development control (Downes and Storch, 2014; Lodder et al., 2014). Instead, they ought to be proactive, adaptive and strategic (Benedict and McMahon, 2006; Garschagen and Kraas, 2010; te Brömmelstroet, 2013). Environmental protection has long been compromised as an objective, but is increasingly acknowledged in official planning policy around the world (i.e. Commonwealth of Australia, 1992); European Commission (EC), 2000; Lodder et al., 2014; US EPA, 2002. WSUD responds to this growing focus on sustainability in urban planning, which is expressed both through the process as well as the outcome of urban planning. For WSUD to succeed, the following three principles should be pursued by urban planning:

1. Adopting a more holistic approach which considers all relevant technical, social, economic and environmental factors related to urban design (Ellis et al., 2004, 2008; Garfi and Ferrer-Marti, 2011; Gurran, 2011; Loucks and Gladwell, 1999; Mitchell, 2006; Mitchell and Cleugh, 2006; Vonk et al., 2005).
2. Considering all relevant scales at which the problem is to be addressed (Ahern, 2013; Coutts et al., 2013; Gunderson and Holling, 2001).
3. Engaging all relevant stakeholders in the planning process from an early stage, through effective communication and cooperation (Ashley et al., 2004; Ellis et al., 2004; Lloyd et al., 2002b; Lodder et al., 2014; Lovell and Taylor, 2013; Martin et al., 2007; Melbourne Water, 2005; Tress et al., 2005), and facilitating community participation (Jakeman et al., 2006; Klosterman, 1997; Lodder et al., 2014; Sujatini et al., 2015).

Planning can therefore greatly benefit from tools, frameworks and computational models developed to support the integration of these principles into the planning process (Geertman and Stillwell, 2004; te Brömmelstroet and Bertolini, 2008).

2.2. WSUD technologies

Considering the main philosophy behind WSUD – minimising the impact of development on the natural hydrological system in terms of water flow and quality – WSUD technologies are designed to facilitate the following natural processes to stormwater flows (Ashley et al., 2004; Wong et al., 2013; Woods-Ballard et al., 2007): retention, detention, conveyance, infiltration, evapotranspiration, treatment and harvesting. Although most technologies are primarily designed to fulfil one main function within the treatment train, they often concurrently fulfil several of the other functions. Table 1 provides a list of WSUD systems based on their potential function (Melbourne Water, 2005; Wong et al., 2013; Woods-Ballard et al., 2007), around which our interdisciplinary framework is constructed.

3. Models for supporting WSUD planning

3.1. Identified needs for Planning Support Systems (PSS)

The term Planning Support Systems (PSS) was introduced by Harris (1989) and is defined to "take the form of an information framework that integrates the full range of current (and future) information technologies useful for planning" and "should be designed to provide interactive, integrative, and participatory procedures for dealing with non-routine, poorly structured decisions". PSS and Planning Support Tools (PSTs) are designed to inform and empower planning processes facing wicked problems by enabling organisation, integration and visualisation of data, facilitation of stakeholder interaction and evaluation of options (Geertman and Stillwell, 2004; Lee et al., 2012; Scholz, 2006; te Brömmelstroet and Bertolini, 2008). A good PSS aids the decision-making process with: (1) a deeper understanding of the problem at hand and (2) formulation and communication of ideas, values and preferences between different stakeholders (Ashley et al., 2004). In doing so, long-range and strategic issues are tackled through group interaction and discussion (Klosterman, 1997), thus following the three principles outlined earlier.

The wicked nature of the decision problem calls for the consideration of a wide variety of decision criteria. Although a plethora of useful PSS, PSTs and models for IUWM, SUWM and WSUD were developed in recent years, commitments to incorporate a complete set of factors (biophysical, social, economic, ecological, environmental and legislative) into their design have never fully eventuated (e.g. Jin et al., 2006; Makropoulos et al., 2008). Even if the focus is broader than biophysical factors, the number of indicators used in current tools typically below 10, and their choice poorly justified. Furthermore, spatial explicitness is lacking in the analysis current tools allow for, even when they are GIS-based; instead they assess the suitability of particular systems, after a location has been chosen (e.g. Viavattene et al., 2008). As such, they don't reflect the rise of spatially explicit multi criteria decision analysis tools, or: GIS Multi-Criteria Decision Analysis (GIS-MCDA) that is prominent in other sectors of urban planning (Malczewski and Rinner, 2015c).

Given the crucial role PSS can play in to fulfil the three principles of the planning process, in combination with the identified abundance of PSS available, it may come as a surprise that their uptake in planning practice has been minimal (te Brömmelstroet and Bertolini, 2008). A variety of possible explanations for this 'implementation gap' have been suggested by literature (Geertman and Stillwell, 2004; Klosterman, 1997; te Brömmelstroet and Bertolini, 2008; Viavattene et al., 2008; Vonk et al., 2005): they may be too generic, complex, inflexible, incompatible, technology-rather than problem oriented, focussed on strict rationality and structured output and they may lack the ability for scenario-building, storytelling and visioning, and lack transparency, user friendliness, an interactive nature and communicative value. Furthermore, prospective users may lack knowledge about the existence and potential of PSS, or lack the capacity, resources (data and trained personnel) and trust to use them.

Although these are all plausible causes, they are primarily based on speculation rather than evidence, and clear understanding of the causes behind the lack of uptake is missing. To increase usefulness and thus uptake, tools should be simple and heuristic rather than detailed and precise (te Brömmelstroet and Bertolini, 2008).

Table 1
Overview of WSUD technologies and their functions.

	Retention/ Detention	Convey-ance	Infil-tration	Evapo-transpiration	Treat-ment	Harve-sting
Aquifer storage and recovery			✓		✓	✓
Bioretention & Raingardens	✓		✓	✓	✓	✓
Green roofs	✓			✓	✓	✓
Green walls/Living walls	✓			✓	✓	✓
Infiltration systems			✓		✓	
Oil and sediment separators					✓	
Permeable pavement	✓		✓			
Ponds and lakes	✓			✓	✓	✓
Sand filters					✓	✓
Screens/GPT's					✓	
Sediment basins	✓				✓	
Swales		✓	✓	✓	✓	
Tanks	✓				✓	✓
Wetlands	✓	✓		✓	✓	✓

Unfortunately, this is at odds with what is currently practiced and promoted by many scholars, who call for the adoption and integration of a multitude of tools, each covering just a small aspect of the planning task (Lovell and Taylor, 2013). Systematic research into the implementation and practical use of tools after their development is missing (Geertman and Stillwell, 2012; Vonk et al., 2005). This type of research is urgently needed (not only in the urban water sector, but also the broader planning discipline) if we are to fully capitalise on the potential of PSS in urban planning.

3.2. *A typology for PSSs in WSUD planning*

Although typically not classified as PSS in urban water literature, we can perceive WSUD-PSS to include models, (analysis-) tools, systems, methods and frameworks which can aid the planning processes by analysing, conceptualising, simulating, modelling and communicating the opportunities and performances of the urban water system and green technologies. They are ultimately designed to inform and support the result of planning: policy-making, strategies, regulations and master plans. WSUD-PSS reviewed in this section vary in terms of their scope (entire water system vs single aspect), architecture, interface, functional aim, complexity, scale (entire city vs household), resolution, focus (water quality vs quantity), type (framework vs integrated model), method and level of adoption. Consequently, their role in the planning process and the planning stage in which they are required, varies.

We organise WSUD-PSS using three thematic planes, spanned by the three dimensions used by Fryd et al. (2012) and adapted from Agarwal et al. (2002), Mitchell (1979) and Tjallingii (1996) (see Fig. 1). In correspondence with these thematic planes – biophysical processes, spatial strategies and adaptive strategies – we categorise PSS in their approach towards WSUD: WSUD as part of the urban water cycle, WSUD as part of the urban form and WSUD as part of water governance, respectively.

It should be noted that Fig. 1 presents an overview of the types of models and tools specific to urban water management and thus relevant to WSUD, but by no means aims to present an exhaustive list of PSS that are available around the world. A comprehensive review of integrated urban water modelling can be found in Bach et al. (2014). Furthermore, our categorisation reflects the main purpose and function of a specific PSS. However, many of the models presented here include aspects of several functionalities.

3.3. *WSUD as part of the urban water cycle*

Delineated by the dimensions time and space, biophysical processes have traditionally been the core focus of urban water management, driven by civil engineering innovations. These innovations have delivered safe and secure water supply, clean sanitation, sewage and urban drainage to modern western cities (Brown et al., 2009; Ferguson et al., 2013b). Water systems are efficient and out-of-sight, and taken for granted by urban dwellers. Designing and analysing these urban water systems has a long tradition, and is supported by two types of models: water balance models and hydrological/hydraulic models. In WSUD planning, these models are frequently used during their design and implementation phases.

3.3.1. *Water balance models*

Water balance models simulate total inflow and outflow of water for an analytical unit within a certain timeframe. This analytical unit may be the household, a precinct or an entire city, while the time step may vary from minutes to days. At the highest level, we find tools and studies such as UVQ and its predecessor Aquacycle, which comprehensively consider the total urban water cycle (Mitchell et al., 2001, 2003); the study by Kuller et al. (2015), connecting the stormwater and potable water balances at the scale of a major airport, and City Water Balance, which is used for the analyses of water balance scenarios at the city scale (Last, 2011). Tools that work with multiple units of measurement include UWOT (Makropoulos et al., 2008), which uses different levels of water quality and criteria from the European SWARD project for assessment (Ashley et al., 2004); and Urban Developer (predecessor: UrbanCycle), which has a flexible and modular structure to simulate the water cycle at different spatial and temporal scales (eWater, 2011b; Hardy et al., 2005).

3.3.2. *Hydrological and hydraulic models*

Hydrological and hydraulic models assess and predict flows of water in piped and channelled drainage and sewerage systems. They are widely applied in urban water management, most notably for flood predictions and urban drainage. In terms of WSUD planning, they are used for detailed design of infrastructure components and compliance checking against design standards.

Two very widely applied models for simulating the components of urban drainage systems and calculating hydrological and pollution impacts of certain measures in the urban landscape are SWMM (Rossman, 2010) and MUSIC (eWater, 2011a). They were developed in the United States and Australia respectively and, since their inception, have supported the implementation of WSUD locally and in the rest of the world. Specifically designed for rain tank modelling in Australia, PURRS is also capable of conceptualising the entire urban water cycle (Coombes, 2002). Stormwater BMP Interactive Model is a web-application that can be interactively used. It

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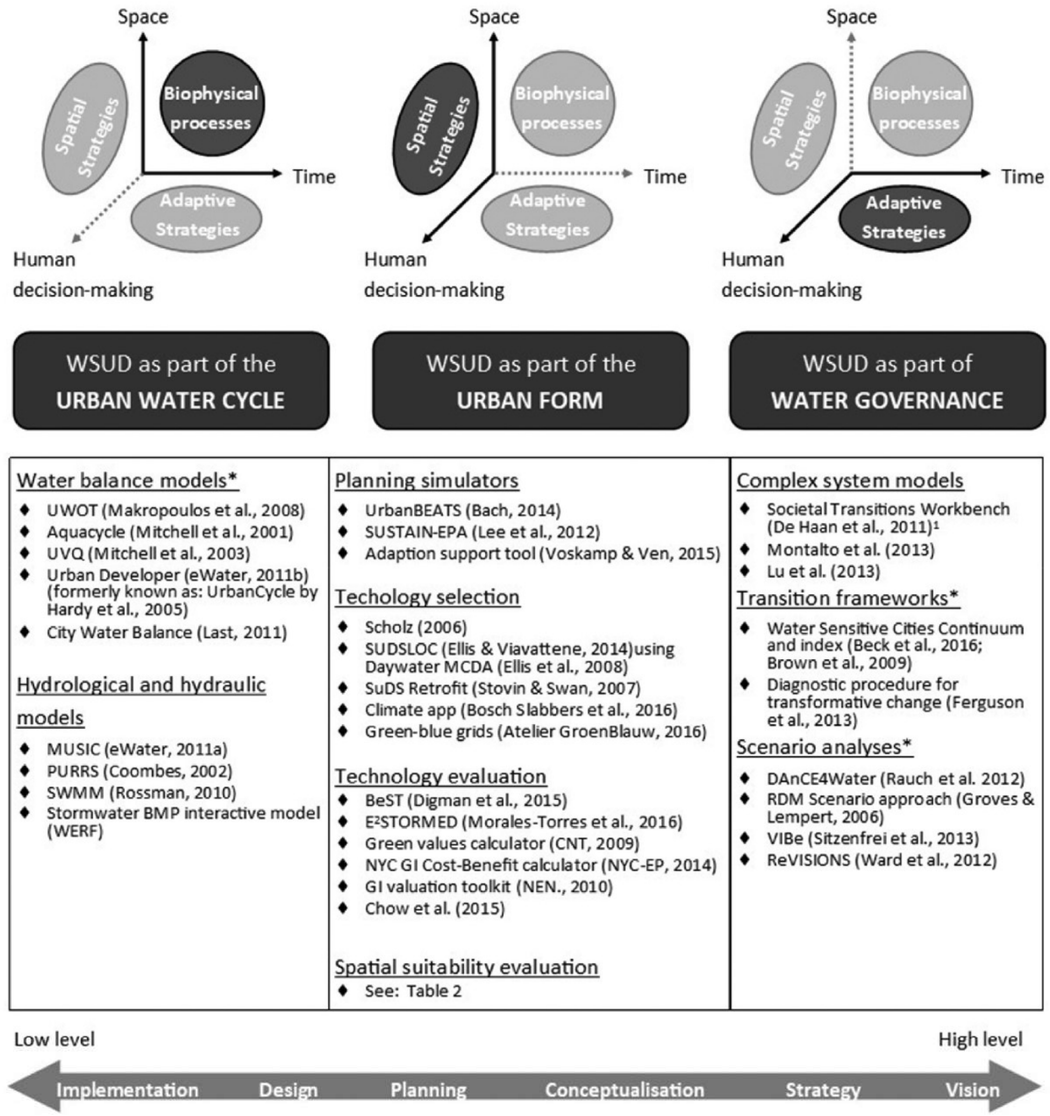

Fig. 1. Typology of (urban) water PSS and PSTs. Top graphs adapted from (Fryd et al., 2012).
*These models are used for a braoder integrated urban water management purpose, rather than WSUD in isolation.

calculates runoff reductions from different management options.

3.4. WSUD as part of water governance

Adaptive strategies are at the highest levels of WSUD planning and include strategic planning and visioning on the metropolitan scale. At this level, delineated by the dimensions of human decision-making and time, the initial ambition to change the fundamental bases our urban water management and planning are built upon is expressed. It is characterised by a focus on systemic, adaptive and long-term change of urban water management. Tools at this level of planning approach WSUD as part of water governance; and include complex system models, transition frameworks and scenario analyses.

3.4.1. Complex system models

Complex system theory is a 'grand theory' with principles that apply to a diverse set of fields, ranging from ecology to sociology and from neurosciences to urban (Batty, 2005, 2010; Scheffer, 2010; Scheffer et al., 2012; Walker et al., 2004). The theory has evolved from resilience theory by Holling (1973) and adaptive systems by Holland (1962), and describes the behaviour of systems, particularly relating to transitions from one stable state to the other. Most useful attempts to model transitions in socio-technical systems were undertaken in the European MATISSE project (Bergman et al., 2008), using the Multi-Level Perspective, originally developed by Rip and Kemp (1998) and further refined by Geels (2002). Although the model framework has yet to be applied to the urban water system, they state the potential of their model to do so. Recently, de

Haan et al. (2016) apply the theoretical framework ‘Multi-Pattern Approach’ from transition theory for exploratory modelling of an urban water management system.

Agent-based models simulate the behaviour of complex and social systems and is gaining increasing popularity in many disciplines. It was found capable of accurately mimicking the behaviour of complex societal systems (Bonabeau, 2002; Macal and North, 2010). Most agent-based models in urban water management focus on simulation of demand-and-supply patterns. However, few have also attempted to model more substantial parts of the urban water system. High-level models have been designed to simulate great societal shifts, such as the ‘Societal Transitions Workbench’ (De Haan et al., 2011). It is grounded in Transitions Theory and draws on the Multi-Pattern Approach, which is used to explain dynamics of transitions in society (de Haan and Rotmans, 2011). Lower level agent-based models include the work of Montalto et al. (2013), who use households as its agents to simulate the spatial uptake of raingardens and green roofs, and the work of Lu et al. (2013), who model the uptake of WSUD under different scenarios, using home-owners, as well as local government and developers as their agents.

3.4.2. *Transition frameworks*

Governance frameworks are generally analogue tools seeking to enable systemic change through conceptualisation of the structure and operation of current urban water systems and their drivers. Apart from contributing to academic insight, they inform policy-making towards governance strategies that steer away from current practice, which is regarded to have undesirable outcomes for society. Examples include the Water Sensitive City Continuum developed by Brown et al. (2009), and its recently developed indexing tool to measure the current ‘transition state’ of a city's water management and sustainability (Beck, 2016). A further tool promotes the transition towards sustainable urban water management (Ferguson et al., 2013a), and provides a platform for planners, policy analysts and decision makers.

3.4.3. *Scenario analyses*

Scenario analysis is a widely applied concept in strategic and visionary planning processes. In a world where uncertainties prohibit reliable predictions, scenarios offer a look into the future by asking the question of what *could* happen rather than what *will* happen. Necessarily, the answer to that question has a multitude of answers, which are explored through scenario exploration.

DAnCE4Water is a complex modelling platform, currently under development (Rauch et al., 2015). It aims to bring together societal, biophysical and urban development aspects and interactions within urban water system transitions to inform adaptive policy making under deep uncertainties.

Groves and Lempert (2007) describe an analytic method derived from an analytic framework for the development of scenarios. Their objective is to enable policy-makers to take *robust* decisions in an uncertain world shaped by climate change. Robust policy is defined as policy that is adaptive and likely to roughly have their anticipated effect under a broad range of possible futures.

Virtual Infrastructure Benchmarking (VIBe) (Sitzenfrei et al., 2013) simulates large numbers of case studies of city systems to analyse their behaviour under different scenarios of growth, climate change and other external factors. This is done virtually, to avoid tedious data gathering associated with the assessment of real world case studies.

The WSUD Toolkit, which is still under development, is a modelling framework that aims to support strategic planning and conceptual design (Dotto et al., 2012). It incorporates WSUD, public health risks, urban heat island, aquatic ecosystem dynamics, governance and environmental economics. It uses scenario simulation and produces performance indicators for urban water systems that incorporate WSUD principles.

ReVISIONS, developed by (Ward et al., 2012), is an integrated modelling framework, performing water balancing for utilities on the neighbourhood scale. It uses socio-economic, land use, transportation, energy and water models. It divides land into tiles, each with specific characteristics and urban form, which impact the water balance. It calculates water parameters for each tile, with the option to include WSUD. The output is used in a multi-criteria assessment (MCA) for the development of scenarios. It has an interactive UI with graphs, maps and dropdown menus.

3.5. *WSUD as part of the urban form*

Spatial strategies are defined by space and human decision-making. Through this lens, we view WSUD planning as a location choice, which is the primary focus of this review. These tools are used during the conceptualisation and planning phases of WSUD. We distinguish four categories of tools based on their function: planning simulation, technology selection, technology evaluation and spatial suitability evaluation. Their highly visual outputs and interactive characteristics provide essential functionality for stakeholder engagement and communication, as well as conceptualisation of options and preferences.

3.5.1. *Planning simulation*

Planning simulation tools have the capacity to simulate spatial layouts of an urban water system, taking into account urban form and hydrology. They are a relatively new phenomenon and consequently less well-known and applied in practice. Two examples of tools equipped with planning algorithms include UrbanBEATS (Bach, 2014) and the ‘siting’ module of SUSTAIN-EPA (Lee et al., 2012). These tools use biophysical factors, urban form and, in the case of UrbanBEATS, planning regulations for the placement of WSUD assets. A certain level of expertise is required to use these systems and the incorporation of expert opinion into their holistic evaluation algorithms is not well catered for. Focusing on laypeople rather than experts is the highly interactive Adaptation Support Tool (Voskamp and Van de Ven, 2015), which allows its users to place systems on a map and evaluates costs and benefits of thus created scenarios.

3.5.2. *Technology selection*

Technology selection tools use MCDA techniques to rate and rank technologies based on their suitability in delivering the required services in certain locations or contexts. They are not spatially explicit as they assess suitability of a technology, rather than location. Therefore, they are applied to rank certain options after the location has been chosen. These tools generally facilitate interaction with the user and expression of certain preferences, thereby catering for cooperation and stakeholder participation. There is a suite of tools available developed in academia as well as outside of academia.

Perhaps the most rigorous model developed in academia so far is SUDSLOC (Ellis and Viavattene, 2014; Viavattene et al., 2008), combining hydraulic and hydrological modelling capabilities, site selection capabilities (which are solely based on biophysical factors) and the technology-specific MCDA (Viavattene and Ellis, 2011; Viavattene et al., 2008). Even though its developers acknowledge its limited number of suitability criteria, it incorporates biophysical as well as socio-economic and planning-related criteria, using the DayWater Multi-Criteria Comparator (Ellis et al., 2008). Less sophisticated are the decision tree and decision matrix of Scholz (2006) and retrofit-SuDS (Stovin and Swan, 2007). While the first is mainly focused on biophysical factors, the latter focuses only on costs. Furthermore, both studies are individual, site specific efforts and have not (yet) been translated into a software that is readily accessible by urban planners.

Web-based tools developed by government and industry include Climate App (Bosch Slabbers et al., 2016), developed by a consortium of the national government and consultancy firms in The Netherlands, as well as GreenBlue Grids (Atelier GroenBlauw, 2016). These web-based applications allow the user to simply select goals, settings and criteria to find (and rank) WSUD technologies to meet them.

3.5.3. Technology evaluation

Similar to technology selection tools, technology evaluation tools use MCDA to assess the multiple benefits of WSUD technologies in general, or for a specific context. These tools can provide quantification, and thereby justification of investments made in WSUD systems.

Several tools are developed to monetise and calculate the economic benefit of WSUD. They include web-based applications developed by government and industry, such as the NYC GI Co-Benefits Calculator (NYC-EP, 2014), as well as excel based tools like the GI Valuation Toolkit (NEN et al., 2010) and BeST (Digman et al., 2015), and multi-criteria frameworks like the KPI framework by Chow et al. (2014). They attempt to capture a wide array of services provided by these systems such as amenity values, ecological values and flood mitigation. The Green Values Stormwater Management Calculator combines calculating hydrological outcomes of systems types and management options, as well as financial outcomes (CNT, 2009). E^2STORMED (Morales-Torres et al., 2016) takes an even more comprehensive approach, evaluating drainage scenarios based on not only economic criteria, but also socio-economic, environmental and even energy-related criteria.

Rather than focusing on WSUD, the MCDA assessment method of Benzerra et al. (2012) focuses on the sustainability performance of conventional urban drainage (and therefore excluded from Fig. 1) in Algeria. It responds to the lack of research relevant to contexts where WSUD is not widely applied (yet).

3.5.4. Spatial suitability evaluation

Spatial suitability is assessed through GIS-MCDA. This is a spatially explicit method for suitability assessment of locations for the introduction of WSUD. Gurran (2011) emphasises the need for strategic planning to be spatially explicit and the related need for an assessment framework that enables spatial analysis. Although optimisation and decision-making are supported by GIS-MCDA, its critical value lies in its ability to perform spatially explicit assessment and produce highly visual outputs which are intuitively interpreted, such as heat maps. It provides the option to include large numbers of varying factors (decision criteria), has flexibility of scale, ease of use, visual and intuitively interpretable output (Ashley et al., 2004; Ellis et al., 2008; te Brömmelstroet and Bertolini, 2008; Wenzel, 2001), combined with a simple, flexible and interactive nature that fully caters for the introduction of preferences and values by experts and lay people alike. As such, the method has great potential to satisfy the three principles for good WSUD planning practice, identified in section 2.1. Therefore, special attention is given to this type of PST in this review.

Methodologically, GIS-MCDA is the process of graphically representing spatially explicit multi-criteria information through the coupling of Geo Information Systems with multi-criteria analysis techniques. Generally this process includes four steps (Malczewski and Rinner, 2015a): (1) value scaling: translating criterion data to suitability values, (2) criterion weighting: assigning relative weights to each criterion, (3) combination rules: combining criteria values and weights to calculate a suitability value and (4) spatial representation: drawing a suitability map. For each of these steps, a multitude of techniques have been developed, depending on the decision at hand. They either cater for multi-attribute or multi-objective decision analysis and their level of complexity varies in terms of risk-aversion, expression of the decision-maker's values and experiences (Tkach and Simonovic, 1997), spatial explicitness and accuracies (Malczewski and Rinner, 2015b, d).

GIS-MCDA has been widely applied in suitability mapping to determine the optimal location in matters related to spatial planning (Malczewski and Rinner, 2015c). The technique has been applied to (urban) water management issues in several studies, summarised in Table 2. Their level of complexity varies in terms of applied techniques (methodology) and criteria included as well as their field of focus. Traditionally, suitability analysis had a strong focus on biophysical factors, disregarding socio-economic, environmental and planning-related factors. As previously mentioned, evidence for the need to include a wider variety of suitability factors is overwhelming in planning as well as WSUD literature, including the assessments and tools in Table 2. Nevertheless, even when this need is explicitly acknowledged, most tools and assessments neglect to incorporate this crucial complexity (e.g. Inamdar et al., 2013; Jin et al., 2006; Kahinda et al., 2008; Rahman et al., 2012; Sekar and Randhir, 2007).

An assessment of 16 GIS-MCDA exercises in water management shows that there is no study or tool which combines a high complexity of factors with a high complexity of methodology (Table 2). Only three tools combine the integration of a medium or high complexity of factors with medium or highly complex method of analysis. Out of these three tools, Makropoulos et al. (2008) only looks at demand management. Although a fairly high number and variety of factors (19) are used by GreenPlanIT (Fronteira et al., 2014), it is still in early stages of development at the time of this review. Furthermore, the output only distinguishes between 'suitable' and 'unsuitable', which leaves little space for nuance and communication of preferences. The work of Viavattene et al. (2008) produces discrete outputs which reduces its spatial explicitness and thereby its communicative value. None of the reviewed studies were found to focus on the two aforementioned sides of suitability, but rather limit themselves to answering 'what WSUD needs', i.e. favourable conditions that are compatible with chosen WSUD technology. Furthermore, there is little to no literature reporting on their systematic application to support a real-world planning process (some studies of retrospective cases have been documented).

The review above reveals that we lack user friendly, flexible and heuristic but methodologically rigorous tools, which considers the full spectrum of suitability factors. A possible explanation may lie in the tendency for planning processes and planning tools to lose transparency and user friendliness with increasing complexity. At the same time, accuracy and interpretability of their output may diminish. Nevertheless, these reasons should not result in a general disregard the complexity of reality by ignoring aspects which are expected to impact WSUD planning. Therefore, we need tools that generate easily interpreted but nuanced output, allowing for reflection and communication of preferences and values to their users, lay people and experts alike. The first and critical step towards such tools is the development of an evidence-based framework of relevant, spatially explicit factors that do, or could potentially influence WSUD location choice.

4. WSUD planning suitability framework

We have already defined the 'suitability for WSUD' to encompassing two aspects: 'WSUD needs a place' and 'a place needs WSUD', highlighting the reciprocal relationship between green

Table 2
Categorisation of GIS-MCDA assessments and tools in water related research and their characteristics: Complexity of factors refers to the number and variety of factors that are included: only one type (e.g. biophysical) or many types? Complexity of methodology refers to the GIS-MCDA techniques applied: ranging from spatially inexplicit to highly explicit and from using only simple weighted linear combination to including several types of analysis and optimisation techniques.

Complexity of factors	Complexity of methodology	Type (name)	Application[a]	References
Low	Low	Assessment	Water Harvesting	(Singh et al., 2009)
		Assessment	Rainwater Harvesting	(De Winnaar et al., 2007)
		Assessment	Rainwater Harvesting	(Kumar et al., 2008)
		Tool (EPA SUSTAIN)	Integrated Urban Water Management	(Lee et al., 2012)
	Medium	Tool (Flext)	**Water Sensitive Urban Design**	(Jin et al., 2006)
	High	Tool	Aquifer recharge (flexible)	(Rahman et al., 2012)
		Tool	Flooding (flexible)	(Ozturk and Batuk, 2011)
Medium	Low	Assessment	Water Harvesting	(Sekar and Randhir, 2007)
		Assessment (SUDS decision-support matrix)	**Water Sensitive Urban Design**	(Scholz, 2006)
		Assessment (Rainwater Suitability Model)	Rainwater Harvesting	(Kahinda et al., 2008)
	Medium	Assessment (Water Opportunity Map)	Integrated Urban Water Management	(Cerreta et al., 2013)
		Assessment *(INDEGO)*	Integrated Urban Water Management	(Brotchie et al., 2014)
	High	Tool (UWOT)	Water Demand Management	(Makropoulos et al., 2008)
High	Low	Tool (Werra River Basin Management)	River Basin Management	(Hirschfeld et al., 2005)
	Medium	Tool (SWITCH BMP decision support system)	**Water Sensitive Urban Design**	(Viavattene et al., 2008)
		Tool (GreenPlanIT)	**Water Sensitive Urban Design**	(Fronteira et al., 2014; GreenPlan-IT, 2015)
	High			

[a] WSUD in bold, as the focus of this paper.

technologies and their urban context. Existing models and frameworks incorporate only part of our proposed definition and, consequently, are limited in guiding the planning and implementation of this infrastructure. This section proposes a new framework that aims to inform, support and promote rigorous urban planning and decision making for WSUD – either through direct application or incorporation in novel planning support tools. We define and present the framework according to these two aforementioned aspects.

Despite its level of detail, we do not claim our framework to be exhaustive. Nevertheless, its large number of factors provides the user with necessary redundancy to select and choose between factors pragmatically, based on data availability and local context. One limitation of the framework is the relatively limited evidence base for some of the listed factors. Future studies should seek to test their relevance.

4.1. *WSUD needs a place*

Table 3 presents a comprehensive list of factors relevant to urban planning and their corresponding indicators. A great number of location-dependent site characteristics impact on operation of WSUD systems. These characteristics, or factors, are relatively well understood and widely recognised and used in implementation guidelines and PSTs (e.g. Armitage et al., 2013; Ellis et al., 2008; Martin et al., 2007). Different categorisations are suggested in the literature on green infrastructure planning. However, to avoid overlaps between factor categories and thus increase clarity, we identify three broad and distinct categories: (1) *biophysical*, (1) *socio-economic* and (3) *planning & governance* (Table 3).

4.1.1. *Biophysical*

For this review, the term 'biophysical' refers to all directly visible and tangible aspects of a landscape, both naturally occurring and man-made. They include aspects related to soil, slope, hydrology, climate, urban fabric and ecosystem type. Biophysical factors are the best represented category in literature, the primary focus of most implementation guidelines and suitability studies and as such, are reasonably well understood and agreed upon (Armitage et al., 2013; Ellis et al., 2008; Ellis and Viavattene, 2014; Goldenfum et al., 2010; Kahinda et al., 2008; Lee et al., 2012; Melbourne Water, 2005; Ozturk and Batuk, 2011; Rahman et al., 2012; Scholz et al., 2006; Woods-Ballard et al., 2007).

Soil type and hydraulic conductivity are relevant to any WSUD asset that relies on infiltration (e.g. Fryd et al., 2012; Martin et al., 2007; Melbourne Water, 2005). This factor becomes prohibitive in areas of low hydraulic conductivity. Similarly, high soil storage capacity is favourable to WSUD types depending on infiltration (Ellis et al., 2008). In terms of water quality, soil contamination (e.g. heavy metals) can be problematic for these types of systems, as infiltrating water and organic acids may mobilise and spread contamination over a larger area (Nieber et al., 2014; Woods-Ballard et al., 2007).

Steep slopes are prohibitive to most WSUD types (Melbourne Water, 2005; Woods-Ballard et al., 2007). Some technologies can be adapted to gentle slopes, like swales. However, for most asset types slopes are unfavourable.

Local hydrological features are critical. Quantity and quality of the water flow passing through a WSUD asset dictate its design, and vary depending on asset location within the natural drainage system as well as the contributing (impervious) catchment area (Bach et al., 2013; Lloyd et al., 2002a). Climate patterns also drive the quantity and quality of water that is received by an asset. Total rainfall, frequencies, peak flows and dry periods are all considered in WSUD design (Beecham and Chowdhury, 2012; Bolund and Hunhammar, 1999; Lloyd et al., 2002a, 2002b). Extended dry periods require the use of drought tolerant plant species and has negative effects on water quality (Lee et al., 2004; Mangani et al., 2005), while tropical rains can lead prolonged inundation of systems (Goldenfum et al., 2010). Local temperatures govern plant selection and evapotranspiration, which are relevant to certain WSUD types (Denich and Bradford, 2010; Roehr and Fassman-Beck, 2015; Schroll et al., 2011). The available flora and conditions of the local ecosystem are potential limiting factors for green technologies (Ellis et al., 2008; Simmons et al., 2007). For example, salt tolerant plant species should be selected for WSUD design in coastal areas with seawater intrusion (Szota et al., 2015).

Finally, man-made landscape features also play a role. Some technologies favour or require specific urban fabrics. For example, green roofs are built on (flat) suitable rooftops. Permeable pavements are favoured in parking lots, sidewalks and areas of low traffic (Goldenfum et al., 2010; Tennis et al., 2004). Accessibility of

Table 3
'WSUD needs a place'. Factors determining the suitability of a location from the perspective of technology operation. Indicator: in bold: the indicator is can be prohibitive for the placement of WSUD; underlined: the indicator has been identified as important for the suitability and is recognised in literature; normal: this indicator is of secondary importance or its relevance is disputed/not well represented in literature. Scale variability: 1: varies with exact location, 2: varies with precincts, 3: varies across neighbourhoods/sub catchments, 4: varies with city district/urban catchment, 5: Varies between cities.

Category	Factor	Indicator	Scale variability
Biophysical	Soil	**B1: Type**	1
		B2: Hydraulic conductivity	1
		B3: Storage Capacity	1–3
		B4: Contamination	1
	Slope	**B5: Slope rate**	1
	Hydrology	B6: Topography (natural drainage channel)	1
		B7: Stream characteristics & condition	3
		B8: Contributing impervious catchment area	3
		B9: Proximity to receiving water body	1
	Climate	B10: Rainfall averages	1–5
		B11: Rainfall extremes	1–5
		B12: Rainfall variability	1–5
		B13: Temperature	5
		B14: Evapotranspiration	1
	Urban fabric	**B15: Roof surface areas**	1–3
		B16: Pavement/parking areas	1–3
		B17: (Public) open space	1–3
		B18: Maintenance: road accessibility	1
	Ecosystem type	B19: Available vegetation	5
		B20: Structure	3–5
Socio-economic	Waste management	SE1: Regular solid waste collection Yes/No	3–5
		SE2: Advanced sanitation/open defecation	3–5
	Demographics	SE3: Income	2
		SE4: Density	2
		SE5: House price	2–3
	Public awareness and values	SE6: Green votes	3
		SE7: Behavioural/attitudinal survey results	2
		SE8: NGO membership	2–3
		SE9: Education level	2
	Social cohesion	SE10: Volunteering	2–3
		SE11: Community club membership	2–3
	Political stability	SE12: Rate of change	4–5
		SE13: Government control and enforcement	4–5
		SE14: Political responsiveness	4–5
Planning & Governance	Land availability	**PG1: Land value**	1–3
		PG2: Ownership type (public/private)	1
		PG3: Ownership: single/multiple occupancy	1
		PG4: Land zoning	1–3
		PG5: Resistance to land-use change	3
	Development opportunity	PG6: Renewal cycles	1–3
		PG7: Priority development areas	3
		PG8: Organisational capacity	4
		PG9: Planning overlays	1
	Development constraint	**PG10: Presence of utility infrastructure**	1
		PG11: Presence of building foundation	1
		PG12: Planning overlays	1
	Development type	PG13: Greenfield	3
		PG14: Brownfields	1–3
		PG15: Infill	1

WSUD assets for regular maintenance is required, depending on the required machinery and equipment (Ellis et al., 2008; Woods-Ballard et al., 2007).

4.1.2. Socio-economic

Socio-economic factors can be understood as the invisible, non-physical urban landscape. They include factors describing the urban social structures such as demographics, socio-economic status and human perceptions. Although some of these factors have been acknowledged to impact the planning of green technologies (e.g. Ashley et al., 2004; Ellis et al., 2004; Garfi and Ferrer-Marti, 2011; Gurran, 2011; Inamdar et al., 2013; Jin et al., 2006; Kahinda et al., 2008; Loucks and Gladwell, 1999; Makropoulos et al., 2008; Martin et al., 2007; Mitchell and Cleugh, 2006; Rahman et al., 2012; Sofoulis, 2010; Vonk et al., 2005) few have included them in their analysis. No study was found that systematically considers a wide range of socio-economic factors.

The presence and frequency of operation of a solid waste management system is essential for the operation of certain WSUD types, such as bioretention systems. In informal settlements in Latin America, Africa and Asia, the absence of such a system results in severe littering, clogging and ultimately destructing green technologies (Hazra and Goel, 2009; Sam Jr., 2002; Tucci et al., 2010; Yap and Thuzar, 2012). Poor sanitation and open defecation in tropical regions in combination with stagnant water in WSUD constitutes a public health risk (Goldenfum et al., 2010).

Population density influences suitability through several channels: high population density is typically related to higher levels of imperviousness (Fronteira et al., 2014; Stankowski, 1972; Wu and Murray, 2003). Furthermore, it translates into increased water demand as well as greater potential for human interference with systems. Income and house price relate to suitability, as green space is more likely to appeal to groups of higher socio-economic status (de la Barrera et al., 2016; Healthy Waterways Partnership, 2005; Morgan, 2013; Torgler et al., 2012). Furthermore, higher house prices reflect higher land value, impacting the costs of implementing WSUD.

Public awareness and values underlie the level of receptivity of a community towards WSUD and its interaction with systems in their neighbourhood. It has been identified as one of the greatest barriers to the uptake of WSUD (Ashley et al., 2004; Bennett and Murphy, 1997; Brown and Keath, 2008; Sharma et al., 2012; Strang, 2001; Thompson and Maginn, 2012). Because this factor cannot be directly measured, it is estimated; either directly by asking people in surveys and interviews, or using *proxies* (measurable indicators, which are hypothesised to represent the subject of interest) (Anderson, 1998; Cross, 2005; Torgler et al., 2012). Examples of proxies — whose validity is often under debate — include: income, political voting behaviour, education level, membership of community and advocacy groups and organisations (Chiesura, 2004; Dolnicar et al., 2011; Domènech and Saurí, 2010; Leogrande and Jeydel, 1997; Mell, 2009; Torgler et al., 2012). It should be noted that environmental awareness as well as norms and values have a reciprocal relationship with WSUD, as people may change after learning about the underlying principles and objectives of WSUD after being exposed to them (Bohner, 2002; Dobbie, 2015).

Social cohesion impacts the way a community uses and takes care of its surroundings (Uzzell et al., 2002). Similar to public awareness and values, this can only be measured using proxies, such as the number of people partaking in volunteering work and levels of membership of social and recreational clubs (Torgler et al., 2012).

Politically stability is favourable to novel types of urban planning and management, which requires strong and ongoing commitment from government and support from political organisations. Without this, the chance of WSUD failure is significant (Goldenfum et al., 2010). Indicators include changes of administration, and political and institutional responsiveness to new developments in society (Allan, 2015; Brown et al., 2007; Brown and Keath, 2008; Feiock, 2004; Innes, 2015), as well as the level of governmental control and support (Goldenfum et al., 2010; Rini et al., 2014). However, measuring these indicators is not a straightforward task.

4.1.3. Planning & governance

This category refers to all rules, regulations, laws and other invisible constructs aimed at governing or guiding current and future use and development of the urban space. They can be anchored in laws and legislations or specified in planning codes, master plans, ordinances and guidelines. They include factors of land availability, development opportunity, development constraints and development type. Although they are often recognised in academic literature (e.g. Bach, 2014; Lee et al., 2012; Martin et al., 2007; Sharma et al., 2012), their practical nature makes them more relevant in detailed statutory planning practice and hence are usually not the prime focus of academic studies.

Land availability depends on land value, ownership structure, zoning and land-use stability (i.e. its resistance to change over time due to redevelopment). High land values or reluctance of land owners can prohibit the placement of green space and WSUD (Olaleye et al., 2013; Rini et al., 2014; Thompson and Maginn, 2012). Land owned by multiple parties further complicates land acquisition for WSUD development (Scholz et al., 2006; Williams et al., 2010). Governmental planning agencies make zoning plans to steer land use. Zoning plans either promote, discourage, dictate or prohibit certain types of developments, which may have an impact on WSUD (Levy, 2015; Thompson and Maginn, 2012). Furthermore, relatively stable land use favours WSUD development. Particularly unstable locations, such as informal settlements in developing cities, may therefore pose problems (Goldenfum et al., 2010; Zhou and Wang, 2011).

Opportunities for development of WSUD may arise from land zoning, but also from other planning measures, such as overlays and priority development areas (Fronteira et al., 2014; Gurran, 2011). Furthermore, opportunities may arise from renewal cycles and high organisational capacity and coordination (Brown and Clarke, 2007; Fronteira et al., 2014; Lloyd et al., 2002a). Speculation suggests that planning agents may take an opportunistic approach towards the implementation of WSUD, capitalising on windows of opportunity (e.g. road repair and maintenance works) to co-implement green technologies.

Some of the factors that provide an opportunity for the development of WSUD, can instead also constrain it. Zoning and planning overlays often prohibit its development, for example around sacred or protected sites (designated by a heritage overlay). Technologies should not be placed in the vicinity of building foundations or utility infrastructure such as gas pipes and electricity lines, as their construction and operation might cause damage (Brotchie et al., 2014; Ellis et al., 2004; Fronteira et al., 2014). Finally, the type of development in which WSUD is to be implemented impacts on suitability. Type and size of WSUD assets that can be implemented differs significantly between greenfield development (developments on land with a non-urban former land use), brownfield development (redevelopment of land with a different, but urban former land use), and infill (implementation of WSUD into otherwise unchanged developments) (Biddle et al., 2006).

4.2. A place needs WSUD

Table 4 presents the factors related to the other side of suitability: 'a place needs WSUD'. While the previous section dealt with the *efficiency* of WSUD in a location, this side of suitability relates to its *effectiveness*, related to the objectives for WSUD in the context of their multiple benefits. Demand for these benefits varies spatially. We organise them following literature on "ecosystem services": "direct and indirect contributions from ecosystems to human well-being" (TEEB, 2010). They have been the subject of study in an interdisciplinary and highly cited field of academia for decades (Lodder et al., 2014). De Groot et al. (2002) were one of the first to categorise these services. Their adapted typology was adopted by the United Nations and can be considered as the current standard (MEA, 2005).

Originally used to evaluate services from the world's great ecosystems (e.g. Costanza et al., 1997), the concept started to be applied to services from urban green spaces as initiated by Bolund and Hunhammar (1999). Over the past decade, evidence is rapidly growing that these green urban infrastructures provide significant and long-term local value due to the high density of beneficiaries relative to the system size in cities (Gómez-Baggethun and Barton, 2013). Comprehensive studies and typologies of urban ecosystem services were developed (Balvanera et al., 2006; Bolund and Hunhammar, 1999; Boyd and Banzhaf, 2007; Gómez-Baggethun and Barton, 2013; Liu et al., 2010) mainly focusing on identifying, quantifying and measuring these services. Although ecosystem services have been linked to water in the urban environment (Lundy and Wade, 2011), a coherent, spatially explicit framework linking ecosystem services to urban planning and WSUD is absent in literature to the authors' knowledge.

Table 4 presents such a comprehensive list of urban ecosystem services relevant to urban planning. Our typology links these

Table 4
'A place needs WSUD'. Factors determining the suitability of a location from the perspective of the 'needs' of a location. Classification of the ecosystem functions, ecosystem services and factors as adopted from the UN 'Millennium Ecosystem Assessment' (MEA, 2005). Indicator: in bold: the indicator represents a primary objective of WSUD, and the technology shouldn't be built if it doesn't meet these criteria (needs); underlined: the indicator represents the secondary benefits that are typically related to urban green and blue spaces, which are widely documented to exist, but are not the prime reason to build WSUD systems; normal: this indicator is of secondary importance and/or its relevance is disputed/not well represented in literature. Scale variability: 1: varies with exact location, 2: varies with precincts, 3: varies across neighbourhoods/sub catchments, 4: varies with city district/urban catchment, 5: Varies between cities.

Ecosystem functions	Ecosystem services	Factor	Indicator	Scale variability
Provisioning	Food production	Food security	P1: Lifestyle	2–3
			P2: Malnutrition (quantity and quality)	3–5
	Fresh water supply	Supply coverage	<u>P3: No. of h/h with potable supply access</u>	3–5
			<u>P4: No. of h/h with non-potable supply access</u>	3–5
			P5: Proximity to demand	1
		Scarcity	**P6: Demand vs supply**	5
			P7: Reliance on non-replenishable supply	5
Regulating	Gas regulation	Air quality	R1: Levels of air pollution	1–5
		Carbon sequestr.	R2: CO_2 equivalent	5
	Climate regulation	Urban Heat Island	<u>R3: Relative temperature increase°C</u>	1–5
			<u>R4: Number of extreme heat days</u>	5
			<u>R5: Heat-related mortalities & morbidities</u>	3–5
	Water regulation	Urban Drainage	**R6: Connected Impervious area**	3
			<u>R7: Flow regime</u>	3
			R8: Presence of centralised drainage infr.	3–5
			R9: Capacity of centralised drainage infr.	3–5
	Water purification	Receiving water	**R10: Water quality (chemical and biological)**	3–5
		Pollution loading	<u>R11: Land use</u>	3
			R12: Direct sewage discharge	3
			R13: Number of annual CSO spills	3
	Natural hazard	Flood control	**R14: Observed flood occurrence**	1–5
			R15: Flood risk from models	1–3
Cultural	Aesthetic/inspiration-nal/educational values	Accessibility/ Visibility	<u>C1: Street activity/visibility</u>	1
			<u>C2: Vicinity Civic land use</u>	1
	Social relations	Demographics	C3: Age	2
			C4: Income	2–4
			C5: Population density	2–3
			C6: Educational level	2–3
		Social cohesion	<u>C7: Volunteering</u>	2–3
			<u>C8: Local social club membership</u>	2–4
			<u>C9: Rates of antisocial behaviour</u>	2–3
	Recreation	Green open spaces	<u>C10: Proximity</u>	1
Habitat or Supporting	Refuge habitat	Distribution of green/blue space	**HS1: Provision levels**	3–5
			HS2: Protection status	1
			<u>HS3: Connectedness</u>	1
		Flora/Fauna Health	HS4: Biodiversity	1–3
			HS5: Species population size	3–5

services to spatially explicit indicators with their corresponding scales of impact and measurement. Even though some of the evidence that directly informed this typology does not relate to WSUD specifically, it can be applied to all types of urban green space. Table 4 aligns to the UN framework (MEA, 2005), but services for which literature suggests limited or no relevance to the context of suitability for sustainable urban water management were excluded. To the best of our knowledge, this is the most elaborate attempt to explicitly place WSUD in the bigger context of ecosystem services literature. This is an important step, as sustainable urban water management can draw on insights from this field while tapping into a wider academic community concerned with sustainable (urban) landscapes. It enables policy-makers as well as academia to adopt a more holistic approach towards urban water management as one part of urban environmental management.

4.2.1. Provisioning

These services relate to the products people obtain from ecosystems (MEA, 2005). In terms of urban ecosystems and WSUD technologies, products obtained from ecosystems are mostly limited to food and, most importantly, fresh water.

Food supply through urban agriculture has long been present, and still is in many African and Asian cities (Drakakis-Smith, 1991). The practice is gaining popularity in developing as well as developed cities around the world, as urban dwellers become aware of their increasing dependence on surrounding rural lands for their food supplies and related vulnerability (Endres and Endres, 2009; Mougeot, 2006; Smit et al., 2001). While novel WSUD technologies that are able to produce food crops, are gradually emerging (Tom et al., 2013), 'conventional' WSUD assets can currently provide urban agriculture through irrigation water supply (Moglia, 2014). Since the relationship between WSUD and urban agriculture is a relatively new field of academic interest, it is not yet well described in the literature. As such, suitability factors are speculative, but might relate to people's lifestyle and their attitudes towards urban agriculture as well as local quality, availability and affordability of food and related malnutrition (Drescher, 2002; Mougeot, 2006).

For some types of WSUD with water supply augmentation as the primary function (e.g. rainwater tanks) (Fletcher et al., 2008; van Roon, 2007), their potential is greater in places with low supply coverage and places suffering from water scarcity. Supply coverage can be measured through the number of households with access to potable and non-potable water supplies, as well as the proximity to other types of water demand such as irrigation (Bakker et al., 2008; Brotchie et al., 2014). Scarcity is measured as the difference between demand vs. replenishable supply and reliance on non-replenishable water supplies ('fossil' water from aquifers), while urgency of the problem is measured through levels of aquifer depletion (Postel, 2000; Rodell et al., 2009).

4.2.2. Regulating

Services in this category relate to the benefits obtained from ecosystems through their regulation of processes essential to and effecting our daily lives (MEA, 2005). These processes include gas, climate and water regulation as well as water purification.

Urban vegetation (particularly trees) is known for its ability to purify air from toxic gases and particles like ozone (O_3), sulphur oxides (SO_X), nitrogen oxides (NO_X), carbon monoxide (CO), and fine dust (PM-10) (Escobedo et al., 2008; Nowak, 1994). Some authors have even claimed its importance for sequestration of the greenhouse gas carbon dioxide (CO_2) (Ahern, 2013; Lovell and Taylor, 2013; McPherson and Simpson, 1999).

Although urban green and blue spaces don't have the kind of impact on our climate that is attributed to the world's forests and oceans, they are well-known for their local cooling effect and mitigation of the urban heat island (Bolund and Hunhammar, 1999; Hardin and Jensen, 2007; Lovell and Taylor, 2013; Rosenzweig et al., 2006; Steeneveld et al., 2014), including WSUD systems (Coutts et al., 2012; Mitchell and Cleugh, 2006). The severity of the urban heat island effect, and thus the need to mitigate it, can be measured by the temperature increase relative to the surrounding rural areas, the number of extreme heat days and the number of heat related morbidities and mortalities (Fronteira et al., 2014; Streutker, 2003; Tan et al., 2010).

Water regulation is a service provided by all WSUD, and main design purpose of most technology types. WSUD as a concept is developed to provide alternatives to traditional piped urban drainage, as discussed earlier in this review. The need for WSUD is therefore primarily driven by (connected) impervious area, the presence and capacity of centralised drainage infrastructure as well as the local flow regime (Bolund and Hunhammar, 1999; Brotchie et al., 2014; Burns et al., 2015; Fronteira et al., 2014; Gómez-Baggethun and Barton, 2013; Melbourne Water, 2005).

Purification and treatment of urban runoff is, together with water flow regulation, the main design purpose of most WSUD technologies. The need for purification of urban runoff depends on its pollution loading as well as the regenerative capacity of receiving water bodies (Walsh et al., 2004a, 2004b). The need for WSUD is measured through physical and biological water quality of receiving waters, including the concentration of pathogens, as well as pollution assimilation. Pollution loading depends on land use, the presence of direct sewer discharges, open defecation and the number of annual combined sewer overflows (CSOs) (Bolund and Hunhammar, 1999; Lau et al., 2002; Lloyd et al., 2002a).

Besides providing urban drainage in normal weather situations, WSUD also mitigates and limits the impacts of extreme rainfall events. Flood control is one of the main design purposes of such technologies (Lloyd et al., 2002b; Mitchell et al., 2007; Wong and Brown, 2009).

4.2.3. Cultural

Cultural services relate to the nonmaterial benefits that people attribute to the aspects of ecosystems, including spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences (MEA, 2005).

Aesthetical and educational services are only enjoyed by people if the WSUD assets are accessible and visible. Therefore, locations near high levels of street activity and the vicinity to public places like civic land uses are considered highly suitable (Brotchie et al., 2014; Lloyd et al., 2002b; Lovell and Taylor, 2013; Mell, 2009). The importance of aesthetic value related to urban vegetation in general (Bolund and Hunhammar, 1999; Dobbs et al., 2011; Jackson, 2003; Smardon, 1988; Ulrich, 1986) and WSUD in particular (Backhaus and Fryd, 2013; Dobbie and Green, 2013; Lundy and Wade, 2011; Rijke et al., 2008; Sharma et al., 2016) is widely acknowledged in literature. Urban green space has a positive effect on mental and physical health (Ahern, 2013; Chiesura, 2004; Jackson, 2003; Lee and Maheswaran, 2011; Lovell and Taylor, 2013; Maas et al., 2006; Mell, 2009). Visible WSUD assets can educate people about the urban water system by making it an integral part of the urban landscape, thus removing it from its traditional invisible, underground position (Ashley et al., 2004; Lundy and Wade, 2011; Rijke et al., 2008; Segaran et al., 2014). Because "out of sight is out of mind", this is also expected to improve the lacking awareness with communities about the importance of (and the problems related to) urban water management.

Positive effects of urban green space on social cohesion within communities, through provision of public space for interaction, have been widely acknowledged (Bennett, 1997; Chavis and Pretty, 1999; EEA, 2011; Gotham and Brumley, 2002; Thompson and Maginn, 2012). Suggested proxies to measure social cohesion include 'number of people partaking in volunteering work', 'membership numbers of social and recreational clubs' and 'rates of antisocial behaviour' (Ahern, 2013; Fronteira et al., 2014; Kuo and Sullivan, 2001; Torgler et al., 2012). The amount and types of green space needed in a place also depend on basic demographic indicators, such as population density and education level (Ahern, 2013; Brodhead, 2009; Lovell and Taylor, 2013). Age and income are less evident but potentially also related to the need for green space (Chiesura, 2004; Fronteira et al., 2014; Lee and Maheswaran, 2011; Maas et al., 2006; Takano et al., 2002). Finally, recreational value of urban green space is particularly relevant as they provide (for many urban dwellers) the only opportunity to enjoy nature in a highly urbanised city (Bolund and Hunhammar, 1999; Chiesura, 2004; Dobbie and Green, 2013; Jackson, 2003; Lundy and Wade, 2011; Rijke et al., 2008; Wong and Brown, 2009). The proximity of each location in a city to its nearest green open space is a common and easily understood measure (Wolch et al., 2014).

4.2.4. Habitat or supporting

Habitat or Supporting services only indirectly impact on people through their importance in supporting and sustaining the other ecosystem services (MEA, 2005). They can also be perceived to bear intrinsic value, not directly or measurably translating into benefits obtained in daily life.

Urban green spaces provide refuge habitat for a wide variety of flora and fauna (Brenneisen, 2006; Kong et al., 2010; Rudd et al., 2002; Sandström et al., 2006). The need for this service depends on the current distribution of green space reflected in provision levels and distance to green space, protection status of local ecosystems and the connectedness of natural areas within cities as well as between the city and its surrounding ecosystems, in order to form an ecological network (Ahern, 2007, 2013; Bolund and Hunhammar, 1999; Fronteira et al., 2014; Hadi, 2013; Kong et al., 2010; Rudd et al., 2002; Sandström et al., 2006; Yap and Thuzar, 2012). Flora and fauna health is reflected in biodiversity and population sizes of species, and supports the quality and sustenance of green spaces. WSUD should be designed and located to support biodiversity (Brenneisen, 2006; Cagelais, 2014; Dobbs et al., 2011).

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Table 5
WSUD planning considerations: linking the suitability factors from Tables 3 and 4 to WSUD technologies of Table 1 as well as information relevant to planning and implementation of WSUD in the urban landscape.

WSUD technology	Footprint	Appli-cation scale[a]	Suitable Urban Environments	Retrofit difficulty	Intru-sive	Private implementation	Extra bene-fits	Benefit type	Relevant suitability factors	Issues
Aquifer storage and recovery	Small	N, B	Low density	Low	No	No	No	Public	**B:** 1–4, 18. **PG:** 4, 10, 11. **P:** 7. **R:** 10.	Needs advanced pre-treatment
Bioretention/ Raingardens	Flexible, small to large	L, S, N, B	Flexible. Streetscape, gardens, parks.	Low	Yes	Yes	Yes	Private and Public	**B:** 1–14, 17–20. **SE:** 1–14. **PG:** 1–15. **P:** 1–7. **R:** 1–11, 14, 15. **C:** 1–6, 9, 10. **HS:** 1-5	Clogging, low resilience against draught, sanitation and tropical disease vectors
Green roofs	N/A	L, S, N, B	Rooftops	Low	No	Yes	Yes	Private and Public	**B:** 9–15, 19, 20. **SE:** 3, 5–9. **PG:** 2, 3, 5–7, 9, 12. **P:** 1–7. **R:** 1–5, 8–10, 14, 15. **C:** 1–8, 10. **HS:** 1, 3-5	Needs irrigation in dry climates, little experience in dry climates, not taken up in models
Green walls/Living walls	N/A	L, S, N, B	Walls	Low	No	Yes	Yes	Private and Public	**B:** 9–15, 19, 20. **SE:** 3, 5–9. **PG:** 2, 3, 5–7, 9, 12. **P:** 1–7. **R:** 1–5, 8–10, 14, 15. **C:** 1 –10. **HS:** 1, 3-5	See: green roofs
Infiltration systems	Small	L, S, N, B	Dense urban areas, along roads and highways	Moderate	Yes/ No	Yes	No	Public	**B:** 1 8, 10 12, 17, 18. **SE:** 1 4, 6 14. **PG:** 1 6, 8 15. **R:** 6–9, 11, 14, 15.	Clogging, soil contamination, system failure
Oil and sediment separators	N/A	S, N, B	sewer inlet	Very low	No	No	No	Public	**B:** 6–8, **R:** 6, 12	
Permeable pavement	N/A	L, S, N, B	Any paved area	Low	No	Yes	No	Public	**B:** 1–4, 10–12, 16. **SE:** 12 14. **PG:** 6. **R:** 8, 9, 11, 14, 15.	High maintenance and system failure
Ponds and lakes	Medium to large	N, B	Public open space, parks	High	Yes	Yes	Yes	Private and Public	**B:** 1, 2, 4–12, 17, 18 **SE:** 1–4, 12–14. **PG:** 1–15. **P:** 3–7. **R:** 3–15. **C:** 1–8, 10. **HS:** 1-5	Bank erosion, algal blooms, flocking birds, mosquitoes, sanitation, tropical disease vectors
Sand filters	Flexible, above or underground	L, S, N, B	Any	Very low	No	Yes	No	Private and Public	**B:** 6–12, 18. **PG:** 2, 3. **P:** 3–7. **R:** 11.	Clogging, high maintenance
Screens/GPTs	N/A	N, B	River, stream, sewer	Very low	No	No	No	Public	**B:** 6–8. **SE:** 1. **R:** 6, 12	
Sediment basins	Flexible, small to large	S, N, B	Flexible. Streetscape, gardens, parks.	moderate to high (depending on size)	Yes/ No	No	No	Public	**B:** 1, 2, 4–12, 17, 18. **SE:** 1, 2, 12–14. **PG:** 1–15. **R:** 6–10, 11, 14, 15.	Sanitation and tropical disease vectors
Swales	Dependent on hydraulics.	S, N	Streetscape: median strip, carpark.	Low	Yes	No	Yes	Public	**B:** 1, 2, 5–14, 19, 20. **SE:** 1 –14. **PG:** 1, 5–11, 13–15. **R:** 1–11, 14, 15. **C:** 1, 9. **HS:** 1-5	High maintenance, sanitation, tropical disease vectors and mosquitoes when inundated
Tanks	Small, above or underground	L, N, B	Any	Very low	No	Yes	Yes	Private and Public	**B:** 10–12. **SE:** 3, 6–14. **PG:** 3. **P:** 3–7. **R:** 14, 15.	Water quality, trade-off between flood protection and water supply
Wetlands	Large	N, B	Public open space	High	Yes	No	Yes	Private and Public	**B:** 1, 2, 4–14, 17–20. **SE:** 1 –14. **PG:** 1–15. **P:** 3–7. **R:** 1 –15. **C:** 1–10. **HS:** 1-5	Mosquitoes, Clogging, low resilience against draught, sanitation, tropical disease vectors

B: Biophysical, SE: Socio-Economic, PG: Planning & Governance, P: Provisioning, R: Regulating, C: Cultural, HS: Habitat or Supporting.
[a] L: lot, S: street, N: Neighbourhood, B: sub-basin/district.

4.3. Connecting WSUD suitability and urban planning

Each type of WSUD technology has different design purposes as well as unique characteristics. Therefore, sets of suitability factors from Tables 3 and 4 apply differently to each technology. As the keystone of our suitability framework, Table 5 provides specific characteristics of different systems related to planning, as well as linking each suitability factor to its technology of relevance (see Table 1 for technologies). Together with the suitability tables, this table completes our proposed framework, aimed at supporting WSUD planning and decision-making processes.

The suitability framework presented in this section has the potential to serve as the basis for comprehensive spatial multi-criteria analyses and other types of WSUD suitability evaluations. However, as form and function of green technologies vary, so do the factors that influence their suitability. Therefore, the relevance and relative importance of the factors presented in this review depend on the WSUD type under consideration as well as the local context (e.g. developing vs developed). Some indicators, such as the presence of urban green spaces, can have positive as well as negative effects on suitability and be relevant to both sides of suitability: it provides a space to implement WSUD, but decreases the need for extra green space.

Besides directly informing planning processes, our framework can serve as the basis for planning support tools (particularly GIS-MCDA) and as the academic basis for choosing suitability factors that are included in other computer-based spatial suitability analyses, depending on the types of infrastructure under investigation. The framework adds rigour to PST's and models that have multi-criteria analysis as part of their functionality, such as scenario analyses and planning algorithms. As such, justification for criteria selection can be provided without a separate, in-depth review of the scattered literature.

5. Conclusion

Water Sensitive Urban Design (WSUD) and similar concepts of green and distributed stormwater management systems are recognised by academia as well as practitioners and policy-makers to be a sustainable way of managing urban water systems in the face of global trends such as increased urbanisation and climate change. This paper reviewed models, tools and frameworks aimed at supporting the planning and implementation of WSUD and presents a novel suitability framework for WSUD planning. Key messages that have arisen from this review include:

- Best planning practice for WSUD requires a holistic, multi-scale and inclusive planning process. Such characteristics can be brought to the planning process by **Planning Support Systems** (PSS). In spite of their abundant development and confirmed potential, PSS uptake has been minimal. Underlying causes have been suggested, but never tested in practice, for which there is thus an urgent need.
- **PSS for urban water systems can be grouped into three categories**, delineated by the three dimensions of spatial planning: space, time and human decision-making. Ordered from low-level to high-level planning, these categories are: (1) WSUD as part of the urban water cycle, (2) WSUD as part of the urban form and (3) WSUD as part of water governance.
- Consideration of all factors relevant to planning, flexibility of scale, stakeholder inclusion and communication are all served by approaches from the second category of WSUD PSS: WSUD as part of the urban form. More specifically, a technique called **GIS-MCDA was found to show the greatest potential** to serve urban planning for WSUD, because of its ease of use, ability to reflect user's preferences, interpretability and visual output.
- A suite of GIS-MCDA tools and assessments can be found in literature. However, none of them were found to be adequately extensive or sophisticated. The most prominent drawback is their lack of inclusion of a broad variety of suitability factors, as the **majority tools and assessment focus on a small number of mainly biophysical factors only.**
- We proposed a comprehensive **WSUD suitability framework, which identifies two sides of spatial suitability: 'WSUD needs a place' and 'A place needs WSUD'.** The former side corresponds to the classical perception of 'suitability', whereas the latter introduces the needs of a place into the framework. This is one of the first known attempts to systematically link WSUD literature to the well-established field of ecosystem services.
- The framework is operationalised by linking the suitability factors to a technology-specific WSUD planning framework. Our completed framework is aimed at **rigorously informing and aiding the planning process for WSUD.** To this end, it can form the basis of a novel planning support tool towards WSUD. Such a tool not only has the potential to **dramatically improve the efficiency and effectiveness of the planning process, but also enhance public and political acceptance** of this novel type of urban water management. Paramount to maximise the usefulness and uptake of such a tool is the need to test it with all stakeholders in the decision-making process in multiple contexts.

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2.3 STRATEGIC PLANNING

2.3.1 Wicked problems

In their ground-breaking publication in the early 70's, Rittel and Webber (1973) argue that (spatial) planning is a "wicked problem". As outlined in their article, 10 characteristics are define a wicked problem: they have (i) no definitive formulation, (ii) no stopping rule, (iii) their solutions are not true or false, rather good or bad, (iv) there is no test of a solution to them, (v) every solution is a "one-shot operation" and there is no learning from trial-and-error, (vi) they have no enumerable set of solutions, (vii) they are essential and unique, (viii) they can be considered a symptom of another wicked problem, (ix) there's a discrepancy to represent them which can be explained in numerous ways and (x) the planner has no right to be wrong (Rittel and Webber, 1973).

Common to wicked problems, they are difficult to define. Trying to define planning and planning theory, one runs into several problems, as identified by Friedmann (1998). These problems are related to the 'lens' through which one observes planning (normative, positive, critical, paradigm-shifting), the inseparable political and institutional context and difficulty to incorporate power relations. He asks questions such as: who are planners? What's included in the planning process (statutory planning or more?) In general, Friedmann (1998) argues, planning is about the relationship between knowledge and action; "conscious intervention of collective actors" (p. 251). Typically, for urban planning, these actions are aimed at producing and changing the urban habitat. How this process is shaped depends on the local context. Although the production of 'plans' is not necessary for good planning, it often serves a political purpose to generate support and funding (Friedmann, 2004).

2.3.2 Strategic planning

One way to approach wicked problems is through the application of strategic planning. The term *strategic planning* is widely used across different disciplines within academia, as well as outside of it in the context of business, the military and other governmental and non-governmental organisations (Friedmann, 2004). As a result, the term has many different definitions and interpretations. Literature about strategic planning is highly charged with semantics. Disagreement or misalignment between definitions used by various authors are reflected in their publications. The term is most widely used in literature around business and management (Friedmann, 2004), however, definitions are usually easily applied to urban planning and infrastructure sectors as well (e.g. Dominguez et al., 2009). A few definitions of strategic planning, as collected by Friedmann (2004), include: " […] a process of deliberative paradigm change" (pp 244-245: Healey, 1997), efforts for "a more coherent spatial logic for land use regulation, resource protection, and investments in regeneration and infrastructure." (p. 113: Albrechts et al., 2003). In the context of SSANTO, the definition from Bryson (2001, 2003) is particularly helpful: "[…] a set of concepts, procedures, and tools that may be used selectively for the different purposes in different situations." (p. 57: Friedmann, 2004).

Planning of urban water management infrastructure can also be considered to fall in the wicked category (Lach et al., 2005; Reed and Kasprzyk, 2009). Water quality problems caused by non-point pollution and related public health and ecological health problems, as well as water supply are critical social needs. Rivers, aquifers and other water bodies are inter-jurisdictional natural phenomena, which adds to the complexity of their management. As such, it can be argued to benefit from strategic planning, as incremental changes are not enough to deal with the changes needed, argue Lach et al. (2005). They discuss the effectiveness of three possible management modes: (1) *controlling tame water problems,* (2) *coordinating* and (3) *domesticating and adaptive management and civic science.* The latter can be argued to be the most strategic one, in a world or increasingly rapid change. Part of such strategies is a system-focus and the involvement of a broad set of stakeholders, including civil society.

Unfortunately, in the urban water sector, like in other infrastructure sectors, strategic planning has received little attention (Dominguez et al., 2009). Strategic planning in the infrastructure sector, and particularly the urban water sector, must consider high capital needs, long time frames, path dependencies and multiple objectives associated with this sector, according to Dominguez et al (2009). They propose a strategic planning approach of four steps: (1) assessment of multiple objectives, (2) scenario analysis, (3) development of strategic options and (4) evaluate the feasibility of options.

Lach et al. (2005) note that the role of science is to provide and present information to this participatory process. This role can be accommodated through the application of models and tools such as SSANTO. Reed and Kasprzyk (2009) argue that "Rigorous model evaluations from social, technical, and scientific perspectives are vital for future water management frameworks." (p. 412).

Furthermore, they note that the most important task for models is to convey knowledge to a broad set of stakeholders, which corresponds neatly to SSANTO's aim.

2.3.3 The role of Planning Support Systems

Academic fields involved in research concerning the problem definition, problem structuring and problem resolution include decision science and operations research. Methods and techniques promoted by the proponents of these fields of research, as well as planning practitioners, include Multi-Criteria Decision Analysis, Cost-Benefit Analysis, Life-Cycle Analysis and many others. These, and other techniques, are regularly captured into guidelines, manuals and computer systems, and can collectively be referred to as Planning Support Systems (PSS).

PSS have an important role to fulfil in achieving strategic planning (e.g. Dominguez et al., 2009). They can assist during each stage of the planning process, from visioning to problem definition to solution analysis to decision-making. It is important to note that PSS themselves do not make planning strategic, nor do they replace human judgement and decision-making. They are merely a tool, albeit powerful, to assist the different steps in this process. Therefore, urban planners and scientist alike need to be mindful of increasingly common traps associated with the application of decision-science and PSS. These traps, as defined by Ackoff (1979), include the tendency to define the problem according to the operation of the PSS of choice, the use of techniques by people who do not know their mathematical and technical implications and decreasing plurality in decision approaches. He mentions that these tendencies have brought operations research as a research field close to becoming irrelevant, as a result of mechanical and rigid decision processes, where the ever changing and diverse reality is ignored. Many PSS, he argues, have become ineffective dealing with the "mess" that is reality, and operations research should be a means, not an end.

Such argument is resonated by Mintzberg (1994a), who debates the very existence of strategic planning by arguing 'planning' can never be 'strategic', as strategies are adaptive and cannot be planned for in a changing world. He points to the tendency that plans are generally made by people who are detached from the daily reality, who formalise and thereby rigidify processes that should be adaptive. Strategic planning and PSS, rather than aid people with thinking, can stop people from thinking, thus argues Mintzberg (1994b).

The rise of participatory planning practices as identified by Lach et al. (2005) also gave rise to participatory forms of modelling (Voinov and Bousquet, 2010). Scientists, modellers and software developers are no longer the sole experts that should prescribe what decisions are best for society. Stakeholders including civil society are the ones bearing the consequences of decisions, and therefore should be involved in this decision-making. There is a need for modelling to facilitate this involvement, according to Voinov and Bousquet (2010). They list seven typologies of stakeholder engagement in modelling, ranging from low to high stakeholder involvement. Participatory Modelling (PM) is the most general in definition. Similar to statements by other authors in this review, they emphasise that modelling is about the process rather than the product. Main goals are to increase and share knowledge among stakeholders and identify and clarify the impacts of solutions (Voinov and Bousquet, 2010). Simplicity and flexibility of the model are key, ideally facilitated on a web-based platform. Thus, PM can help us move towards better decision-making that is more democratic and informed (Voinov et al., 2016).

Throughout this thesis, the term strategic planning is regularly used to refer to two phenomena. Firstly, it refers to the planning process that leads to the implementation of WSUD infrastructure. In this sense, the definition of Albrechts et al. (2003) describes our meaning best. SSANTO could be part of the set of concepts, procedures and tools that is described in the definition of Bryson (2001, 2003). Secondly, we refer to strategic planning in a narrower sense, as the strategic placement of WSUD systems in the urban landscape. In this sense, strategic refers to a deliberately chosen location that is considered to score relatively high in terms of the objectives of the decision-maker, which could include, or be a subset of the criteria from the suitability framework presented in Chapter 2.2. In the second case, we generally refer the antonym of strategic: ad-hoc.

2.4 RESEARCH GAPS

The critical review resulted in the identification of the following research gaps:

- The suitability framework seeks to capture, organise and operationalise knowledge about the relevant planning considerations for WSUD placement. To the authors' knowledge, no previous research has systematically implemented or, indeed, identified a comprehensive collection of spatial WSUD suitability criteria.
- As combined in the suitability framework, there exists a great amount of knowledge on considerations for WSUD planning. There is, however, a lack of empirical testing of the extent to which this information is being utilised in the planning practice, both in terms of process and physical outcomes.
- While the 'implementation gap' (lack of uptake of PSS in the planning practice, despite their identified benefits) has been widely diagnosed in urban planning and its causes have been hypothesised, few studies have sought to empirically determine the validity of these hypothesised causes.
- Although a plethora of PSS are available that perform GIS-MCDA, their inclusion of criteria and sophistication of methodology vary. No studies were found that combine a high level of methodological sophistication while considering a comprehensive set of criteria.
- While GIS-MCDA is used in WSUD planning and prioritisation studies, few have attempted to automate and simplify the process to enable its application in the day-to-day planning decision-making.
- Most research focuses on WSUD, planning and PSS in a western context. Although developing countries face similar issues with degradation of urban waterways and flooding due to rapid urbanisation and climate change, research on planning support for these contexts is very limited.

2.5 RESEARCH DESIGN

This PhD addresses the key research gaps through testing of the hypotheses and corresponding research questions, in line with the main aim of the PhD to

"add robustness to, as well as streamline the process of decision making for urban planning of WSUD through explicit consideration of location-specific context, represented by relevant biophysical, socio-economic and planning related factors as well as local needs".

The aim is achieved through five research objectives:

1. Create a structured and comprehensive definition of spatial suitability for WSUD placement
2. Understand current spatial and organisational trends of WSUD planning using Melbourne as a suitable case study due to its considerable history with the practice;
3. Develop a methodology for spatial evaluation of suitability for WSUD within a city;
4. Incorporate this methodology into a GIS-Based Multi-Criteria Decision Analysis tool;
5. Test the tool for a developed (i.e. Australia) and developing (i.e. Indonesia) context through case studies and end-user engagement.

2.5.1 Research questions and hypotheses

To address these objectives, the following research questions (RQ) and hypotheses (H) have been formulated:

RQ1: *How can we define spatial suitability for WSUD, i.e. which are the relevant spatial contextual factors and the reciprocal relationship that these green systems have with the urban landscape they sit in?*
H1: Spatial suitability goes beyond traditionally used biophysical factors to include aspects related factors such as to economical, ecological, social and planning factors.

RQ2: *To what extent are the relevant WSUD spatial suitability considerations, identified through answering RQ1, reflected in the spatial distribution of WSUD systems in Melbourne?*

H2: Spatial distribution of WSUD in Melbourne correlates with biophysical and urban form related factors, but not with socio-economic and other factors.

RQ3: *What is the perception of the level of strategic WSUD planning and the role of PSS by practitioners in Melbourne and how can we close the implementation gap in this context, if there is one?*
H3a: Planning processes for WSUD placement are ad-hoc and opportunistic and the use of PSS limited to a small number of prominent examples.
H3b: We need PSS that are user-friendly, conceptually simple, relevant and connect to the planning practice

RQ4: *How can we provide planning support that enables the strategic placement of WSUD systems by considering spatial suitability through a broad set of relevant factors?*
H4: WSUD planning support can be provided by the development of an guided methodology drawing on the spatial capacities of GIS-MCDA in a simple and user-friendly digital environment.

RQ5: *What is the need for, and applicability of a tool such as the one mentioned in H4 in the planning context of urban Indonesia?*
H5: Planning support in the form of a GIS-MCDA is needed to improve the relatively young planning processes in Indonesia, but will be challenged by the difficulty to acquire quality input data.

2.5.2 Thesis with published work

This interdisciplinary work applied methods and knowledge from civil engineering, urban planning, decision science and social science to test the abovementioned hypotheses. The current and following four chapters each test one of the hypotheses, and are presented in the form of peer-reviewed journal articles. An overview of these articles can be found in the 'List of publications'. In the final chapter, the synthesis of the work is made by presenting a recapitulation of the conclusions, discussing the strengths and weaknesses of the evidence, analysing the implications to practice and suggesting potential future research avenues.

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CHAPTER 3

SPATIAL ANALYSIS OF WSUD DISTRIBUTION

Waar kikkers zijn daar is ook water

“Where the frogs are, there must be water”

--There’s always a kernel of truth in gossip--

3.1 INTRODUCTION

This chapter explores the spatial distribution of WSUD currently existing in Melbourne. To this end, a unique spatial database of WSUD systems throughout the Melbourne metropolitan area, acquired from Melbourne Water, was cleaned, completed and analysed. Important criteria from the suitability framework presented in Chapter 2 were compared to the locations of WSUD systems to assess whether there are relationships between them. Background, methodology, results, discussion and conclusions of this work were published in *Landscape & Urban Planning* and are presented in section 3.2.

This work responds to the second objective of this PhD: **"Understand current spatial and organisational trends of WSUD planning in Melbourne"**, more specifically to the 'spatial' part of this objective. To this end, this section seeks to answer research question RQ2: *To what extent are the relevant WSUD spatial suitability considerations, identified through answering RQ1, reflected in the spatial distribution of WSUD systems in Melbourne?*

To answer this research question, the following hypothesis was tested:
H2: Spatial distribution of WSUD in Melbourne correlates with biophysical and urban form related factors, but not with socio-economic and other factors.

Testing of this hypothesis was conducted using spatial statistical and general statistical techniques including spatial correlation, principle component analysis and exploratory spatial regression. The dependent variable *WSUD location* was tested against several independent variables, including biophysical, socio-economic and urban form related variables.

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3.2 SPATIAL ANALYSIS OF WSUD DISTRIBUTION

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Research Paper

What drives the location choice for water sensitive infrastructure in Melbourne, Australia?

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ABSTRACT

Distributed and green urban drainage infrastructure known as Water Sensitive Urban Design (WSUD) is increasingly being implemented in cities globally to combat climate change and urbanisation effects. Rigorous consideration of the urban context in terms of biophysical, socio-economic and urban form related factors is crucial for optimal design outcomes. The extent to which the urban context is considered in current planning and decision-making processes remains unclear. This study investigates this relationship between current WSUD infrastructure in Melbourne (Australia) and each of the aforementioned factors for the first time. We obtained and pre-processed one of the most extensive and complete geo-located WSUD asset databases in the world (containing over 2000 WSUD assets), and undertook an evidence-based analysis of WSUD planning outcomes. Relationships were investigated using spatial analysis techniques (e.g. overlaying), as well as a number of statistical methods (e.g. exploratory regression). It was found that biophysical and urban form factors strongly explained variability in WSUD location choice, while socio-economic factors appeared to be overlooked. Our findings imply that the current WSUD planning practices are primarily governed by standard engineering design. Opportunistic WSUD planning leads to unintentional outcomes that fail to capitalise on the full potential of WSUD benefits. Increased investment in asset inventory development and analysis is critical to inform WSUD planning moving forward. Knowledge gained from this and additional studies can further planning through application in planning-support systems, to deal with the complexity and diversity of the broad set of decision criteria.

1. Introduction

Water Sensitive Urban Design (WSUD) refers to the introduction of distributed 'green' technologies in the urban landscape for stormwater treatment, detention and reuse with the primary aim to protect and restore natural waterways, decrease the risk and severity of floods and diversify sources of water supply (Dietz, 2007; Wong & Brown, 2009; Woods Ballard et al., 2007). This innovative approach to water management and similar concepts (e.g. Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS) and Best Management Practice (BMP)) are increasingly being implemented around the world as a strategy to adapt to the pressures of increasing urbanisation and climate change on urban water management (Fletcher et al., 2014; Wong & Brown, 2009). Aside from the abovementioned benefits, WSUD serves a broader set of functions, such as increasing the aesthetic value of neighbourhoods (Backhaus & Fryd, 2013; Dobbie & Green, 2013), providing recreational space (Dobbie & Green, 2013; Wong & Brown, 2009), mitigating urban heat island effects (Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2012; Mitchell & Cleugh, 2006; Steeneveld, Koopmans, Heusinkveld, & Theeuwes, 2014), and educating communities about urban sustainability (Lundy & Wade, 2011; Rijke, De Graaf, Van de Ven, Brown, & Biron, 2008). WSUD is a relatively young addition to urban planning practice and although technical design guidelines have been developed, rigorous and experience-based information on the relationship between urban planning and water management is lacking (Sharma, Cook, Tjandraatmadja, & Gregory, 2012). Anecdotal evidence from municipal planning practitioners suggests that WSUD practice has predominantly been driven by

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'opportunistic' approaches in both infill developments (retrofitting rain gardens in road renewal sites), or greenfield developments (leaving WSUD integration as the last planning consideration), which may result in less than optimal planning outcomes (Allan, S., personal communication, 1 September 2015; Innes, S., personal communication, 23 October 2015; Chaffin et al., 2016; Fronteira, Kauhanen, & Kunze, 2014). WSUD implementation and management guidelines necessary to prevent such opportunistic approaches are scarce (Roy et al., 2008) and largely issued on local (municipal) scale. Only for new (greenfield) developments is centralised regulation present (DELWP, 2017).

A growing body of literature reports on the factors that determine the 'suitability' of a location for WSUD implementation (e.g. Ashley, Booker, & Smith, 2004; Ellis, Deutsch, Mouchel, Scholes, & Revitt, 2004; Martin, Ruperd, & Legret, 2007; Scholz, 2006). Traditionally, various abiotic (non-biological) biophysical factors (hereafter simply referred to as 'biophysical') are considered for design and placement of WSUD and stipulated in guidelines (e.g. Melbourne Water, 2005; Woods Ballard et al., 2007), such as hydrology (e.g. rainfall), soil, slope and imperviousness. However, recent literature suggests that a wider variety of spatially variable factors can impact the functioning of these technologies, including socio-economic and urban form (e.g. Barbosa, Fernandes, & David, 2012). For example, high public literacy and awareness of the function and benefits of WSUD may improve community acceptance and interaction with WSUD. Such literacy and awareness, in turn, is expected to be more easily attained by communities with high environmental awareness and higher education levels, as is the case for public acceptance of similar green innovations such as water recycling schemes (Dolnicar, Hurlimann, & Grün, 2011; Domènech & Saurí, 2010).

Besides suitability, the 'need' for WSUD varies spatially, due to the diverse benefits green technologies offer for storm water quantity, quality and amenity (Ashley et al., 2013; Marlow, Moglia, Cook, & Beale, 2013; Wong & Brown, 2009). For example, neighbourhoods with low levels of greenery significantly benefit from the introduction of WSUD, while relatively pristine waterways benefit more from pollution mitigation than degraded waterways (Walsh, Fletcher, & Ladson, 2005). Public exposure to WSUD is high in frequently visited open spaces such as train stations and shopping precincts. Hence, optimising WSUD placement requires the planning process to consider a wide variety of factors. A recently developed suitability framework attempts to capture this variety (Kuller, Bach, Ramirez-Lovering, & Deletic, 2017). Opportunistic planning approaches overlook these factors, reducing the benefits obtained from WSUD (Schifman et al., 2017).

Growing knowledge about 'suitability factors' is accompanied by a growing number of planning support tools for WSUD. Various planning frameworks incorporate some form of suitability assessment based on multiple factors/criteria (e.g. Jin, Sieker, Bandermann, & Sieker, 2006; Lee et al., 2012). Although these tools predominantly focus on biophysical factors, there is an encouraging trend towards incorporation of a wider variety of aspects, including socio-economic factors (e.g. E2STORMED, 2015; Fronteira et al., 2014; Viavattene, Scholes, Revitt, & Ellis, 2008). Application of such tools and frameworks could drastically improve planning practices without overly increasing their complexity (Geertman & Stillwell, 2004; Lee et al., 2012; Vonk, Geertman, & Schot, 2005). Nevertheless, currently available planning-support systems remain underused for a number of reasons including lack of relevance and user-friendliness (te Brömmelstroet & Bertolini, 2008; Vonk et al., 2005). This raises the question to what extent biophysical, socio-economic and urban form factors have been guiding planners' decision-making processes to date.

However, no structured investigation has been conducted to examine location choices for WSUD in metropolitan regions, assessing the impacts of the abovementioned factors. The difficulty of acquiring data on the location, type and size of WSUD assets for an entire metropolitan region may underlie this scarcity. However, this information is crucial in WSUD planning and applications. To understand how the complex urban context impacts the current practice of WSUD planning, the present study aims to characterise WSUD composition (i.e. choice of technology type) and distribution in relation to the urban context for metropolitan Melbourne (Australia). More specifically, we focus on:

(1) exploring Melbourne's current WSUD inventory in terms of types, land uptake and service area,
(2) investigating relationships between WSUD location and the urban context in terms of biophysical, socio-economic and urban form factors,
(3) assessing to what extent the current practice aligns with WSUD planning best practice as informed by local and current national guidelines.

We hypothesise that biophysical factors consistently and strongly drive location choices for WSUD, as they can prohibit their implementation. We would also expect WSUD to be often present in relatively flat areas (as prescribed by design guidelines, e.g. Melbourne Water, 2005) and close to waterways (as WSUD in Melbourne is traditionally driven by the water authority, which is in charge of the larger urban waterways: Brown & Clarke, 2007). Furthermore, we hypothesise socio-economic factors to be weakly related to the locations of WSUD. While socio-economic factors aren't prohibitive to implementation of WSUD, they can decrease its feasibility (CRCWSC, 2014). In contrast, urban form factors are expected to significantly relate to the locations of WSUD. For example, areas of high-intensity land-uses (e.g. commercial centres, high density residential) are space constrained and should therefore include smaller WSUD assets.

To the author's knowledge, this is the first systematic analysis of a geo-located WSUD dataset, using one of the most extensive and complete inventories currently available. Furthermore, for the first time the relationship between a wide variety of spatially variable factors are compared to WSUD placement. In doing so, it increases our understanding on how the complex urban context impacts the current practice of WSUD planning. Lessons from this study are vital to move WSUD planning away from opportunistic practices.

2. Methodology

2.1. Data collection and preparation

Melbourne is a rapidly growing city and currently houses 4.5 million residents, making it the second largest city in Australia. It is a sprawled city (i.e. 'low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas' – EEA, 2006: page 6), similar to others across the country (Coffee, Lange, & Baker, 2016; McLoughlin, 1991), North America and, increasingly, also Europe (Batty, Besussi, & Chin, 2003). It was selected as our case study for its comparatively large experience with the implementation of WSUD (Ferguson, Brown, Frantzeskaki, de Haan, & Deletic, 2013) and the availability of a unique, georeferenced, metropolitan-wide WSUD asset database.

2.1.1. WSUD data acquisition and pre-processing

Melbourne Water, the local water authority, undertook an extensive mapping study of all WSUD assets in 2012, which was collated into a spatial database. The database only includes assets that are primarily built as stormwater management structures, thereby excluding other structures that have an impact on stormwater management (sometimes referred to as 'passive systems', such as lawns and ponds). The assets in the database are managed by different parties, including the local water authority (for assets with a catchment of over 60 ha – Melbourne Water, 2017), local government and private parties. The scattered nature of management responsibilities is reflected in the scattered nature of data on the distribution of WSUD assets. Although the database contains significant imperfections in terms of accuracy and completeness, this database is one of the most extensive spatial databases of decentralised stormwater infrastructure in the world, and was therefore used in our study. In total, 2018 WSUD assets were compiled (as a GIS point shapefile), including information about type, geolocation, address, year of construction, size (area) and asset ownership. Although many additional WSUD assets have since been constructed (Melbourne Water, 2013), no further updates were made to this database. Therefore, we adopted the base year for our analysis as 2012 (i.e. the most recent year included in the database).

Two of the most crucial shortcomings of the raw database were: incorrect geo-locations and missing data on asset sizes. To remove these inaccuracies and complete the information, we invested considerable effort in verifying the entries and infilling the missing data into the original database. Missing information was sourced through contacting local councils, retrieving satellite imagery and conducting numerous site visits. Thus, the fraction of WSUD assets without size information was reduced to under 10%. All remaining missing system sizes were subsequently estimated, using median system sizes based on type and general location (classified as inner city, middle suburbs and outer suburbs) according to Buxton and Tieman (2005).

After cleaning, the database contained complete and verified information on 2051 WSUD assets from 5 WSUD types: *(1) Box/Pit*, including planter box rain gardens and tree pits, *(2) Rain gardens*, including all other types of rain gardens and bio-retention systems, *(3) Swales*, vegetated drainage ditches, *(4) Ponds & Lakes*, containing all constructed open water bodies and *(5) Wetlands*, containing all constructed wetland systems.

2.1.2. Collection of urban biophysical, socio-economic and urban form data

We collected data on biophysical, socio-economic and urban form as our independent variables. The selection of these variables (summarised in Table 1) was based on availability and relevance. The included biophysical factors, surface slope and distance from natural waterways, are regularly considered in design (Melbourne Water, 2005; Woods Ballard et al., 2007) and suitability analyses of WSUD (e.g. Jin et al., 2006; Lee et al., 2012).

Socio-economic factors such as environmental awareness and related acceptance (e.g. Sharma et al., 2012; Thompson & Maginn, 2012; Wong & Brown, 2009), and education level (e.g. Chiesura, 2004; Lovell & Taylor, 2013; Mell, 2009) have been identified by the scientific literature as potentially impactful. IRSAD and IER are census-based indicators measuring aspects of socio-economic advantage and disadvantage, developed by the Australian Bureau of Statistics (ABS, 2013). While the former provides a rank of overall socio-economic advantage and disadvantage, the latter focuses on the financial aspect of relative advantage/disadvantage. Detailed information on these indicators can be found in ABS (2013). We included a 'heat vulnerability index' (Loughnan, Tapper, Lynch, McInnes, & Phan, 2012) in our analysis, considering the mitigating effects of WSUD on urban heat islands (e.g. Ahern, 2013; Bolund & Hunhammar, 1999; Lovell & Taylor, 2013). Scarcity of indicator data posed a barrier to the inclusion of socio-economic factors. To overcome this barrier, the use of proxy variables, describing phenomena which cannot be directly measured or for which data cannot be obtained, is common practice in social sciences (e.g. Montgomery, Gragnolati, Burke, & Paredes, 2000). We represented 'environmental awareness' and 'sense of community' with the proxies 'first preference votes for The Greens in federal elections' and 'people engaging in voluntary work for a local organisation or group', respectively (see Table 1). Despite the inherent limitations related to the use of proxies, direct measurement of these indicators fell outside the scope of this study.

Finally, urban form factors describe artificial planning and urban landscape characteristics such as land use and location of assets. They were expressed either in relation to the general city structure or in relation to nearby features such as streets. A water-centric land-use classification detailed by Bach, Staalesen, McCarthy, and Deletic (2015) was used for this analysis. As urban form changes with distance to the centre in a sprawling city such as Melbourne (Galster et al., 2001; McLoughlin, 1991), this factor was also investigated. Special attention was given to the presence (relative quantity and size) of WSUD in 'streetscapes', as a crucial subtype of the urban landscape. These are all public open spaces around roads and streets, which hold a special position because of their prominence in people's day-to-day experience of the city. As urban form factors are primarily concerned with WSUD appearance and integration in the landscape (including characteristics such as shape and size), we focussed our analysis on WSUD land uptake: the amount of space taken up by an asset and its distribution across land uses, rather than the asset's service provision.

Table 1
Factors selected for the spatial analysis of WSUD.

	Name	Description	Spatial unit*	Source**
Biophysical	Slope	Slope of the surface [%]	Location	VIC Data
	Topography	Distance to natural waterways [m]	Location	VIC Data
Socio-Economic	Age of development	Time since first development in an area [years]	Suburb	Melbourne Museum
	Population Density	Permanent residents from census [p/km^2]	Suburb	ABS
	House price	Median price of house sales in 2014 [AU$]	Suburb	DELWP
	Education Level	Proxy: People holding a bachelor degree [fraction]	Suburb	ABS
	Environmental Awareness	Proxy: First preference votes for 'The Greens' in 2002 and 2010 federal elections [fraction]	Electoral district	VEC
	Sense of Community	Proxy: People engaging in voluntary work for a local organisation or group [fraction]	Suburb	ABS
	Heat vulnerability	Ordinal index ranging from 1 to 10 (low–high vulnerability)	Postcode	Loughnan et al. (2012)
	IRSAD	Index of Relative Socio-economic Advantage and Disadvantage. Ordinal index with arbitrary scale.	Suburb	ABS
	IER	Index of Economic Resources. Relative indicator. Ordinal index with arbitrary scale	Suburb	ABS
Urban form	Land use	Two types of land-use classifications: by the Victorian government and adapted from Victorian zoning regulations.	Location	VIC Data; Bach et al. (2015)
	Distance to centre	Distance to Melbourne's geographic centre [km] (centroid of the four inner councils according to Buxton and Tieman (2005))	Suburb	Calculated

* The smallest spatial unit of the source data.

** VIC Data: government data repository for the state of Victoria, accessed through www.data.vic.gov.au. Melbourne Museum: unpublished dataset from May 2015. ABS: Australian Bureau of Statistics, census data 2011, accessed through www.abs.gov.au. DELWP: Victoria Department of Environment, Land, Water and Planning, accessed through www.delwp.vic.gov.au. VEC: Victorian Electoral Commission, accessed through www.vec.vic.gov.au.

2.1.3. *WSUD data preparation*

We distinguished between two types of urban factors data: (1) spatially explicit data, which included biophysical and urban form factors and (2) non-spatially explicit data, which contained all socio-economic factors. The second type of data cannot be directly spatially analysed (due to its aggregated nature). Therefore, we defined a metric that aggregates WSUD data over a geographic unit (suburbs): *Relative WSUD* (RW). RW is dimensionless, and represents the fraction of a geographic unit's impervious surface stormwater runoff that is serviced by WSUD. RW typically varies between 0 (no impervious area serviced by WSUD) and 1 (all impervious areas serviced by WSUD). RW values occasionally exceed 1, as WSUD can treat upstream areas outside the geographic unit under consideration. RW allowed us to normalise the WSUD data set against varying rainfall pattern, asset type and connected impervious area. It was calculated as follows:

$$RW_j = \sum_{i=1}^{n} \frac{A_i}{\theta_i(e_j A_j) \times \alpha_{ij}} \quad (1)$$

where RW_j is Relative WSUD in geographic unit j (in our case suburb), θ_i indicates WSUD size relative to serviced impervious area, A_i is the area of WSUD asset i, α_{ij} the adjustment factor for technology i, used to adjust for differences between rainfall patterns and geography of geographic unit j (in some cases derived from a function, see Eq. (2)), e_j is the impervious fraction of geographic unit j, A_j is the area of geographic unit j, n is the number of assets in geographic unit j. Metropolitan Melbourne is divided into four rainfall regions, defined by α_{ij}:

$$\alpha_{ij} = \beta_{tj}(MAR_j) \times \gamma_{tj} \quad (2)$$

where β_{tj} and γ_{tj} are adjustment factors depending on WSUD type t and geographic unit j (the reader is referred to chapter 2 of 'WSUD engineering procedures' for the values of β_{tj} and γ_{tj} – (Melbourne Water, 2005)), and MAR_j is the mean annual rainfall in geographic unit j (Melbourne Water, 2005).

2.2. *Data analysis*

2.2.1. *Spatial analysis*

All the spatial analyses were performed using the ESRI spatial software ArcMap. We analysed biophysical and urban form factors by overlaying the WSUD database with these datasets. We then compared the results to Melbourne's 'typical' (median) values, which were obtained using a Monte Carlo method. In total, 200,000 random points (approx. 100 × the number of WSUD assets) were sampled across our spatial domain to determine a 'typical' distribution of slope and waterway distance. As convergence occurred for both factors, we deemed the sample size to be sufficiently large. The distance to the geographic centre of Melbourne was calculated using the geographic centre (centroid) of the four inner-city councils as our datum. We identified this point using the definition of inner-city councils proposed by Buxton and Tieman (2005).

For 'Land use', the number and land uptake of WSUD assets were analysed per land-use category to determine trends in the distribution of WSUD. Streetscapes, as a subtype of urban landscapes, received additional attention in our analysis. We statistically compared the abundance of streetscapes to the abundance (land uptake and serviced area) of WSUD located in streetscapes to see if WSUD was overrepresented.

2.2.2. *Statistical analyses*

We conducted three stages of statistical analyses on the socio-economic factors to examine potential interrelationships with WSUD planning:

2.2.2.1. Simple correlation analysis. We determined correlations and cross-correlations using a correlation matrix in the statistical software SPSS. The normality assumption could not be verified, as a third of suburbs had an RW value of 0. Therefore, we used the Spearman's rho correlation coefficient, which is the non-parametric version of the standard Pearson correlation coefficient, and can overcome the issue of non-normally distributed data sets (Myers, Well, & Lorch, 2010).

2.2.2.2. Evaluating relationships. We applied three techniques to further investigate relationships, as strong cross-correlations between nearly all factors were initially found. This pointed to a single factor that drove all cross-correlations and, thus, required normalisation. Exploratory spatial regression, stepwise regression and Principle Component Analysis (PCA) were performed on the data. We organised our data against four different definitions of the metropolitan region boundaries to account for the effect of Melbourne's unsymmetrical sprawl (Beed, 1981; Department of Infrastructure, 1998): (1) all urban and peri-urban suburbs, (2) exclusion of suburbs of 'rural' councils, (3) elimination of suburbs with a population density of under 500p/km^2 and (4) elimination of 'fringe' suburbs, further than 30 km from the geographic urban centre (as defined previously).

Exploratory spatial regression is the process of generating several regression models that include one, two, or up to any number of factors (Rosenshein & Scott, 2011). This iterative process consecutively eliminates the worst performing factor in terms of explanatory power (% of explored models in which the factor was selected) and consistency (tendency towards either a positive or negative relationship to the dependent variable). This method was applied using ArcMap's 'exploratory regression tool', to select the best performing proxy for factors that can be represented by several proxies (e.g. the fraction of people with a bachelor degree outperformed school diploma and postgraduate degree as a proxy for education level). Furthermore, it showed that there was little gain in including more than one factor in the regression model, pointing towards a single variable driving all cross-correlations.

To improve our confidence in the analysis, we cross-checked these findings through stepwise regression and Principle Component Analysis (PCA), using the statistical software SPSS. In our analysis, each suburb average represented one data point. Stepwise regression is an automated process that includes and excludes predictors based on the t-statistic of their estimated coefficients (Draper & Smith, 2014). PCA is a technique for dimension reduction developed by Hotelling (1933), where the eigenvectors of all factors are projected on a lower, and in our case 2-dimensional frame. The eigenvectors that are most aligned with the dependent variable (RW) and with the highest eigenvalue (i.e. longest vectors) have the highest predictive power. Both analyses confirmed the existence of a single dominating variable.

2.2.2.3. Correlation analysis of data subsets. We normalised our dataset for *distance to centre* as a potential single dominating variable, representing the relative location of a region in the metropolitan area. We used the second definition of the metropolitan boundaries described earlier in this paragraph: eliminating regional councils. We divided Melbourne into spatial 'rings', based on *distance to centre*. The number of rings was determined through stepwise addition of classes in the symbology field of the shapefile within ArcMap, until all correlations between RW and *distance to centre* were removed. We used Jenks natural breaks classification method, which seeks to minimise variance within classes while maximising it between them (Jenks, 1967). Five rings (as opposed to the three rings used by Buxton and Tieman (2005)) were found to be the minimum necessary to remove the influence of the *distance to centre* with RW. Rings were given the following names from low to high *distance to centre*: (a) central (b) inner suburbs (c) middle suburbs (d) outer suburbs (e) fringe.

To investigate the relationships between each factor and RW, we repeated the simple correlation analysis for each ring individually, following the data normalisation and division into subsets, based on the five selected rings of Metropolitan Melbourne.

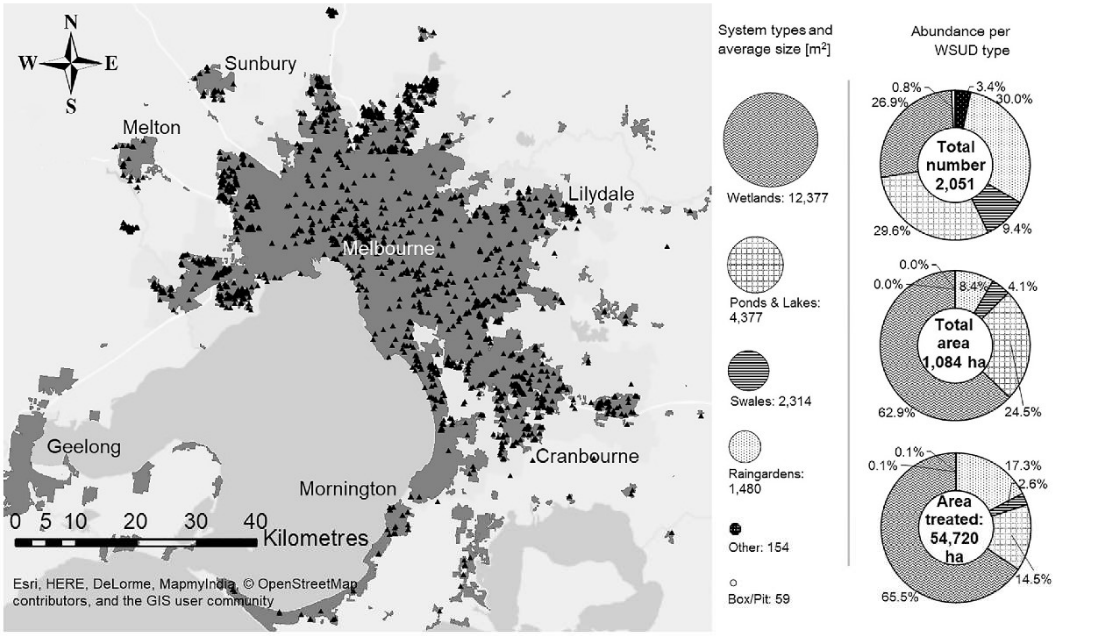

Fig. 1. Spatial and typological distribution of WSUD in Melbourne; black triangles on the map represent the locations of WSUD assets in 2012.

3. Results & discussion

3.1. Descriptive statistics

The distribution, number, land uptake and service area of the various WSUD assets in the Melbourne metropolitan area are shown in Fig. 1. Comparisons between system numbers, sizes and serviced area revealed their level of 'compactness'; rain gardens represent 30% of the number of WSUD assets, 17.3% of service area but only 8.4% of the total land uptake by WSUD in Melbourne, reflecting their compact size. In contrast, wetlands have a 26.9% share in number, 65.5% share in service area and 62.9% share in land uptake. Differences in compactness illustrate how different WSUD assets are suited for dense inner-city areas (rain gardens) or sprawling suburbia (wetlands).

3.2. Biophysical factors

In line with our hypothesis, the observed patterns of WSUD placement suggest an important role for biophysical factors in the location choice for WSUD. WSUD is typically placed on lower slopes (median < 1%), and rarely on slopes above 5% (Fig. 2), in accordance with design guidelines (Melbourne Water, 2005). While guidelines for placement near waterways are absent, WSUD is placed close to natural waterways – often at the outlet of stormwater drainage systems, capturing and treating runoff from impervious areas in the catchment to protect waterway health (Walsh et al., 2005). This placement towards the end of catchments is unfortunate, as source control within catchments is shown to be more effective than 'end-of-pipe' solutions for pollution control (e.g. Bressy et al., 2012; Walsh et al., 2005) as well as for flood management (Urich et al., 2013).

3.3. Socio-economic factors

Against our hypothesis, all but two socio-economic factors were highly and inversely correlated to RW (except for *Index of Economic Resources* - IER which is proportional to RW) (Fig. 3a). Exceptions are *Index of Relative Socio-Economic Advantage and Disadvantage* (IRSAD) and *Heat Vulnerability*, where no correlations were observed (Fig. 3a). As nearly all factors were cross-correlated, we used stepwise regression (Fig. 3b), exploratory spatial regression (Fig. 3c) and PCA (Fig. A1, , Appendix 1) to investigate relationships. All these techniques pointed towards just two strong predictors for RW: *distance to centre* and *age of development*, which are highly correlated to each other (Fig. 3b). As these factors were strong predictors for all socio-economic factors as well, normalisation was required.

Results show that the predictive strength of *distance to centre* and *age of development* depends on the definition of the metropolitan boundary, as Melbourne's sprawl is asymmetrical and historically occurred in south-easterly direction, along major railway lines and highways (Beed, 1981; Department of Infrastructure, 1998) (Fig. 4i). During Melbourne's expansion, the metropolitan area encapsulated existing settlements along its fringes. Therefore, *distance to centre* performs best when the metropolitan boundary is defined to exclude 'fringe' and 'shire' councils along the urban periphery (i.e. an attempt to symmetrise sprawl – Fig. 3b and c). The performance of *age of development* is more robust against changes in the definition of the metropolitan boundary, but slightly weaker overall.

Five 'urban ring' subsets of data were acquired after normalisation for *distance to centre* (Fig. 4h), as described in Section 2.2.2. Following normalisation, we found that nearly all correlations between socio-economic factors and RW were eliminated (Table 2). Only in the fringe ring did some correlations remain, potentially caused by the distortion of Melbourne's unsymmetrical sprawl pattern. Several circumstances may explain the relationship between RW and *distance to centre*. Further from the dense inner city, decreasing urban densities remove space constraints. Cities sprawl from their centre through consecutive addition of urban developments in their fringes, leading to older and more established areas close to the centre (Department of Infrastructure, 1998). Retrofitting in older established areas is more challenging and costly due to a fixed urban context. Therefore, system placement is preferred in less established areas further from the centre. Furthermore, Melbourne's planning regulations prescribe all new greenfield developments to implement WSUD (DPCD, 2016), while requirements for WSUD implementation in infill developments are only present in a

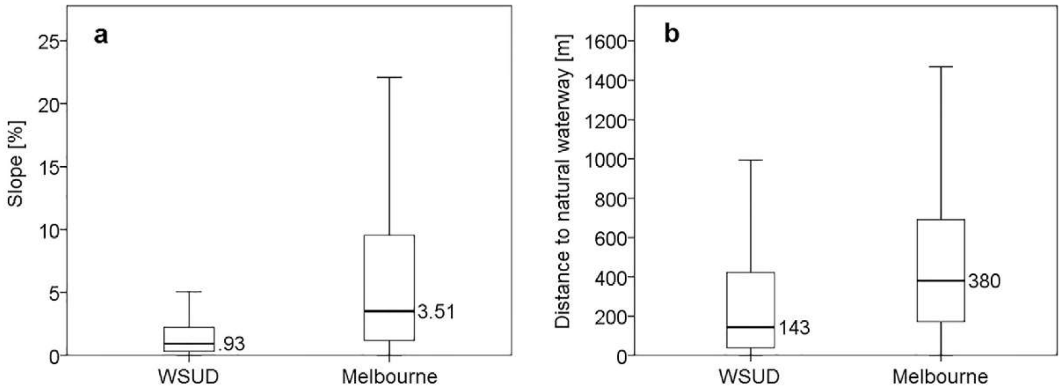

Fig. 2. Relation between the (a) slope and (b) distance to natural waterways of WSUD locations, compared to Melbourne averages.

small number of jurisdictions. Finally, higher RW in fringe areas aligns with recent insights on stream health protection, prioritising protection of pristine peri-urban catchments (Urrutiaguer, Rossrakesh, Potter, Ladson, & Walsh, 2012).

These results suggest a tendency for WSUD to be located in communities of relatively low house prices, environmental awareness, sense of community and education level as well as high economic resources, as they tend to be located further from the centre (note: such a city structure is typical for Australian cities; however, this could be different in other parts of the world). Such tendency is most likely unintentional, given the emphasis on physical factors and hydrology in the planning practice (Schifman et al., 2017). A potential lack of understanding and appreciation for WSUD, resulting from low environmental awareness and education levels, may cause a lack of acceptance and intentional and unintentional maltreatment of these assets, jeopardising their operation (Chaffin et al., 2016; Sharma et al., 2012). This highlights the need for investment in human, social and cultural capital through education campaigns about the function and benefit of green infrastructure, to support the uptake and acceptance of WSUD practices among residents. Such investments were proven highly effective for the uptake of rain gardens and rain tanks (Green, Shuster, Rhea, Garmestani, & Thurston, 2012), and were shown to dramatically increase people's acceptance (Mathey, Rößler, Banse, Lehmann, & Bräuer, 2015). At the same time, WSUD has the potential to educate communities about the importance of urban water and stream protection, increase a sense of community by serving as a public open space (Dobbie & Green, 2013; Rijke et al., 2008) and increase property prices through their amenity value (Mahan, Polasky, & Adams, 2000).

a Spearman's rho correlations		RW	Age of Development	Distance to Centre	Population Density	House Price	Education Level	Environmental Awareness	Sense of Community	Heat Vulnerability	IRSAD	IER
RW	Correlation Coefficient	1.000	-.271**	.317**	-.239**	-.242**	-.199**	-.258**	-.248**	-.098	-.065	.155**
	Sig. (2-tailed)	.	.000	.000	.000	.000	.000	.000	.000	.080	.249	.006
	N	317	283	317	317	305	317	317	317	317	317	317
Age of Development	Correlation Coefficient		1.000	-.747**	.561**	.692**	.704**	.689**	.578**	.149*	.314**	-.271**
	Sig. (2-tailed)		.	.000	.000	.000	.000	.000	.000	.012	.000	.000
	N		283	283	283	277	283	283	283	283	283	283
Distance to Centre	Correlation Coefficient			1.000	-.623**	-.711**	-.798**	-.760**	-.479**	-.110*	-.329**	.325**
	Sig. (2-tailed)			.	.000	.000	.000	.000	.000	.050	.000	.000
	N			317	317	305	317	317	317	317	317	317
Population Density	Correlation Coefficient				1.000	.518**	.590**	.501**	.361**	.227**	.152**	-.298**
	Sig. (2-tailed)				.	.000	.000	.000	.000	.000	.007	.000
	N				317	305	317	317	317	317	317	317
House Price	Correlation Coefficient					1.000	.915**	.613**	.842**	.060	.763**	.198**
	Sig. (2-tailed)					.	.000	.000	.000	.293	.000	.000
	N					305	305	305	305	305	305	305
Education Level	Correlation Coefficient						1.000	.707**	.782**	.029	.709**	.054
	Sig. (2-tailed)						.	.000	.000	.605	.000	.338
	N						317	317	317	317	317	317
Environmental Awareness	Correlation Coefficient							1.000	.530**	.005	.370**	-.183**
	Sig. (2-tailed)							.	.000	.924	.000	.001
	N							317	317	317	317	317
Sense of Community	Correlation Coefficient								1.000	-.057	.756**	.289**
	Sig. (2-tailed)								.	.308	.000	.000
	N								317	317	317	317
Heat Vulnerability	Correlation Coefficient									1.000	-.186**	-.241**
	Sig. (2-tailed)									.	.001	.000
	N									317	317	317
IRSAD	Correlation Coefficient										1.000	.656**
	Sig. (2-tailed)										.	.000
	N										317	317
IER	Correlation Coefficient											1.000
	Sig. (2-tailed)											.
	N											317

c	Distance to Centre~		Age of Development~	
	Position	% Significant	Position	% Significant
All metro suburbs	2	28	1	88
No Rural Councils	1	100	2	47
No pop. Dens. <500	3	45	1	84
No fringe areas	1	96	2	55

b	Distance to Centre			Age of Development			Cross Correlation
	p-value	Corr. Coeff.	Stepwise^ Regression R^2	p-value	Corr. Coeff.	Stepwise^ Regression R^2	
All metro suburbs	0.739	0.016	x	<0.0005	-0.208	0.061	-0.744
No Rural Councils	<0.0005	0.317	0.104	<0.0005	-0.271	x	-0.747
No pop. Dens. <500	<0.0005	0.300	x	<0.0005	-0.248	0.070	-0.744
No fringe areas	<0.0005	0.288	0.074	0.002	-0.193	x	-0.734

Fig. 3. Correlation matrix between RW and all socio-economic factors per suburb, excluding rural councils and (a) comparative performance to predict RW for variables: *distance to centre* and *age of development* through correlation and stepwise regression (b) as well as exploratory regression (c). Shaded cells indicate (a) highly significant correlations between RW and the socio-economic variables, (b,c) outperformance over the other variable. *Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed). ^All four stepwise regressions resulted in a single factor to be selected for the optimal model. ~'Position' indicates the relative strength of the factor compared to the 8 factors used in this exploratory regression, whereas '% Significance' indicates the percentages of trials in which this factor was identified a significant contribution to the predictive model. In all trials the direction of the relation n was consistent (positive for *distance to centre* and negative for *age of development*).

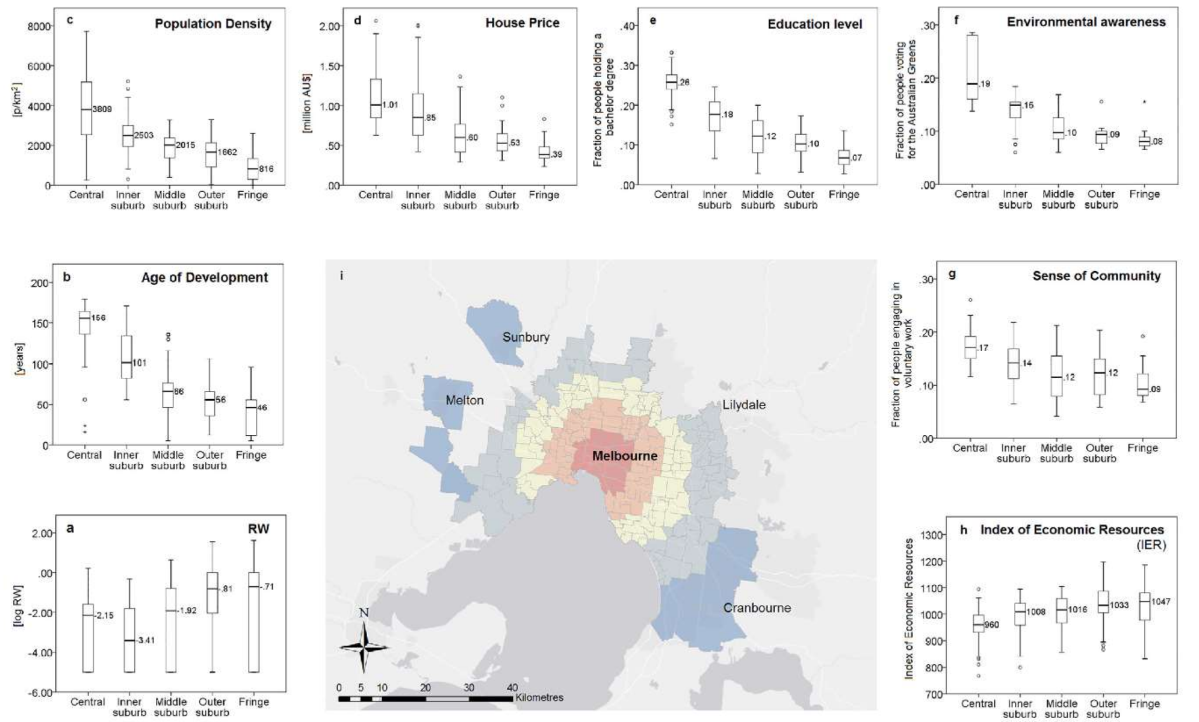

Fig. 4. (a): Relationship between *distance to centre* and RW, (b–h): relation between the significantly correlating socio-economic factors and *distance to centre* and (i): map of central-inner-middle-outer-fringe rings.

Our results indicate that socio-economic factors are currently not considered in location planning directly. The disregard of most socio-economic factors may be caused by a lack of knowledge and awareness among planning practitioners. This presumption is reinforced by the low representation of socio-economic criteria in WSUD guidelines and regulations.

3.4. *Urban form factors*

Fig. 5 shows that larger WSUD assets tend to be placed further from the city centre, confirming the "design bulls-eye" suggested by Charlesworth (2010). Rain gardens have the most even distribution, pointing to their versatility and flexibility. Very small assets, such as box rain gardens and tree pits, tend to be placed in inner-city areas (Fig. 5). Large assets such as ponds, lakes and wetlands are predominantly placed in outer suburbs and fringe areas. Swales sit between these extremes, with the majority of assets situated in middle and outer suburbs.

Fig. 6a shows the distribution of WSUD in terms of frequency (y-axis) and the total land uptake (x-axis) among different land-use types. It shows us that land uses of high density and public exposure such as 'mixed high-density residential & commercial', 'low density trade' and 'high density residential' have a high density of very small assets. The exception is 'mixed trade & industry' where density is low, but system sizes are large. Relatively open and predominantly publicly owned land uses such as 'floodway' and 'service and utility' have many large assets. The exception is 'reserves' where fewer WSUD assets are placed. Some land uses that might benefit most from the educational and amenity benefits of WSUD, i.e. 'education' and 'health and community' (schools, hospitals, libraries etc.) have a low occurrence of assets.

Streetscapes received special attention in our analysis. Quality of streets is at the core of urban productivity, sustainability, quality of life and social inclusion (UN Habitat, 2013). They form a major part of all impervious surfaces in the city and are typically publicly owned. Fig. 6b

Table 2
Normalisation for *distance to centre*: correlation coefficients between socio-economic factors and RW per urban ring.

Factor	Centre		Inner Suburbs		Middle Suburbs		Outer Suburbs		Fringe	
	Corr. Coeff.	p*	Corr. Coeff.	p*	Corr. Coeff.	p*	Corr. Coeff.	p*	Corr. Coeff.	p*
Age of development	–	–	–	–	–	–	–	0.01	–	–
Population Density	–	–	–	–	–	–	–	–	–	–
House Price	–	–	–	–	–	–	–	–	–	–
Education Level	–	–	–	–	–	–	–	–	–	–
Environmental Awareness	0.346	0.01	–	–	–	–	–	–	−0.318	0.043
Sense of Community	–	–	–	–	–	–	−0.405	0.001	−0.430	0.005
Heat Vulnerability	–	–	–	–	–	–	–	–	–	–
IRSAD	–	–	–	–	–	–	–	–	–	–
IER	–	–	–	–	–	–	–	–	–	–

* Only significant correlations (p-value of 0.05 or below) are shown in the table.

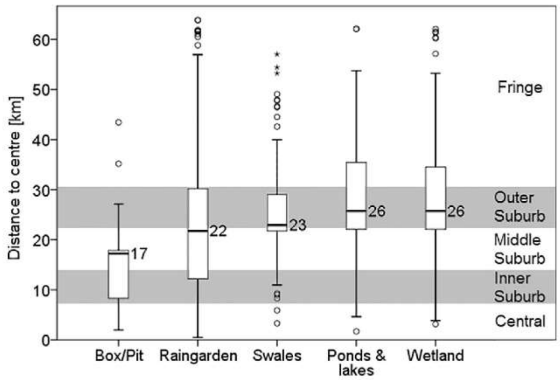

Fig. 5. Distribution of WSUD types and their *distance to centre*, sorted by increasing mean system size.

shows a heavy overrepresentation of WSUD in Melbourne streetscapes, with over 21% of all assets representing nearly 15% of serviced area in this urban landscape, which represents only 6% of Melbourne area. Assets are relatively small, illustrated by the difference between the share in number (21%) and land uptake (9%) of assets. Anecdotal evidence from municipal planning practitioners suggests that opportunistic planning practices may explain the overrepresentation of WSUD in streetscapes, as councils tend to utilise street renewal and roadworks to co-implement assets (e.g. Allan, personal communication, 1 September 2015; Innes, personal communication, 23 October 2015).

These findings are generally in line with our hypothesis. Although urban form factors are not always as prohibitive as some biophysical factors, they are still well understood and thoroughly considered in current urban planning practice.

The results of this paper reflect the relatively ad-hoc WSUD planning practices in Melbourne in which certain biophysical and urban form factors are considered, whilst socio-economic factors are largely overlooked. This has, unintentionally, led to an uneven distribution of WSUD systems and their attributed benefits across the Melbourne Metropolitan area. In turn, this results in reduced effectiveness (i.e. optimising benefits and co-benefits).

To prevent these undesirable outcomes, strategic WSUD planning practices and tools should be employed, rigorously considering all aspects of the specific urban context, actively involving all relevant stakeholders, and remaining adaptive to an uncertain and ever-changing reality. Such tools and methods are increasingly being adopted by sustainable urban water management practitioners and include, but are not limited to: planning simulators (e.g. SUSTAIN-EPA: Lee et al., 2012), (spatial) multi-criteria decision analysis (e.g. Fronteira et al., 2014), adaptive governance (e.g. Schifman et al., 2017), participatory approaches to promote social and cultural learning (e.g. Shuster & Morrison, 2008) and experimentation (e.g. Chaffin et al., 2016; Farrelly & Brown, 2011).

4. Conclusion

This is the first study to systematically investigate the relationships between WSUD distribution and biophysical, socio-economic and urban form factors for a greater metropolitan region. We used one of the most extensive and complete spatial WSUD databases in the world. Despite its status as 'front-runner', the asset data for Melbourne are still imperfect and needs significant levels of engagement. Nevertheless, clear trends could be observed. Numerically, rain gardens, ponds, lakes and wetlands are equally abundant, while wetlands overwhelmingly account for the greatest land-uptake with two-thirds of the WSUD total.

The manifestation of WSUD as an integrated part of the urban landscape is reflected by its reciprocal relation with the urban context, as highlighted by our study results. Strong relationships between WSUD distribution and biophysical, socio-economic and urban form factors were revealed. Constraints from biophysical factors as well as urban form underpin WSUD placement; however, socio-economic factors are

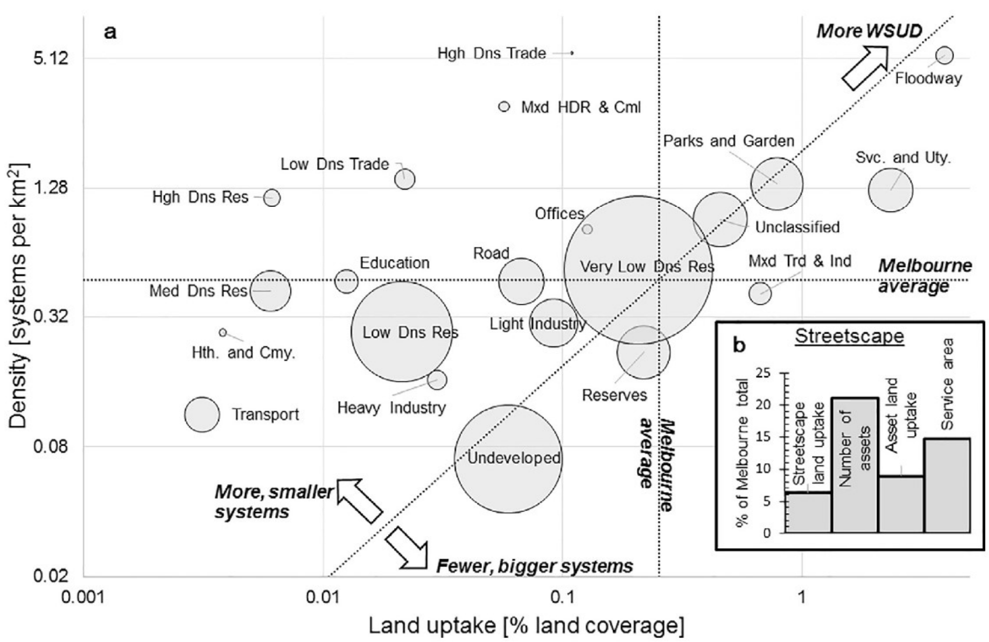

Fig. 6. (a) Prominence of WSUD among land-use types in terms of system count (vertical axis) and size (horizontal axis). Each circle represents a land-use type, circle size represents the area of that land-use type in Melbourne. The horizontal and vertical lines represent the average density and land uptake of assets, while the diagonal is the *iso*-size line at the average system size in Melbourne. (b) Prominence of WSUD in streetscapes.

disregarded. Biophysical circumstances can prohibit WSUD placement, while socio-economic factors seem to have a more accidental, potentially unintended effect. Urban areas that may highly benefit from WSUD may thus be overlooked. Intrinsically interwoven, these three aspects constitute the physical and social fabric of city scapes, which build the stage for WSUD integration.

Melbourne's current policy and guideline frameworks do not prevent ad-hoc and opportunistic planning practices to dictate WSUD placement. Ad-hoc planning does not promote equitable distribution of WSUD. In Melbourne it has led to the overrepresentation of WSUD in communities with low environmental awareness, low education levels and low sense of community, as a result of the specific urban structure.

To make WSUD successful, it is critical for urban planners to start incorporating a wide variety of biophysical, socio-economic and urban form factors in their decision-making. Currently, we lack understanding of the urban context in relation to WSUD placement, restricting our capacity to increase strategic approaches. This study is a first attempt to address this gap, but increased efforts from government and water authorities/utilities to create and maintain high quality asset inventories are called for. Therefore, recent trends towards more strategic and integrated planning for WSUD are encouraging and have the potential to significantly improve the outcomes of water quality, flood safety and amenity for urban communities.

Future research should focus on replication of this work in comparable urban landscapes with WSUD found across Australia and North America, such as the green champion city of Portland in the USA (Netusil, Levin, Shandas, & Hart, 2014), as well as for those in Europe and Asia, where urban growth is governed by different patterns. Including other/more factors is important, as our study is limited and doesn't include important variables such as land ownership. The outcomes of this and future studies should be used to raise awareness among urban planners about the outcomes of their current processes. They call for the development and application of practice guidelines, strategic approaches and planning support systems that enable integration of a broader set of criteria in addition to biophysical design parameters.

Appendix A

See Fig. A1

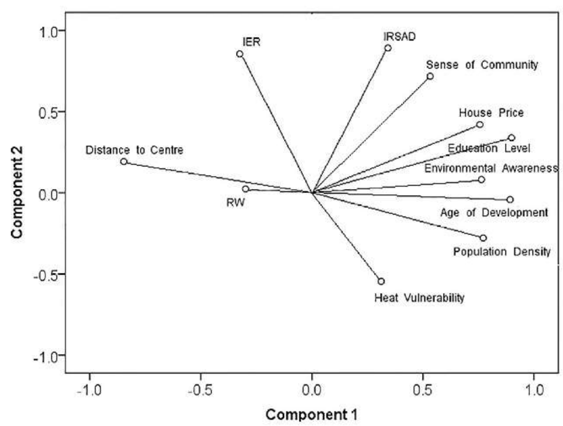

Fig. A1. Component plot in rotated space.

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3.3 ACKNOWLEDGEMENTS

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3.4 FINAL REMARKS

This chapter tested hypothesis H2: Spatial distribution of WSUD in Melbourne is largely driven by biophysical and urban form related factors, while socio-economic and other factors are largely disregarded. The hypothesis was found to be valid. Biophysical factors are strongly related to WSUD placement. Even though there is also a strong relationship between socio-economic factors and WSUD locations, against the hypothesis, this relationship seems accidental and the result of a different driver: the distance to the city centre and/or the age of development. As this study was merely an analysis of planning outcomes, conclusions about the causes of these outcomes remain somewhat speculative. The results of this study suggest an ad-hoc and opportunistic planning process to drive the spatial distribution of WSUD in Melbourne. This potential lack of strategy is concerning, as money and effort invested in WSUD may not result in optimal outcomes for urban communities in terms of equity, environmental protection, flood protection and other benefits derived from green technologies. The planning practices that lead to these sub-optimal outcomes are the subject of the following chapter.

CHAPTER 4

WSUD PLANNING PRACTICE

In troebel water is het goed vissen

"It is good fishing in turbid waters"

--Unclear or chaotic situations provide an opportunity for gain--

4.1 INTRODUCTION

To provide the best possible planning support, this PhD has deeply engaged with the planning practice. Relevant aspects to consider for strategic planning of WSUD were discussed in Chapter 2 and compared to the current distribution of WSUD systems in Melbourne in Chapter 3. This chapter discusses Melbourne's urban planning practices and identifies strengths and weaknesses. It also explores the needs and opportunities for planning support systems (PSS) to enhance them. Background, methodology, results, discussion and conclusions of this work have been published in *Environmental Science & Policy* and are presented in section 4.2. This research was approved by the Monash ethics committee (Appendix B).

This work responds to the second objective of this PhD: **"Understand current spatial and organisational trends of WSUD planning in Melbourne"**, more specifically to the 'organisational' part of this objective. To this end, this section seeks to answer research question RQ3: *What is the perception of the level of strategic WSUD planning and the role of PSS by practitioners in Melbourne and how can we close the implementation gap in this context, if there is one?*

To answer this research question, the following hypotheses were tested:
H3a: Planning processes for WSUD placement are ad-hoc and opportunistic and the use of PSS limited to a small number of prominent examples.
H3b: We need PSS that are user-friendly, conceptually simple, relevant and connect to the planning practice

Testing of these hypotheses was conducted using qualitative research methods drawn from social sciences. These methods included semi-structured interviews (for interview protocol, refer to Appendix C) and workshops with planning practitioners from local- and state government, consultancies, the water authority and a water utility.

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4.2 WSUD PLANNING PRACTICE AND PSS

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Building effective Planning Support Systems for green urban water infrastructure—Practitioners' perceptions

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Strategic planning

ABSTRACT

The multiple benefits of adopting distributed, green stormwater technologies in the local environment are increasingly recognised, particularly in relation to water quality, flood mitigation, amenity and aesthetics. To advance the integration of these systems into everyday decision-making practices, Planning Support Systems (PSS) are considered vital. Despite several PSS available to support planners and key decision-makers, their uptake remains constrained; a phenomenon known as the 'implementation gap'. While scholars have hypothesised why the adoption of PSS is limited, there remains little empirical investigation regarding the reasons why. This paper tests the hypotheses underlying the implementation gap in relation to water sensitive urban design (WSUD) planning. Drawing on the tacit experience of 24 key urban water planning professionals in the front-runner city of Melbourne, Australia, in-depth semi-structured interviews were undertaken to unpack the contemporary planning processes used and reveal characteristics leading to success and failure of PSS application. Data analysis revealed WSUD planning professionals regard the adoption of PSS as a significant step towards improving contemporary decision-making practices, which are regarded as opportunistic rather than strategic. PSS use was widespread, though the type, intensity and sophistication of use varied among interview participants. Confirming the hypotheses from planning literature, practitioners suggested PSS need to be user-friendly and align closely to planning practice. Additionally, however, it was found that it is crucial for PSS to meet industry conventions. Suggested improvements to current PSS included incorporating socio-economic factors alongside biophysical and planning factors, hence the role for GIS-based suitability analysis tools. Overall, this study provides current and future PSS-developers with critical insights regarding the type, function and characteristics of an 'ideal' PSS aimed at enhancing the usefulness and uptake of PSS, and thus improve planning that supports expediting green infrastructure implementation.

1. Introduction

1.1. Background

Cities around the world are confronted with the negative impacts of increasing urbanisation and climate change. Impervious surfaces and changing weather patterns cause urban waterway degradation and increase flooding risks (Gill et al., 2007). Responding to this situation, Water Sensitive Urban Design (WSUD) in Australia, and similar concepts such as Low Impact Development (LID) in the US, Sustainable Urban Drainage Systems (SUDS) in the UK and Sponge Cities in China, have gained attention over the past decades as an adaptation and mitigation strategy that increases the liveability and resilience of cities (Fletcher et al., 2014). At the core of this strategy are distributed 'green' drainage infrastructures, such as raingardens and constructed wetlands. The application of varied multi-functional green infrastructures is aimed at protecting water quality, mitigating flood risks and providing additional benefits, such as improved amenity values, micro-climate and ecological habitat (Wong and Brown, 2009). Globally, the number of WSUD systems being adopted is growing. To ensure that technologies perform to their full capacity and deliver the full suite of benefits, due attention to their context is required to achieve successful integration into the urban landscape (Kuller et al., 2017).

WSUD departs from large scale, centralised single-objective urban

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drainage systems that are predominantly hidden from the public eye. However, the multi-functionality of WSUD technologies widen the policy and decision-making contexts, for well-designed and well-situated WSUD assets can go beyond just urban drainage, to incorporate biodiversity targets, improved aesthetics and amenity and potential micro-climate benefits, among others (Fletcher et al., 2014; Sharma et al., 2016). With this in mind, strategic planning practices are required to incorporate all aspects of the urban context for WSUD integration: biophysical, socio-economic and urban form (Kuller et al., 2017). The multitude of relevant aspects and considerations make WSUD planning a complex task that calls for vertical (between different levels of government) and horizontal (among municipalities) alignment and integration of key policy and decision-making contexts. Indeed, Morison et al. (2010) highlight the importance of high levels of internal (between departments within an organisation) and external (between organisations) collaboration required to accomplish this integration (Morison et al., 2010). Currently, vertical misalignment of high-level policy is exacerbated by differences between municipalities in their levels of capacity and commitment to WSUD planning (Morison and Brown, 2011).

Effective planning for integrating WSUD technologies into the landscape requires an understanding of the varying functionalities associated with different WSUD approaches, a high-level of planning expertise and readily available data. Yet, current WSUD scholarship continues to highlight how the internal capacity of municipalities, where the majority of detailed WSUD planning is undertaken, is constrained by factors such as insufficient technical skills, high levels of staff turnover and lack of dedicated resources, among others (e.g. Brown et al., 2009a; Morison and Brown, 2011). To overcome these internal challenges, external expertise from engineering consultancies is typically sought. This has led to ad-hoc and opportunistic planning practices, which may result in long-term, sub-optimal outcomes (Kuller et al., 2018). Indeed, as Malekpour et al. (2015) highlight, reactive and incremental approaches to planning are ill-suited to guide a transition towards widespread adoption of WSUD approaches.

1.2. WSUD: urban planning and Planning Support Systems

Planning Support Systems (PSS) may be well suited to aid urban planning practitioners (Klosterman, 1997) and may help to overcome the challenges associated with collaboration and alignment of goals and interests in the water sector (Crona and Parker, 2012; Gibson et al., 2017). A myriad of PSS is available to planning practitioners (Kuller et al., 2017), including several recent PSS focussed on supporting WSUD implementation, such as UrbanBEATS (Bach, 2014), SUDSLOC (Ellis and Viavattene, 2014) and more (refer to Fig. 1) (Brown et al., 2009b; eWater, 2011; Fronteira et al., 2014; Makropoulos et al., 2008; Montalto et al., 2013; Morales-Torres et al., 2016; Rossman, 2010; Sitzenfrei et al., 2013; van de Ven et al., 2016).

The application of PSS is widely promoted in academic scholarship (e.g. Geertman and Stillwell, 2012; Klosterman, 1997; te Brömmelstroet, 2013) based on the recognised value of PSS in dealing with the growing complexities of urban planning tasks (Geertman, 2016; Poch et al., 2004). Nevertheless, the reported level of PSS uptake among planning professionals remains low (e.g. Gibson et al., 2017; te Brömmelstroet, 2013; Uran and Janssen, 2003; Vonk et al., 2005). The causes of this 'implementation gap' have been widely hypothesised over the past two decades. Although still the subject of academic debate, there is a growing consensus the implementation gap is the result of: limited exposure to and experience with PSS, a lack of data availability and quality, low user friendliness, and the simplicity and limited usefulness of outputs (te Brömmelstroet, 2013; Vonk et al., 2005). Despite these insights, there remains a lack of empirical research focussing on practitioner perceptions regarding the causes of this WSUD planning the implementation gap (McIntosh et al., 2007).

Contemporary PSS scholars point to a lack of direct engagement between PSS developers and everyday planning practices and practitioners, as the core of the implementation gap (e.g. Crona and Parker, 2012; McIntosh et al., 2007; Pelzer et al., 2015; Rodela et al., 2017; te Brömmelstroet, 2013; Vonk et al., 2005). Indeed, the failure to directly engage with PSS end-users has led to a range of weaknesses in PSS design, which ultimately act as barriers to uptake, which are summarised in Table 1. Reflecting the temporal challenge in relation to advancing PSS uptake, Table 1 reveals how similar challenges to those identified by Lee (1973) almost half a century ago are still relevant. Lee's (1973, p. 164), "seven sins of large scale models" p. 164: Lee (1973) closely mirror the contemporary barriers, including, among others: "hyper-comprehensiveness" (the drive to include too much detail in models), "hungriness" (the need for data inputs), "complicatedness" (high number of variables and relationships) and "mechanicalness" (deterministic, inflexible, inhumane thinking process of computers). Geertman (2016) concedes that many of these challenges are present today, though does acknowledge they vary depending on the domain of planning.

1.3. Aims and objectives

To advance WSUD implementation and avoid opportunistic implementation, this paper characterises practitioner's perceptions regarding the underlying issues associated with PSS adoption within the Australian urban context of metropolitan Melbourne. Drawing on the tacit experiences of contemporary planning practitioners engaged in WSUD practices, this qualitative research seeks to: (i) identify the perceived strengths and weaknesses of current WSUD planning processes, (ii) assess the current level and scope of PSS uptake and how this could be improved into the future to expedite WSUD implementation and (iii) compare the barriers to PSS uptake from literature with those found for WSUD planning. For the first time, the implementation gap is empirically tested for WSUD planning. It is one of the few attempts, to date, to empirically test the hypotheses for the PSS implementation gap in urban planning in general. Many important causes hypothesised to underlie the implementation gap were confirmed by our findings, such as user friendliness and relevance to the planning process. However, some other issues were found that were not before described to play a role in PSS uptake, most notably whether a PSS is industry convention. This research is undertaken in the context of the development of a novel planning support tool and will inform its design. In addition, it is anticipated that this research will provide PSS developers with critical insights regarding success factors for PSS uptake, enabling them to develop more successful models and tools to further urban planning practices.

2. Research approach

To explore how PSS can improve WSUD planning, two overarching research questions were formulated: (1) How are the characteristics of current WSUD planning practices and their outcomes perceived by planning practitioners? (2) What is the current and potential role that PSS can play to improve WSUD planning and (3) how can we improve the suitability of PSS towards this strategic planning for WSUD? While the answers to questions 1 and 2 are captured in the interview data, the discussion posits key design feature that might be necessary to improve PSS for WSUD planning (question 3). This qualitative research adopts a single case study design Creswell (2012) across multiple scales. Melbourne (Australia) was selected as our case study location. Melbourne has been on the journey towards WSUD for over a decade (CSIRO, 1999), gaining experience with WSUD implementation on the ground (e.g. Melbourne Water, 2005) as well as in policy throughout all levels of government (Brown et al., 2013). A strategic commitment towards WSUD is expressed from state (DELWP, 2016a,b), as well as local levels of government (e.g. City of Melbourne, 2017; City of Whittlesea, 2012), shaping an enabling context for ongoing WSUD development. We

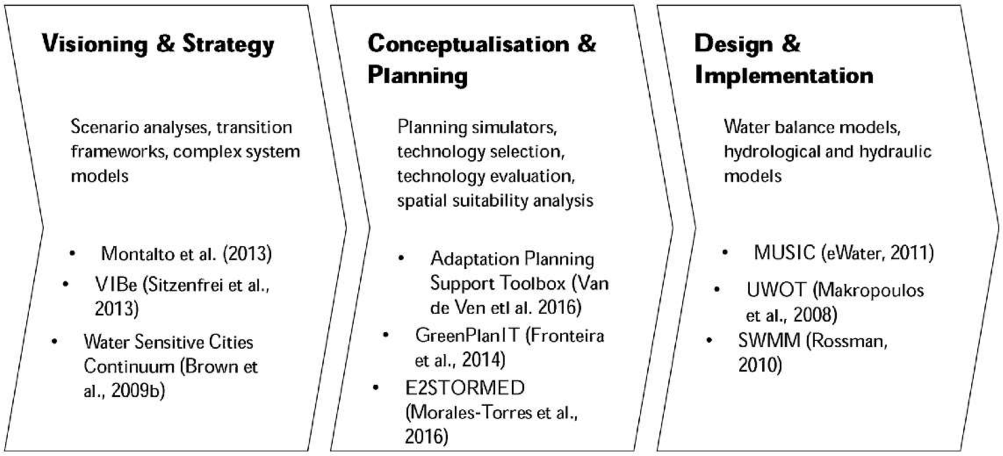

Fig. 1. Planning stages (top) and with associated PSS types (middle) and examples (bottom).
Adapted from Kuller et al. (2017).

Table 1
Barriers to a wider uptake of PSS, as identified in contemporary PSS literature.

Category	Issue	Description	References
Inputs	Data availability	Existence and availability of required data	Vonk et al. (2005)
	Data quality	Quality of available data	Vonk et al. (2005)
Outputs	Relevance	Outputs useful to the planner. Special emphasis on the need for spatial outputs	Vonk et al. (2005), Uran and Janssen (2003), te Brömmelstroet (2013), Hajer et al. (2010) and Gibson et al. (2017)
Design	Complexity	The dichotomy between complexity and useability	te Brömmelstroet (2013), Geertman, 2016, te Brömmelstroet et al. (2014) and Gibson et al. (2017)
	Transparency	Openness about processes and assumptions	Vonk et al. (2005), te Brömmelstroet (2013), te Brömmelstroet et al. (2014)
	Flexibility	Capacity to deal with different inputs, requirements and link to other tools	Vonk et al. (2005) and te Brömmelstroet (2013)
	User friendliness	Ease of use, graphical interface	Vonk et al. (2005) and te Brömmelstroet (2013)
Scope	Too technical	Focus on technical issues rather than planning process and 'soft values'	te Brömmelstroet (2013), te Brömmelstroet et al. (2014) and Pelzer et al. (2015)
	Meeting planners needs	Supply focussed rather than demand focussed. Strong need to engage more with the planning practice	Vonk et al. (2005), te Brömmelstroet and Bertolini (2008), Uran and Janssen (2003), te Brömmelstroet (2013), Geertman (2016), te Brömmelstroet et al. (2014), Pelzer et al. (2015) and Gibson et al. (2017)
User	Experience	Experience with PSS of individuals and organisations	Vonk et al. (2005), te Brömmelstroet and Bertolini (2008) and Gibson et al. (2017)
	Awareness	Awareness of the existence and potential of PSS	Vonk et al. (2005)
	Capacity and support	Expertise within the organisation and support (manuals, online help, etc.) to user of PSS	Vonk et al. (2005)

focussed on both state and local levels of government, where policy and implementation of WSUD occurs. Furthermore, our focus extends to private engineering consultants, to whom parts of the planning process are outsourced by government organisations.

Data collection included in-depth semi-structured interviews of between 45 and 90 min each (Creswell, 2012). Research participants were selected to represent practitioners typically involved in WSUD planning from the state context, through to municipal governments, utility services and engineering consultants, which provided a vertical representation sample (Fig. 2). Horizontal representation was achieved by selecting individuals from across the metropolitan area: inner, middle and outer municipalities. This was considered necessary for across greater metropolitan Melbourne there is a large variance in urban form, age, demographics and socio-economic characteristics, planning priorities and commitment to WSUD (Morison et al., 2010). A total of 24 practitioners were interviewed across 19 interviews.

Interview questions were grouped in two broad themes, aligned with the main research objectives. Participants were asked: (i) to identify what aspects within their organisation may improve the planning process, (ii) if they had ever used PSS and why (not), and (iii) to suggest a list of good/bad characteristics related to PSS that they are aware of. To form a reliable and balanced insight regarding participant's tacit knowledge and experiences, questions were formulated both negatively and positively (e.g.: "What are the success factors of your organisation's planning process?" and "What could improve in your organisation to make the planning process more successful?"). Further probing questions were used to encourage deeper conversation regarding the subject's detailed experience and opinion.

Interviews were analysed through using transcription, followed by an iterative process of coding and grouping answers into emerging 'themes', in line with the interview questions. Themes were assessed for their relative importance through quantification of occurrence and compared between municipal and non-municipal respondents. Further grouping of different and opposing answers within themes was performed, to uncover story lines across the interviews. Although descriptive statistics were gathered about issue mentions to build evidence for relative importance of the emerging themes, no further quantitative or statistical analysis was performed as this study's set-up was qualitative in nature.

The findings from the interviews were validated through a stakeholder workshop and analysis of relevant secondary data. The workshop involved 16 people from similar organisations as the interviewees (state government, water utility, councils, private consultant) and was designed to cross-check (validate) the answers provided by

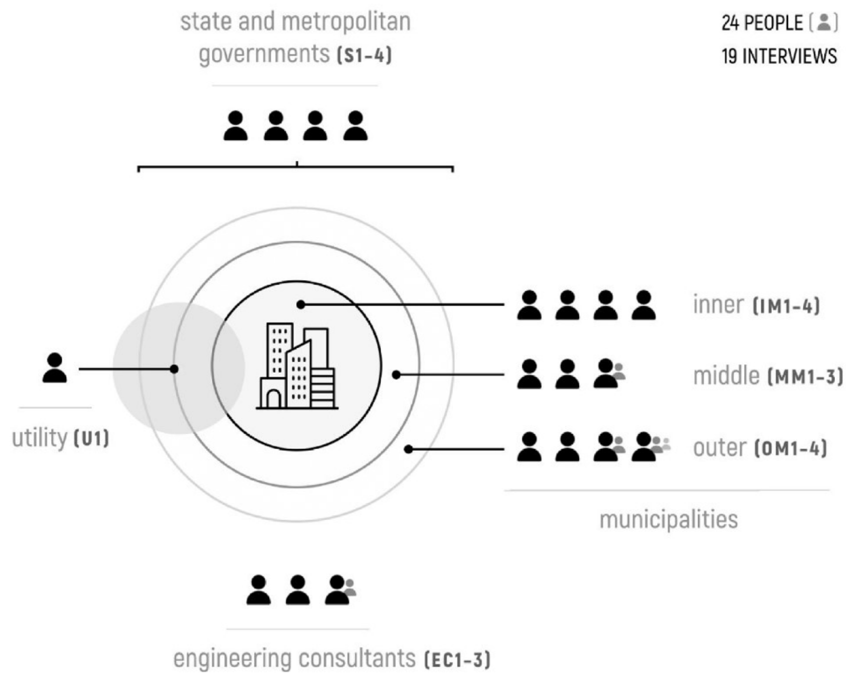

Fig. 2. Representation of research participants from the interviews.

interviewees, assist in deepening our understanding and to consolidate the results. In addition, secondary data, including government policy documentation and municipal strategies and planning documents, were examined to provide context and insight regarding the enabling context for WSUD planning and decision-making.

3. Results

3.1. Contemporary planning processes

Considerable experience with WSUD planning has been gained by planning practitioners in Melbourne over the past decade. Nevertheless, it is still regarded as a relatively novel concept. Important to note is the difference between planning for greenfield- (development of rural land) and infill (development of existing urban land) developments. While the former is relatively well structured and set in policy (e.g. clause 56.07 of the Victorian Planning Provisions, which sets the requirement for integrated water management in residential subdivisions: DELWP, 2017), the latter is significantly more challenging. Greenfield developments occur in the outer municipalities, while infill is done mostly in the inner and middle municipalities.

Across all stakeholder groups, respondents identified internal (between departments within the organisation) and external (between organisations) collaboration as key for advancing WSUD planning (Table 2). Despite this recognition, insufficient levels of external collaboration were identified, particularly between municipalities. This was found to be caused by restrictive differences between municipalities in levels of commitment to WSUD and the sophistication of internal planning processes. Individual respondents, who self-identified as being less committed to WSUD, highlighted organisational rigidity and risk-averse management styles, hindered process and practice innovation. A recent initiative by state government, called *Water for Victoria,* facilitates regional collaboration through platforms that aim to bring together planning professionals from all municipalities within an urban catchment (DELWP, 2016a). This initiative illustrates the growing recognition of the need for increased collaboration at catchment scales and the potential for PSS to facilitate this.

While reactive, opportunistic and ad-hoc approaches were identified as the greatest threats to good WSUD planning, most respondents indicated the need for local water strategies to address this. Municipal respondents noted that these would be useless without the backing of legislation and policies across all levels of government, to mitigate against the challenges of changes in government and resulting priority setting. Another barrier identified by some respondents was long turnaround times (of up to 10 years, according to respondent OM3) between the conception and implementation of WSUD strategies.

Finally, the challenge of building a business-case reflecting the benefits of green systems was identified as a significant challenge by respondents across organisations. These benefits are very difficult to measure and translate into dollar values. Although an increasing amount of research is emerging (e.g. Boyer and Polasky, 2004; Niu et al., 2010; Tapsuwan et al., 2014), its application is not currently apparent in practice. One potential solution according to our participants was the development of better 'tools' and models. Tools were furthermore identified as important to aid strategic planning by optimising locations for WSUD.

Despite the challenges and barriers to contemporary planning practices identified above, there was a feeling of optimism among participants, along with a strong sense that progress has been made in WSUD planning and implementation over the past decade. Participants showed great willingness to learn and work towards removing the remaining barriers.

3.2. Planning Support Systems in WSUD planning

Interviews revealed that tools and models are commonly used by municipal and non-municipal practitioners. MUSIC (Model for Urban Stormwater Improvement Conceptualisation) (eWater, 2011) and spatial software such as ArcGIS are most commonly used. These PSS are so well integrated into existing planning processes through state-based

Table 2
Issues with current planning processes for WSUD, as identified by Melbourne planning practitioners. Ordered from high to low frequency.

Issue[a]	Qualitative explanation examples[b]
Internal and external collaboration (6,9)	• It is good that we are here to negotiate between stakeholders (S4) • "Collaboration is not always happening, it is easy to just focus on your own core business. Collaboration is ad-hoc, not formalised. That's why we're starting [inter municipal] forums." (S1) • "Every organisation has its own role and goals and agenda. Sometimes they conflict. Melbourne Water is most important for WSUD." (U1) • "There is a lot of talk about Integrated Urban Water Management, but it is not happening. Everybody is chasing their own KPI's." (EC3) • "To improve between departments, we try to publish together. Having young people also helps." (OM3) • "What is good is that everyone in the water sector talks to each other." (MM2) • "Our project steering team worked really well to get buy-in from the entire municipality." (OM1) • "We still work together with other departments, but that is more about managing existing [WSUD] assets." (IM4)
Opportunistic and ad-hoc planning (5,8)	• "Municipalities used to be very opportunistic, following road renewal, which is poor in terms of strategy." (S3) • "Planning is opportunistic, putting assets whenever they [municipalities] have money, wherever they can." (EC1) • "We are too reactive. We may be throwing money at things we don't want." (MM2) • "[We use] mostly opportunistic and ad-hoc planning. We are not being holistic about WSUD, now only focussing on flood." (MM1) • "We are not comparing locations or looking at catchments strategically." (IM1) • "For new developments, developers usually just chuck WSUD in, and I have to go out and check it." (MM3) • · "We need to plan them [WSUD] better, where they suit, where they're needed." (IM3)
Presence/absence of local strategy or water plan (3,8)	• ·"The urban water cycle is integrated, so should planning be." (S1) • "We need our systematic approach back." (IM3) • "We have an in-house strategic plan that drives our commitments to WSUD. We have guidelines though for WSUD covering the whole process, which helps." (OM1) • "Recently we have moved to a more strategic approach, with priority catchments based on Directly Connected Impervious, … Early stages, trying to do it such that projects don't delay too much." (OM3) • "We have no strategic plan anymore, and no money anymore either." (IM4)
Justification, business case (4,6)	• "Furthermore, we don't have proper ways to measure costs and benefits." (S2) • "[Our new framework shows] where to allocate risks, costs and benefits. Where and who are benefitting and paying. Also [it enables] to see extra benefits." (S1) • "We need a better way to strategically balance different priorities…, we don't integrate the extra benefits or compare between department wishes but consider them separately." (IM1) • · "Problem is that the drivers aren't necessarily economic, it doesn't financially stack up 'cause the extra benefits are amenity, draught [mitigation], bbq's etc." (MM3)
Presence/absence of legislation and policies (2,6)	• "…but mainly it is all about legislation, and the legislation has to change to incorporate incentives for municipalities and developers… Standards accepted by industry like the guidelines and 80-45-45 [reduction targets] really help." (S4) • "We've streamlined statutory planning and got all experts we need." (IM2) • "We need organisational policy to take the discretionary element out of it [planning]." (OM1) • "Our guidelines should have WSUD as a requirement." (MM1) • "We hold the hands of developers to design it [WSUD], and we have the backing of our policy, which is very important. Before it was very hard to make them do what we wanted." (MM3)
Community issues (0,8)	• "The 'will' needs to be there with all the people involved [including community] to do things. This is what I found worked so well in The Netherlands." (OM2) • "Smaller systems are less accepted when not maintained…. Acceptance is also an issue for [water] recycling." (MM2) • "People hate raingardens." (IM3) • "Residents have a stake as they pay [for WSUD], and they're not always in favour. Lot of what I do is communication therefore." (OM4)
Differences between municipalities (1,7)	• "There's some municipalities that are ahead of others." (OM3) • "We are not as advanced as IM2." (MM2) • "…we're far ahead of other municipalities." (IM2) • "We're different from other municipalities in that we do more with infiltration." (OM4)
Need for tools/models (2,4)	• "Limited models and tools [available] for infill planning." (S2) • "A tool could be incredibly helpful. We are trying to do a 4-year planning thing and make that more visual. Trying to find a way with our GIS." (IM4) • "Also a graphic DSS approach for finding the locations [for WSUD] in catchments is important." (MM1) • "[My role is] opportunity mapping, finding locations [for WSUD]." (IM2)
Organisational rigidity (2,4)	• "[There is] limited innovation, especially for brownfields." (S2) • "[A problem is] rigidity and the amount of rules, no freedom or out of the box thinking, which leads to just ticking boxes. If you only want simple assets that are easy to maintain, it is difficult to innovate." (EC3) • "WSUD is a novelty, but planners are comfortable with the risk it brings and accept failure." (OM3) • "I was surprised how hesitant they [managers at municipality] were [towards WSUD]." (MM1) • "People do what they're used to [traditional drainage]." (IM4)
Progress (1,5)	• "In 50 years from now, sustainability will be the norm, and everything will be changed and accepted." (S4) • "Appreciation for WSUD is growing." (MM3) • "We are learning. Over the years our engineers became more skilled with MUSIC [model]." (MM2) • "Info for decision making is growing the past five years." (OM3)
Time constraints (2,2)	• "…tough timeframes, which lead to suboptimal results and cutting corners." (S4) • "Consultants are asked a lot for little money, especially with rate capping [decreased municipal income]." (EC1) • "Bigger team would be good." (IM4)
Turnaround times (1,3)	• "The time between plan and implementation is 10 years." (OM3) • "Implementation takes 1–2 years. Wetlands take longer, about 5 years. Processes are slow moving." (MM2)
Reliance on personnel's expertise (0,4)	• "Our planning is risky, as it relies on people's experience." (OM1) • "We've been losing expertise after restructuring." (MM1) • "…but up to now decision making is done manually, depending on people's knowledge." (IM1)

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Table 2 (*continued*)

Issue[a]	Qualitative explanation examples[b]
Costs (2,1)	• "Race to the bottom for getting the cheapest consultancy." (EC1) • "With rate-capping our budgets are constrained, pushing towards traditional drainage." (IM4)

[a] Between brackets: (# non-municipal respondents, # municipal respondents).
[b] IM: Inner Municipality, MM: Middle Municipality, OM: Outer Municipality, S: State government, U: Utility, EC: Engineering consultancy.

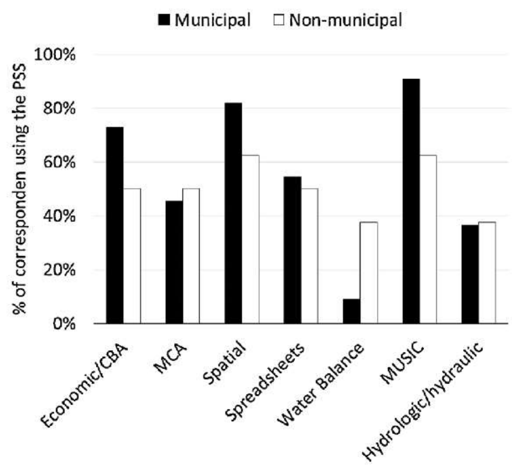

Fig. 3. Types of WSUD-PSS used by planning practitioners in Melbourne. CBA: Cost-Benefit Analysis, MCDA: Multi-Criteria Decision Analysis.

regulation (i.e. MUSIC) and standard industry practice (i.e. spatial software), that municipality respondents often forgot to mention these when they were asked about PSS usage. Other widely applied PSS included Cost-Benefit Analysis (CBA) and spreadsheet-based tools (Fig. 3). The main driver behind adopting a PSS is the requirement from a manager or outside organisation (e.g. client for a consultancy). Furthermore, individual choice and industry convention play a big role. Even though a certain level of engagement with PSS is common, their application tends to be limited to WSUD functional design and asset management. Specialised PSS, designed to aid strategic planning for WSUD, were rarely used and limited to non-municipal stakeholders, due to the barriers listed in Table 3, including user friendliness and training requirements.

Simplicity within a PSS was identified as paramount for planning practitioners to start utilising it. Key aspects such as: user-friendliness, minimal training requirements and low complexity (i.e. a heuristic rather than accurate) were identified as critical success factors for PSS (Table 3). Whilst non-municipal respondents acknowledged the need for PSS to adequately reflect the complex nature of reality within the tools, benefits were also recognised in the trade-off between complexity and usability. Tools that are considered "industry convention", such as MUSIC, were generally preferred, enjoying higher levels of confidence among users in the sector. As is the case with MUSIC, the process of becoming an industry convention is often driven by their position as a requirement in policy and regulations. However, MUSIC alone is not enough to facilitate strategic planning of WSUD, as its focus is limited to technical design and sizing of infrastructures (see Fig. 1). Furthermore, interviewees noted the relevance of output generated by tools as important, with emphases being placed on producing visual outputs such as maps. Such outputs are easily understood by non-experts and provide a strong vehicle for communication of ideas and opportunities both within as well as between organisations. Technical specifications, including the availability and quality of required input data, flexibility, transparency and accuracy also play a role, albeit to a lesser extent.

Familiarity with tools and their potential to aid planning practices was only occasionally put forward. However, limited awareness of the PSS available to practitioners, particularly among municipality respondents, indicated this is an important barrier to PSS uptake as well. Costs associated with acquiring PSS were found to play a very limited or no role in the decision to use them. In fact, whenever costs were mentioned, they were specifically denied to play a role. This may partly be due to the cost of adopted PSS being relatively insignificant. Important to note with each of the barriers identified in this study is that they reflect the perception of the practitioners interviewed. This reality may not always resemble the actual limitations of PSS, as pointed out by Gibson et al. (2017).

When discussing key facets a PSS needs to possess, interviewees agreed that a variety of biophysical, socio-economic and urban form factors should be considered. Notably, while all three were considered important by most respondents (urban form: n = 17, biophysical: n = 16 and socio-economic: n = 14), a clear hierarchy of importance emerged based on the frequency of interviewees' responses. While about half of the responses related to urban form and a third to biophysical factors, less than a fifth of factors mentioned were socio-economic. Although socio-economic factors being recorded less, many participants highlighted that these factors, such as environmental awareness and socio-economic status, were important components in the overall planning process and, to date, have been largely overlooked.

3.3. *Comparing barriers to PSS uptake*

Comparing WSUD planning with other urban planning practices, the relative novelty of WSUD is reflected in both the development and uptake of PSS. A small number of fundamental tools are widely utilised, but the development of tools aimed at strategic planning is recent and their uptake still limited. If we compare the causes of the implementation gap from Table 1, with our barriers to PSS uptake in WSUD planning from Table 3 (see Table 4), great similarities are apparent in the issues that can stifle and promote the uptake of PSS, as all but one of the topics identified in Table 1 also play a role for WSUD planning.

Notably, WSUD planners did not identify a focus on technical outcomes as a negative issue of PSS. As the process of WSUD planning inherently integrates water engineering with urban planning, this points towards a greater need for technical details. Furthermore, whether or not a tool is industry convention has a great impact on its use for WSUD planners, as illustrated by the success of MUSIC (eWater, 2011). This is closely related with the amount of trust that planners put in PSS. Neither issue was encountered by planners from other fields.

In response to the call by Geertman (2016) to focus on success stories rather than barriers to the uptake of PSS in order to close the implementation gap, we extend our focus on MUSIC. This tool used for WSUD sizing and design was widely seen as a hallmark of success by the Melbourne planning community. Although it certainly is not free of criticism, it is widely used and well appreciated. Multiple qualities, as identified by its users, are at the base of this success and include the perception that the tool is: (i) industry convention, (ii) a requirement in policy, (iii) relatively simple to use and intuitive, (iv) well supported and transparent through training and documentation, (v) robust and trustworthy. These findings, and the other findings from Table 4 are crucial lessons in the context of the development of novel PSS approaches to support WSUD planning in the future.

Table 3
Characteristics inhibiting and promoting PSS uptake as identified by planning practitioners in Melbourne. Ordered from high to low frequency of mention.

Issue[a]	Qualitative experience examples[b]
User friendliness (5,7)	• "MUSIC is simple and easy to run, without technical skills." (S3) • "Intuitiveness is important, not even simplicity." (U1) • "Functionality rather than ease of use. We don't care about the looks." (EC3) • "Models need to be simple to use for planners, as there is a large turnover." (OM3) • "Needs to be super, super simple for people to use it." (OM2) • "It needs a good user interface and manual, so you can learn it yourself. MUSIC is great, very intuitive." (OM4)
Training, time investments (4,8)	• "MUSIC is a good example, it seems to work, easy to use and training is provided." (S2) • "Training time it takes [to learn a tool] is important." (U1) • "We don't use tools because we don't have time [to learn them]." (MM2) • "It [MUSIC] is complex and you need training. Colleagues struggle, so do developers." (MM3)
Complexity dichotomy (5,5)	• "Although complex tools are useful, 90% of the users will only use the basic functionality." (S2) • "Tools that do more than their core, become too cumbersome to use." (S1) • "Complexity is a trade-off, depending on the task at hand...Only adding complexity where it adds rigour." (EC1) • "Don't put too much in one too. Simple enough to use, but robust enough to drive a wide range of outcomes." (IM2) • "I prefer not to use a too complex model, as I don't know how to do or interpret it." (IM1)
Industry convention (5,5)	• "People rely too much on MUSIC. There is no competition, so there's a monopoly." (S3) • "If everybody uses them and trusts the results, a community builds around it that keeps it being developed further." (U1) • "...but there needs to be a critical mass of users." (IM2) • "If it's a requirement, it makes it easier." (IM3) • "...but also how it syncs with what other municipalities do." (MM1)
Clean, relevant, compatible output (4,5)	• "...and the effectiveness of output it generates that is easy to interpret." (EC3) • "Making the message clear, simple and quick to understand by using visuals makes the likelihood of it going up with directors or funders higher." (IM1) • "Storm [a WSUD PSS] is simple to assess [the output], you get a score. People who don't know WSUD can still use it." (MM3)
Costs[c] (3,5)	• "...but if we really need it, paying shouldn't be a problem." (S1) • "To a degree cost and open source are important. I am a huge open source fan." (U1) • "Money not so much [of an issue], I am happy to fund that from a strategic point of view." (OM1)
Input data (quality, quantity) (3,4)	• "The value of the answer should justify the effort of inputting, so the less input the better." (S2) • "On a detailed scale, data is very limited, which is a big problem." (IM2) • "...low level of data input and no expertise needed. ...control over inputs." (IM1)
Flexibility (3,4)	• "Source is very flexible, you can tweak it to do what you want." (U1) • "I like to be able to access command line interfaces, so I can do batch running." (EC1) • "...customisability, so it can be used in the local context." (OM4)
Trust (4,3)	• "the problem with a tool when it is not scientifically sound is that sceptics with shoot it down." (S2) • "Trust of the data is very important, especially to engineers." (IM3) • "I trust MUSIC, so much money has gone into development. It's robust, doesn't need replication." (MM3)
Transparency (5,0)	• "Jargon is another problem. ...difficult to navigate, not transparent, black box is not used by people." (S3) • "MUSIC is well documented and transparent, so I trust it." (U1) • "Transparency is generally important...but if it is too complex, you don't need to know the algorithms." (EC1)
Accuracy (2,1)	• "GIS need to be geographically accurate." (S4) • "Making it as simple as you can without losing too much accuracy, because there is no point in coming up with a simple, but wrong answer." (EC1)
Familiarity (1,1)	• "There's lots of them [PSS] out there, but municipalities just don't know about them." (S3) • "We don't know about them and don't have them." (MM2)

[a] Between brackets: (# non-municipal respondents, # municipal respondents).
[b] IM: Inner Municipality, MM: Middle Municipality, OM: Outer Municipality, S: State government, U: Utility, EC: Engineering consultancy.
[c] Even though costs were mentioned reasonably frequently, with only one exception these mentions were dismissing its role.

4. Discussion

4.1. Challenges to WSUD planning

Despite the proven benefits of, and ongoing commitment towards WSUD, the planning and implementation of WSUD still faces challenges. These challenges, as identified by our research participants, are not exclusive to the WSUD planning process. For example, need for collaboration to mobilise knowledge and increase the capacity of local planning actors is widely recognised (e.g. Allmendinger and Tewdwr-Jones, 2002; Healey, 1998). Indeed, Brand and Gaffikin (2007) argue that as our world becomes increasingly complex and unpredictable, collaborative planning becomes essential. WSUD planning provides a fitting example of such increased complexity for at least two reasons: it responds to multiple objectives (e.g. water quality improvements, flood mitigation and amenity) and has a reciprocal relationship with the urban landscape, of which it is an integral part (Kuller et al., 2017). Although planning practitioners acknowledged the fact that governance structures around urban water management in Melbourne are relatively advanced, they emphasise the need for ongoing improvement of collaborative practices, particularly within their organisation. PSS provide a great potential to support and enable collaborative approaches by providing a platform for discussions and a vehicle for communication of ideas among stakeholders of diverse backgrounds and views (Kahila and Kyttä, 2009). Particularly GIS-based PSS with visual outputs have proven beneficial to planning (e.g. Balram and Dragićević, 2005; Smith et al., 2013).

Opportunistic planning practices dominate WSUD implementation. Although participants accept the importance of strategic, integrated planning when it concerns the complexity of water management, ad-hoc decision making still prevails, as illustrated by the following quote from a state government participant (S3):

– "It [the *living rivers* project, a WSUD implementation project in Melbourne] started off at a very opportunistic basis, so we went to councils [municipalities] and say: *Are you planning any road renewal projects….?* […] *Would you put a raingarden in as you're doing it?* You know, it's cheaper once you're ripping up the road to do it, but that's um, in terms of a strategic approach that's very poor." –

Commonly, systems are implemented as part of road renewal, which provides a window of opportunity for cheap integration – thereby ignoring the need to consider a variety of context-specific factors crucial

Table 4
Comparing barriers to uptake of PSS as recognised with the planning literature (Table 1) and WSUD planning respondents (Table 3). The size of the circle indicates the level of importance. No circle means this issue wasn't identified to play a role.

General urban planning	Issue	WSUD planning
	Inputs	
●	Data availability	●
●	Data quality	●
	Outputs	
⬤	Relevance	⬤
	Accuracy	•
	Trust	●
	Design	
●	Transparency	•
●	Flexibility	●
⬤	User Friendliness	⬤
	Scope	
●	Complexity dichotomy	⬤
●	Too technical	
⬤	Meeting planner's needs	●
	User	
●	Experience	•
●	Awareness/ familiarity	•
●	Capacity	⬤
	Industry convention	⬤

for their success. The negative consequences of these opportunistic practices are increasingly felt: failing systems, high maintenance costs and deteriorating public attitudes towards WSUD. Despite the strong and continuing emphasis of planning literature on the need for strategic planning and policies (Albrechts, 2004; Solesbury, 2013), opportunistic planning practices are still prevalent. Fortunately, its negative outcomes are triggering the realisation in the WSUD planning community that strategic approaches are called for, embedded in clearly targeted policies. After collaboration, strategic approaches and policies are the most widely identified solutions to current planning issues.

Strategic planning is aided by PSS through tools such as Multi-Criteria Decision Analysis (MCDA) and Cost-Benefit Analysis (CBA) (Nijkamp and van Delft, 1977; Shefer and Kaess, 1990). They allows us to integrate what Lee (1973) called "soft values", such as socio-economic factors, with hard values of biophysical and urban form factors. MCDA and CBA also play a crucial role in building the business case for 'alternative' stormwater management practices (e.g. Urrutiaguer et al., 2010). Building a business case for WSUD was often perceived as problematic, since many benefits of green systems are indirect, public and difficult to measure. CBA and MCDA are particularly well equipped to deal with the high number of competing needs that inner-city municipalities face in their land-use planning. When coupled with GIS, MCDA has additional potential and a wide application towards strategic and spatially explicit forms of urban planning (Malczewski and Rinner, 2015).

Our findings confirm previous work done by Roy et al. (2008) regarding the limitations and variations in organisational capacities between municipalities and their organisational rigidity. They specifically emphasise "fragmented responsibilities, lack of institutional capacity, lack of legislative mandate, lack of funding and effective market incentives, and resistance to change" (Roy et al., 2008, pp. 344) among the most important impediments towards sustainable urban water management. Evidently, these impediments are persistent, as we still found them to be topical a decade onwards.

4.2. PSS for WSUD planning: an implementation gap?

Moving forward, it is suggested WSUD planning become increasingly (i) collaborative: connecting people and interests within as well as between organisations responsible for delivering WSUD; (ii) strategic: targeting measures that are sensitive to their environment and bring the greatest overall benefit and supported by enabling policies and local as well as regional strategies; and (iii) accountable: drawing from clear, communicable and quantified evidence on benefits to justify investments and incorporating community voices, preferences and interests in the process. An increased uptake of PSS could greatly stimulate a move towards better planning outcomes by addressing all three issues outlined above. It is therefore encouraging to find that most participants were positive and eager to learn and most claimed that improvements in the understanding of, and planning approach to WSUD were made in the past five to ten years.

It would be premature to declare the existence of the 'implementation gap' that was identified to exist for PSS uptake in other fields of urban planning. However, many of the ingredients identified in PSS literature regarding the "cause" of the implementation gap were present in WSUD planning (Table 4). Critical review of literature reveals the need for new tools that can support strategic planning for WSUD (e.g: Kuller et al., 2017; Lerer et al., 2015). In recent years, an encouraging trend towards the development of such tools is observed, with MCDA and GIS-based methods coming to the fore.

5. Conclusion

While urban planning practices greatly benefit from PSS, their uptake remains low. This phenomenon, known as the 'implementation gap', has emerged as a result of the lack of engagement from the developers of such tools with the planning practice. PSS development has become supply, rather than demand driven. Our research responds to this trend by deeply engaging with planning practice and the role of PSS through the analysis of planner's experiences and assessment of the existence, potential causes and solutions to the implementation gap for WSUD planning. For the first time, the implementation gap and its hypothesised causes are empirically studied for WSUD planning. Thus, it paves the road towards the development of more successful planning tools to support WSUD implementation.

Despite the more than 25-year history of development in this area, WSUD practices have not reached maturity yet. Most importantly, ad-hoc and opportunistic planning practices lead to sub-optimal outcomes. Eminent enthusiasm and goodwill from local practitioners is challenged by disappointing performance of WSUD systems. Processes are slowly improving through adaptive management resultant from practitioners' reflective learning. Some of the greatest room for improvement is to be made in inter and intra organisational collaboration, while bridging differences in capacity and sophistication between planning agents. Furthermore, strategic approaches to WSUD placement and justification for business cases are urgently required.

Although they should not be regarded as a panacea, certain PSS can be well-suited to assist these improvements. Indeed, a selected number of PSS is commonly used by WSUD planners, but their focus is mostly on technical design. Although isolated cases of strategic PSS application exist, their wider uptake is lacking. Therefore, great benefits are expected from the implementation of more tools aiding with strategic planning.

The infancy state of WSUD planning and the fact that PSS development is only starting to take off render it too early to diagnose an implementation gap. However, most of the ingredients (causes) for this gap to occur were found to be eminent, such as data availability and quality issues, user friendliness and relevance to the planning practice. Therefore, action is needed from PSS developers, who need to actively engage with on-the-ground practices to tailor and shape their planning tools. The findings of this study should be taken to heart, to prevent the implementation gap from opening in the field of WSUD planning.

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4.3 FINAL REMARKS

This chapter tested hypotheses H3a: Planning processes for WSUD placement are ad-hoc and opportunistic and the use of PSS limited to a small number of prominent examples; and H3b: We need PSS that are user-friendly, conceptually simple, relevant and connected to the planning practice. Both hypotheses were found to be mostly valid.

All municipalities have a budged for WSUD and have implemented WSUD in the past. WSUD is largely seen as an effective way to improve water quality as well as liveability. Municipalities are faced with the question of where to invest their WSUD budget: better maintaining existing assets, repairing broken assets, implementing new assets. The next decision to be made concerns the location of these investments. For municipalities with large greenfield developments, such decisions are less constrained by the spatial context than for largely established municipalities.

While there are large differences between municipalities in terms of attention for, and the capacity to achieve good urban planning of WSUD, the majority of systems are placed opportunistically. Typically, there is no set structure for implementation of WSUD, and depending on the available budget and road renewal cycles, new WSUD systems are implemented. There is a widely shared call for more strategic planning, as the outcomes of current planning processes are generally perceived as sub-optimal. Currently, the Victoria state government is taking the initiative to have a better spatial strategy for WSUD implementation and management across municipalities in the metropolitan area. The positive role that PSS can play towards achieving strategic planning are acknowledged by most practitioners. However, they critique current tools and models to be too complex, not user-friendly and not supported by industry

These and other findings of this study are crucial in the development of SSANTO. By taking the critique and advice from practitioners to heart, we increase the chance of truly supporting planning practice. Together with the suitability framework presented in Chapter 2 and the information on the outcomes of current practice presented in Chapter 3, the findings from this chapter provided a rigorous knowledge base for the development of a successful PSS. The development and testing of SSANTO are presented in the following chapter.

CHAPTER 5

SSANTO: DEVELOPMENT AND TESTING

Spijkers op laag water zoeken

“Looking for nails at low tide”

--Making irrelevant or far-fetched comments about minor details--

5.1 INTRODUCTION

In this chapter, all the work presented in chapters 2-4 is brought together through the development of a novel planning support system (PSS) for suitability analysis: **S**patial **S**uitability **AN**alisys **TO**ol (SSANTO). The tool enables urban planners with varying levels of modelling expertise to conduct a thorough suitability analysis for the placement of WSUD systems including rain gardens, infiltration systems, green roofs, swales, rain tanks, ponds & lakes and constructed wetlands. This geo-information systems (GIS) based tool applies the systematic knowledge from the suitability framework (Chapter 2) combined with techniques from multi-criteria decision analysis (MCDA) to generate easily interpreted outputs that support decision-making. Thus, SSANTO reduces a process that would normally take a great amount of time and resources to a simple stepwise process that can be concluded within 30 minutes. Background, methodology, results, discussion and conclusions of this work will be submitted for publication in the *Journal of Water Resources Planning and Management* and are presented in section 5.2.

This work responds to the third and fourth objectives and first part of the fifth objective of this PhD: **"Develop a methodology for spatial evaluation of suitability for WSUD within a city", "Incorporate this into a GIS-Based Multi-Criteria Decision Analysis tool"** and **"Test the tool for a developed (i.e. Australia) and developing (i.e. Indonesia) context through case studies".** To this end, this section seeks to answer research question RQ4: *How can we provide planning support that enables the strategic placement of WSUD systems by considering spatial suitability through a broad set of relevant factors?*

To answer this research question, the following hypothesis was tested:

H4: WSUD planning support can be provided by the development of a guided methodology drawing on the spatial capacities of GIS-MCDA in a simple and user-friendly digital environment.

Testing of this hypothesis was conducted using methods from decision science and engineering/modelling, building on the knowledge acquired from Chapters 2-4. The journal article presented in section 5.2 contains supplementary materials. For these supplementary materials, please refer to Appendix D.

5.2 SSANTO: DEVELOPMENT AND TESTING

A planning-support tool for spatial suitability assessment of green urban stormwater infrastructure

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Abstract: Distributed green stormwater management infrastructure is increasingly applied worldwide to counter the negative impacts of urbanisation and climate change, while providing a range of benefits related to ecosystem services. They are known as Water Sensitive Urban Design (WSUD) in Australia, Nature-Based Solutions in Europe, Sponge City technologies in China, and Low Impact Development (LID) in the USA. Urban planning for WSUD has been ad-hoc, lacking strategy and resulting in sub-optimal outcomes. The purpose of this study is to help improve strategic WSUD planning and placement through the development of a Planning Support System (PSS). This paper presents the development of Spatial Suitability ANalysis TOol (SSANTO), a rapid GIS-based Multi-Criteria Decision Analysis tool using a flexible mix of techniques to map suitability for WSUD assets across urban areas. SSANTO applies a novel WSUD suitability framework, which conceptualises spatial suitability for WSUD implementation from two perspectives: 'Needs' and 'Opportunities' for WSUD. It combines biophysical as well as socio-economic, planning and governance criteria ('Opportunities') with criteria relating to ecosystem services ('Needs'). SSANTO was tested by comparing its outputs to the results of manual GIS-based multi-criteria studies conducted by a WSUD consultancy for a case study in Melbourne, Australia. Testing confirmed the validity of SSANTO's algorithms and demonstrated its capability to reflect and potentially enhance the outcomes of an equivalent manual strategic planning processes. Manual GIS based suitability analysis is a time and resource intensive process. Through its rapid suitability analysis, SSANTO facilitates iterative spatial analysis for varying scenarios and stakeholder preferences, thereby promoting collaborative planning and deepening our understanding of the relationship between diverse and complex urban contexts and urban planning outcomes for WSUD.

Keywords: Water Sensitive Urban Design (WSUD); urban planning; location choice; GIS-MCDA; ecosystem services; sustainable urban water management

Declarations of interest: *none*

1. Introduction

Distributed green stormwater management systems are increasingly applied in cities around the world to increase resilience of urban drainage systems in response to the challenges posed by urbanisation and climate change. These nature-based stormwater management solutions – referred to as Water Sensitive Urban Design (WSUD) in Australia and in this paper, and alternatively known as Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS), Best Management Practice (BMP), Green Infrastructure (GI), and more recently as *Sponge City* and Nature-based Solutions (Fletcher et al., 2014) – are primarily designed to protect surface water quality and mitigate the flood risk that results from low surface permeability in cities. In addition to these primary functions, WSUD provides a suite of benefits including amenity and recreational values, mitigation of urban heat islands, an alternative source of water provision and habitat for increased biodiversity.

Strategic planning approaches are critical for the spatial allocation of WSUD to suit the physical as well as social urban landscape that they will become part of, while optimising the benefit that can be derived from them (Thévenot, 2008). However, current planning of WSUD is often the result of opportunistic and ad-hoc decision-making processes, which is reflected in its current spatial distribution (Kuller et al., 2018a). Such opportunistic practices may result in less than optimal outcomes for both infrastructure operation and service delivery. The application of planning support systems (PSS) have the potential to drastically improve the outcomes of planning processes through their capacity to combine, analyse and present diverse spatial information in a format that is meaningful to stakeholders (Geertman and Stillwell, 2012; Klosterman, 1997). They can be used to promote collaborative planning and strategic decision-making. Consideration of multiple criteria is essential to respond to both the multi-faceted nature of WSUD and the urban environment it is integrated into.

A plethora of PSS, models and tools have become available to the WSUD planner over the past two decades. Recent reviews of tools and models for WSUD planning conclude that current models and tools are insufficient (Kuller et al., 2017; Lerer et al., 2015). Specifically, they need to be more (i) spatially explicit, (ii) broader in scope (in terms of technologies and assessment criteria), (iii) more comprehensive and (iv) rigorous. Furthermore, a recent study reveals that causes behind an identified lack of uptake for PSS in urban planning

– referred to as the 'implementation gap' (Vonk, 2006) – are also present in WSUD planning (Kuller et al., 2018b). Some of the most important barriers to the adoption of such tools include: (i) lack of user-friendliness, (ii) too much time and effort required, (iii) too complex, (iv) not widely used in industry and (v) do not produce relevant outputs. Perhaps the most significant cause of these shortcomings is a lack of engagement between PSS developers and the planning practice.

Engagement with WSUD planning practice suggests a specific need for spatially explicit tools. Kuller et al. (2017) specifically reviews recent tools that integrate Multi-Criteria Decision Analysis (MCDA) with spatially explicit algorithms using Geo-Information Systems (GIS), which has the potential to benefit planning (Massam, 1988). GIS-MCDA offers capabilities to integrate the complexities emerging from both a technical and social perspectives, such as the integration of social, environmental and economic factors as well as consideration of non-monetary values (Ferretti and Montibeller, 2016). Complex, multidisciplinary, multi-stakeholder and group decision-making processes are facilitated through techniques offered by GIS-MCDA (Boroushaki and Malczewski, 2010; Jankowski and Nyerges, 2001). The considerable assessments and tools currently available have one or, in most cases, more of the following three limitations: (i) insufficient or incomplete number of assessment criteria, (ii) insufficient methodological sophistication and (iii) lack of automation and reproducibility.

In response to these limitations, this study aims to develop a WSUD planning support system that automates user(s)-driven spatial suitability assessment for the planning of green stormwater management systems in urban environments. We specifically focus on the following objectives:

(a) Operationalising a novel and comprehensive WSUD suitability framework proposed by Kuller et al. (2017); this is achieved through coupling the indicators related to the criteria of the 'two sides of suitability' – *WSUD needs a place* and *a place needs WSUD* – to spatial datasets;
(b) Advancing spatial WSUD suitability mapping by applying a mix of GIS-MCDA techniques on the above criteria, in a flexible and replicable manner;
(c) Developing a user-friendly spatial software, which supports strategic decision-making by integrating the above in alignment with practitioner insights (Kuller et al., 2018b);

(d) Testing the PSS on an existing real-world case study in Melbourne, where suitability analysis was performed previously by industry stakeholders.

By utilising a novel suitability framework, for the first time, ecosystem services and the community needs for green infrastructure, as well as suitability related to the biophysical, social and urban context underlying WSUD performance are systematically incorporated into a WSUD PSS. Such integration is critically lacking in literature and practice until now, as discussed by Prudencio and Null (2018). The strength of the presented tool lies in its capability to automate advanced spatial MCDA techniques, which normally require a considerable amount of time and human resources. In doing so, the tool can generate easily interpreted output, thereby facilitating deeper collaboration between stakeholders.

2. Development of SSANTO

Spatial Suitability ANalysis TOol (SSANTO), which automates spatial suitability assessment for the planning of green stormwater management systems in urban environments, was developed to meet four objectives:

(a) Presents an easy-to-use interface that enables use by experts as well as non-experts and practitioners

(b) Performs quick but rigorous assessment of the complete array of relevant factors in a spatially explicit way

(c) Combines suitability assessment with the spatial assessment of needs, using principles from ecosystem services

(d) Produces ready-to-use intuitive outputs that can be interpreted by experts as well as lay people.

2.1 Theoretical background

SSANTO operationalises the WSUD suitability framework developed by Kuller et al. (2017), as presented in Figure 1. To 'measure' suitability, this framework starts from the notion of 'two sides of suitability': ***'Opportunities'*** (referred to as 'WSUD needs a place') and ***'Needs'*** (referred to as 'A place needs WSUD'). The former (Opportunities) describes favourability of locations for the implementation of green stormwater infrastructure based on the biophysical, socio-economic and planning & governance contexts. The latter (Needs) describes locations based on their need for the benefits derived from WSUD related to provision (e.g.

irrigation water harvesting), regulation (e.g. water quality), cultural values and ecological habitat. Each of these categories contain a number of suitability factors (Figure 1).

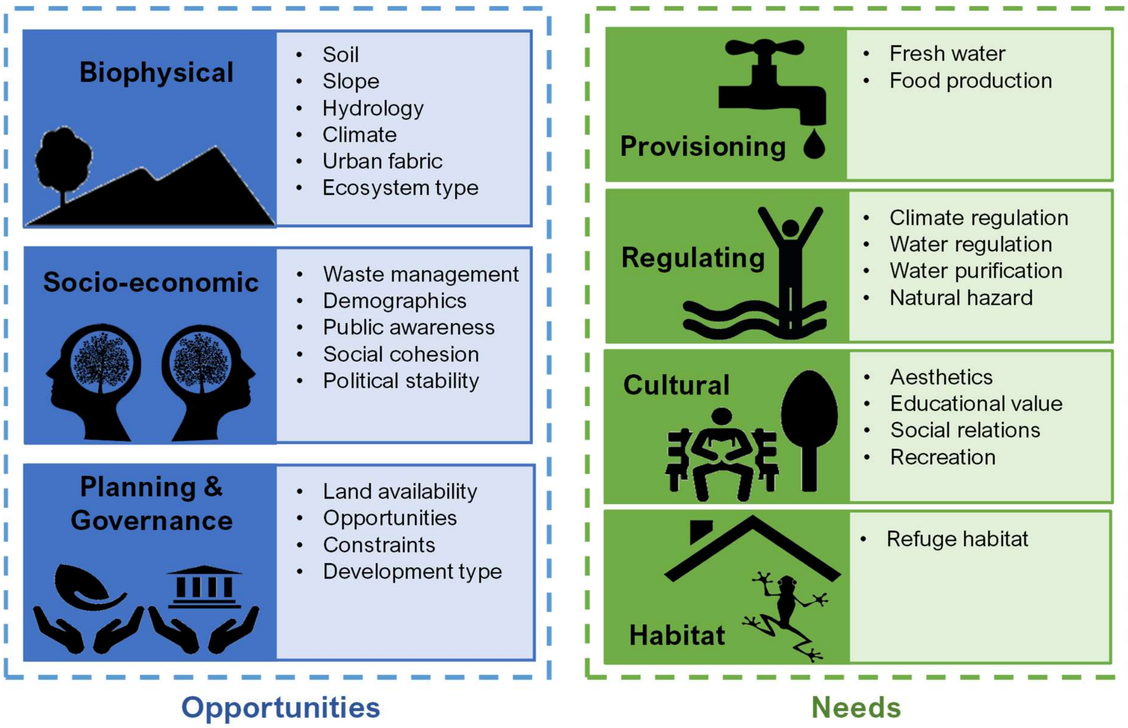

Figure 2: Suitability framework (simplified) adapted from (Kuller et al., 2017). Both sides of suitability comprise of categories (in rectangles with icons) and their factors.

SSANTO allows the user to build suitability maps for both sides of suitability by following a four-step procedure adapted from Malczewski and Rinner (2015): (1) compiling geodatabase, (2) masking, (3) value scaling, and (4) combining (Figure 2).

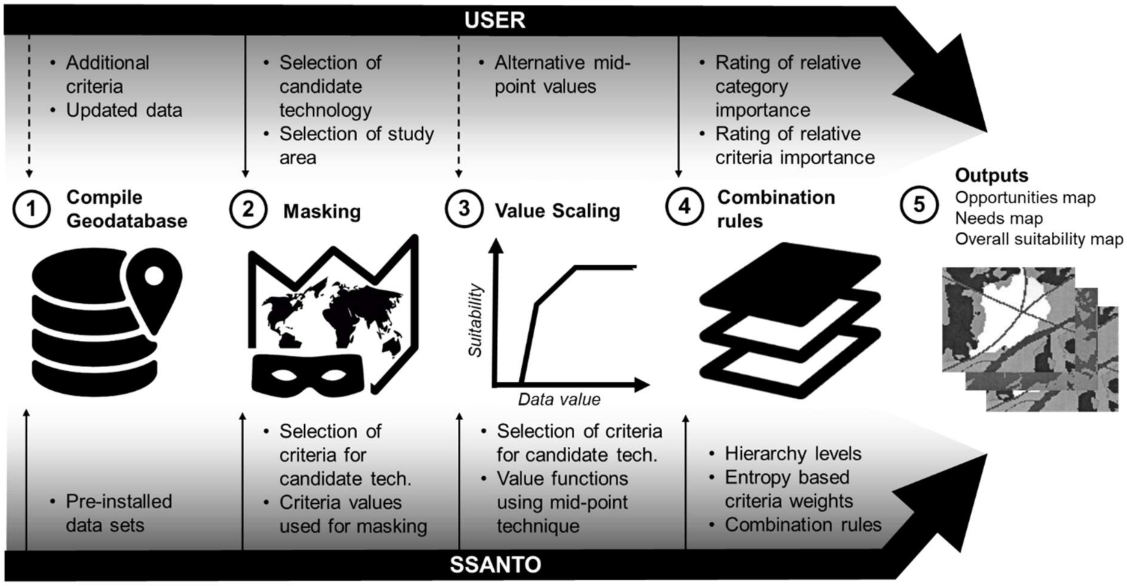

Figure 3: SSANTO's workflow, representing the 4 steps and related user-defined and programmed inputs as well as outputs.

In the ***first step – compiling geodatabase***, all relevant spatial datasets are compiled into a geodatabase. Spatial data corresponding to each measurable indicator from the suitability factors in the framework are sought. Spatial MCDA tools such as SSANTO are typically data-hungry (Lee Jr, 1973) and their application may suffer from a lack of readily available data (Ferretti and Montibeller 2016). In certain cases, alternative datasets can be used to measure an indicator (e.g. Rhea et al., 2014). For example, landfill sites as well as petrol station locations can act as a proxy to the indicator 'soil contamination'. Proxies should be applied with caution, as their relation and representation of the actual indicator may not always be straightforward (Marttunen et al. 2018).

The ***second step - masking***, is the process of removing all areas where at least one aspect of the urban context constrains infrastructure implementation. Two types of masking are possible, depending on the type of data: (1) Boolean masking and (2) masking using a threshold value. The former is used for discrete data (e.g. features) while the latter is used for continuous data (e.g. slope).

Before we can combine and compare diverse criteria, raw spatial datasets need transformation to a common suitability scale (Malczewski and Rinner 2015). This process is the ***third step – value scaling*** in SSANTO's workflow. Value scaling answers questions of the following kind: *What does a slope of 5.5% mean for the suitability of a location for the implementation of rain gardens?* Value scaling is an essential step in GIS-MCDA, and a mathematical representation of human judgement and knowledge in the form of 'value functions' (Keeney, 1992). Value functions describe the relationship between raw data values and suitability values, thus representing various datasets in comparable units. The shape of a value function is unique to its corresponding criterion and WSUD system type. For simplicity, linear value functions are commonly applied (Malczewski and Rinner 2015). However, Stewart (1996) showed that the shape of value functions matter, and that using a linear form is often an over-simplification of reality. As an alternative, value functions of a piecewise linear form to account for non-linearity can be used (Malczewski and Rinner 2015, Pereira and Duckstein 1993).

Fourth step involves ***combining*** all criteria. As not all aspects carry the same importance for the final suitability, criteria also need to be weighted. Weights can be elicited from stakeholders or calculated. *Hierarchical weighting* is commonly applied for decision problems that can be divided into sub-objectives, also reflected in the suitability framework used in this study. Weight definition can be the source of biases, which are discussed by Marttunen et al. (2018). According to them, hierarchical weighting suffers most from splitting and asymmetry biases as well as higher variance, where user weights are affected by the structure of objectives and sub-objectives (i.e. criteria) in a branch of a hierarchy. *Non-hierarchical weighting* may suffer from range insensitivity and equalising biases. The former occurs when the range of possible criterion values is insufficiently reflected in weights while the latter occurs because of the user's tendency to avoid assigning very high or low weights. *Entropy-based weights* are calculated weights which reflect the information-density of the data. Lower entropy means higher variation in the data, more discriminative power and therefore higher criterion weights. Fully or partly entropy-based weights mitigate all biases associated with user-defined weighting and can be useful when combined with other weighting methods (Nijkamp and van Delft 1977).

According to Ferretti and Montibeller (2016), the inherent subjectivity of user-defined criteria weights in GIS-MCDA necessitates participatory processes with stakeholders. They argue that the rating method responds to the observed need for simple weight elicitation protocols. The simplicity of the rating method comes at the cost of certain biases (Eisenführ et al., 2010). Therefore, the flexible architecture of SSANTO allows for the future addition of other weighting methods for the user to choose from, if they wish so.

After weighting, a model is applied to combine all criteria and create a suitability map. The weighting method and combination rules are closely related to each other. Malczewski and Rinner (2015) describe a range of methods varying in complexity, ranging from simple linear additive models to complex and non-linear ideal point and outranking methods. One of the most widely applied methods is weighted linear combination (WLC). As an intuitive method to decision-makers, this method was chosen for its simplicity. WLC assumes linearity (constant marginal values) and additivity (mutual preferential independence). Although the assumptions behind WLC are not easily applied in spatial decision problems, it was found to perform almost as well as far more complicated, non-linear methods such as reference-point methods (Hwang and Yoon, 1981a) and can be easily implemented in GIS using map algebra (Tomlin, 1990).

2.2 Software architecture

SSANTO can perform individual suitability analyses for seven different WSUD infrastructure types: (1) Bioretention & rain gardens, (2) Infiltration systems, (3) Green roofs, (4) Ponds & lakes, (5) Swales, (6) Rainwater tanks, and (7) Constructed wetlands. The tool's flexible architecture allows for easy extension to include additional infrastructure types. SSANTO was built as a Python add-in to the spatial software ArcMap by Esri, connected to several python toolboxes and coded in Python version 2.7 (Figures 1S-3S supplementary material). The tool has four separate modules (discussed below) that automate the four steps of the analysis (see Section 2.1 and Figure 2).

2.2.1 Compiling geodatabase

For SSANTO, data were gathered following a pragmatic approach. Firstly, all data that were relevant and readily available in online governmental data repositories, were added to the geodatabase. Secondly, all reasonable effort was taken to acquire data for factors that were still missing data and were considered high importance by the suitability framework (see Kuller et al., 2017). For example, flood extents were deemed important data, but not publicly available. This data was separately acquired from the relevant municipality. No measurements or surveys were undertaken for this study, which fully relied on the availability of existing datasets. SSANTO's flexible structure allows easy addition of new criteria and corresponding datasets. Table 1 provides a summary with the most important datasets used in SSANTO. The full list of datasets currently embedded in the tool, with explanation and sources, can be found in Table 1S of the supplementary materials.

The geodatabase contains geolocated spatial data in two formats: vector and raster. Three types of vector data can be distinguished: (1) features, (2) overlay, and (3) aggregated (Table 1). Examples of feature data are the roads dataset and building footprints. Overlay data include planning overlays such as heritage sites. Demographic data, such as environmental awareness, are aggregated over administrative tracts, such as census tracts.

There is often more than one way to measure an indicator from the suitability framework using spatial data. For example, we measured the cultural factor 'visibility' using different maps containing information about points of interest (POI), busy pedestrian areas such as commercial zones and residential densities (Table 1). All spatial input datasets were pre-processed to fit the required format type, study area and naming convention used in SSANTO. For the start screen, a datafile containing municipality boundaries was used to help study area selection.

Table 1: Summary of datasets used in SSANTO for both sides of suitability (Figure 1) with corresponding indicator and category from suitability framework. Complete table of datasets used in SSANTO, including data sources and further explanation can be found in Table 1S of supplementary materials.

	Category	Indicator	Dataset	Data type	Proxy
Opportunities	Biophysical	Slope	Digital Elevation Model (DEM)	Raster	
		Roof areas	Building footprints	Features	
	Socio-economic	Environmental awareness	Election results	Aggregated	✓
		Sense of community	Volunteering	Aggregated	✓
	Planning & Governance	Utility infrastructure	Easements	Features	
		Cultural Heritage	Cultural Heritage Sites	Overlay	
		Land ownership	Cadastre	Features	
Needs	Provisioning	Proximity to water demand	POI (Points of Interest)	Features	✓
	Regulating	Heat vulnerability	Heat vulnerability	Aggregated	
		Connected impervious area	Directly connected imperviousness (DCI)	Aggregated	✓
		Floods	Flood extents	Raster	
	Cultural	Visibility	Land-use, POI	Features	✓

2.2.2 Masking

This process is executed following study area and infrastructure type selection by the user. Constraining criteria and threshold values are specific to WSUD type and are hard-coded in SSANTO. Commonly applied masks include:

- Slope (threshold, depending on WSUD type)
- Building footprints (Boolean)
- Distance to airports (threshold, depending on WSUD type)

For example, wetlands cannot be built on slopes over 5.5% (Melbourne Water, 2005) or near (<1km) airports (ICAO, 2012). Raw raster-based data is reclassified into a Boolean, using the threshold value to create masked data. For example, a threshold value of 5.5% for slopes results in a mask map where areas where slope > 5.5% are assigned a value of 1 (representing true), and all other areas are assigned a value of 0 (false). For vector-based data that is already binary, reclassification is not required. The complete list of masks and threshold values specified per WSUD type can be found in Table 2S of the supplementary material.

As SSANTO performs raster-based analysis, vector-based mask data is merged and converted into raster format. After conversion, the final mask is created by merging these masks with those from the raster data. The output of this step is a Boolean raster mask map, where cells to be excluded (masked) have value 1 (true).

2.2.3 Value Scaling

SSANTO uses value functions of the piecewise linear form (Malczewski and Rinner, 2015; Pereira and Duckstein, 1993). SSANTO uses pre-set value functions (as opposed to user-defined value functions) to enhance user-friendliness. To define global value functions for each criterion and WSUD type, values range between 0 and 100 for *minimum, maximum, midpoint, first quart, third quart* and *direction* (a graphical explanation is provided in Figure 4S, supplementary material). These values were either (i) acquired using a panel of scientific experts, (ii) taken from literature, (iii) derived from Melbourne averages and deviations, or, if no other information was available, (iv) at the authors' discretion. Although value scales are predefined, they can be customised where required. A table containing all criteria and their value scales for each WSUD type currently available in SSANTO can be found in the supplementary materials (Table 2S).

Not all criteria could be represented by simple piecewise linear value functions. Criteria with convex/concave value functions are assigned two value scales, one for the increasing- and one for the decreasing section of the curve. Criteria without pre-defined value scales were assigned one by means of an algorithm, based on the structure of the dataset. Binary criteria (planning overlays) were included in the suitability calculations Their value scales only contain two parameters: true and false. Alternatively, they can be added to the output map separately. In this case, the features of the dataset remain unchanged and are overlaid on the output suitability map, providing additional information to the user (e.g. 'careful, this area is heritage listed'). Several criteria, such as land ownership, are categorical. For these criteria, the value function is replaced by individual suitability value assignment for each category.

SSANTO's value scaling algorithm was built for raster data, performing raw-data to suitability-data calculations on a cell-by-cell basis. Vector-based data is first transformed into raster data using a uniform and customisable cell size across datasets (20m x 20m). Raster-based data is resampled where necessary, to fit the resolution. The outputs of this third step in the workflow of SSANTO are suitability maps for each criterion in raster format, using a suitability scale ranging between 0 (least suitable) and 100 (most suitable).

2.2.4 Combination rules

The first step is criteria weighting. SSANTO offers a mix of weighting options, aimed at managing the biases discussed in section 2.1, while maximising useability. These methods include hierarchical and non-hierarchical user-elicited weights, entropy-based weighting and a combination of these. Although the WSUD suitability framework is hierarchical, the options for non-hierarchical weighting as well as the initial retention of information on the number of sub-objectives mitigates asymmetry- and other hierarchy-related biases (Marttunen et al. 2018).

The 'rating' method was applied for user-defined weightings (Malczewski and Rinner, 2015). The user is asked to score criteria relative to each other on a scale from 0 (exclude) to 100 (most important). The list of criteria for rating depends on the selected area of interest and WSUD type. It is compiled by SSANTO's algorithms, based on the information in Table 2S of the supplementary materials. Pairwise comparison as used in AHP was considered to compromise user-friendliness of SSANTO. It has been criticised for inflated spread of weights and inconsistencies (Lienert et al., 2016; Malczewski and Rinner, 2015), which may require users to redo the entire process.

Hierarchical user-based weights are acquired in two steps: rating categories and rating individual criteria. The user window for rating criteria is presented in the supplementary materials (Figure 3S). SSANTO calculates final weights using the following equations:

$$w_c = \frac{r_c}{\sum_{c=1}^{j} r_c} \quad \text{(Equation 1)}$$

$$w_{kc} = \frac{w_c r_{kc}}{\sum_{k=1}^{l} r_{kc}} \quad \text{(Equation 2)}$$

where w_c is the weight of the c^{th} category, r_c is the user-defined rating for the c^{th} category (ranging between 0 and 100), w_{kc} is the weight of the k^{th} criterion in the c^{th} category and r_{kc} is the user-defined rating for the k^{th} criterion (ranging between 0 and 100) in the c^{th} category, so that $\sum_{k=1}^{l} w_{kc} = w_c$ and $\sum_{c=1}^{j} w_c = 1$. Non-hierarchical weighting omits Equations 1 and 2, such that:

$$w_k = \frac{r_k}{\sum_{k=1}^{n} r_k} \quad \text{(Equation 3)}$$

where w_k is the weight of the k^{th} criterion. Entropy weights depend on the amount of variation (information) in the data. They are used to prioritise those criteria that enhance the decision-maker's ability to distinguish between decision options. Completely homogenous data (all cell values are equal) results in an entropy value (E_k) of 1, while completely heterogenous data (all cell values are different, covering the full range of possible values) result in an E_k of 0. Entropy weights (w_{E_k}) are then calculated for each criterion based on the entropy for that criterion, compared to the total entropy in all criteria. Overall, the calculation of criteria weights is as follows (Shannon and Weaver, 1963):

$$E_k = -\frac{\sum_{i=1}^{m} p_{ik} \ln(p_{ik})}{\ln(m)} \quad \text{(Equation 4)}$$

$$p_{ik} = a_{ik} / \sum_{i=1}^{m} a_{ik} \quad \text{(Equation 5)}$$

$$w_{E_k} = \frac{1 - E_k}{\sum_{k=1}^{n} (1 - E_k)} \quad \text{(Equation 6)}$$

where a_{ik} is the suitability value of the k^{th} criterion at the i^{th} location, so that $\sum_{k=1}^{n} w_{E_k} = 1$. Finally, user-defined criteria weights can be combined with entropy weights using the following equation (Hwang and Yoon, 1981b; Malczewski and Rinner, 2015):

$$w_k^* = \frac{w_{E_k} w_k}{\sum_{k=1}^{n} w_{E_k} w_k} \qquad \text{(Equation 7)}$$

The second step is combining weighted data, for which the WLC model was selected. To meet the additivity assumption, SSANTO gives a warning message when potentially dependent criteria are selected simultaneously by the user. WLC was deemed the most appropriate model, considering (i) the consequential flaws of alternative combination method's underlying assumptions and (ii) our endeavour for simple, intuitive and transparent methodologies. SSANTO's algorithm applies WLC on a cell-by-cell basis, using the following function (Malczewski and Rinner, 2015):

$$V(A_i) = \sum_{k=1}^{n} w_k v(a_{ik}) \qquad \text{(Equation 8)}$$

where $V(A_i)$ is the final suitability (between 0-100) for the i^{th} location (raster cell), w_k is the weight of the k^{th} criterion and $v(a_{ik})$ is the value function as defined in the previous section, for the k^{th} criterion and i^{th} location.

SSANTO's architecture is flexible and allows for iterative analyses to respond to some of the key challenges of GIS-MCDA as identified by Ferretti and Montibeller (2016), including the issues discussed in section 2.1. Because of the nature of GIS-MCDA, a certain level of uncertainly and bias is unavoidable. Clear reporting on the effect of model choices to the user is therefore critical. This is achieved through clear user guidance and default settings that minimise unwanted biases.

2.2.5 Output

SSANTO's final outputs are suitability maps in raster format and suitability statistics for the selected study area and technology type. Three suitability maps can be generated: (1) Opportunity map, corresponding to 'WSUD needs a place', (2) Needs map, corresponding to 'a place needs WSUD' and (3) an overall (combined) suitability map (refer to section 3.2 for graphical examples). The final map is produced by either (i) collating all criteria from both suitability sides and weighting them together, or (ii) treating the Opportunities map and Needs map as individual criteria and repeating the weighting process for them. A numerical summary of the underlaying criteria values and impact (a combination of value, weight and deviation from average), which explain the resulting suitability score, can be obtained for each individual location (see Figure 5S in the supplementary materials for an example). Furthermore, overall summary statistics of the suitability maps are generated, including mean suitability, extremes, and suitability distribution histograms.

SSANTO does not consider system size of WSUD, catchment hydrology, treatment trains or quantitative and qualitative performance. As such, it is meant to be used in conjunction with other models such as MUSIC (eWater, 2011) for design, UrbanBEATS (Bach, 2014) for options generation or even an agent-based model for green infrastructure uptake by Castonguay et al. (2018), which explicitly requires some form of suitability maps as inputs.

2.3 Testing SSANTO

Suitability is not a physically (objectively) measurable metric, but a reflection of stakeholder's preference and expertise. Model validation is usually performed by comparing model outputs to measured data, e.g. rainfall, temperature, stormwater flows or flood depths. Suitability estimations, however, is scarce because of large investments required to generate them. Furthermore, suitability estimates depend on the applied definition of suitability. Therefore, testing models such as SSANTO should extend beyond simple validation of their algorithms. It needs to include the testing of their ability to rapidly reproduce the outcomes of planning processes and iteratively run varying scenarios and input data. The added value of SSANTO ultimately depends on its capacity to support and improve the rigour and speed of WSUD planning processes.

To test its performance, SSANTO's outputs were compared to the outcomes of a suitability mapping and prioritisation study carried out by a consultancy firm called E2DesignLab. This section describes the case-study location, E2DesignLab's methods and outputs, SSANTO's setup for testing and the method for comparing E2DesignLab's outputs with SSANTO's outputs.

2.3.1 Case study description

The City of Darebin is a local government area in the suburbs directly northeast of the centre of Melbourne, Australia. Its population is just under 150,000 in an almost fully built-up area of 53 km^2 (ABS, 2016). Darebin is situated in the Lower Yarra Catchment with Merri Creek forming its western border and Darebin Creek forming its eastern border (Figure 3). Natural waterways in Darebin have been degraded due to urban development and communities are facing occasional flood events.

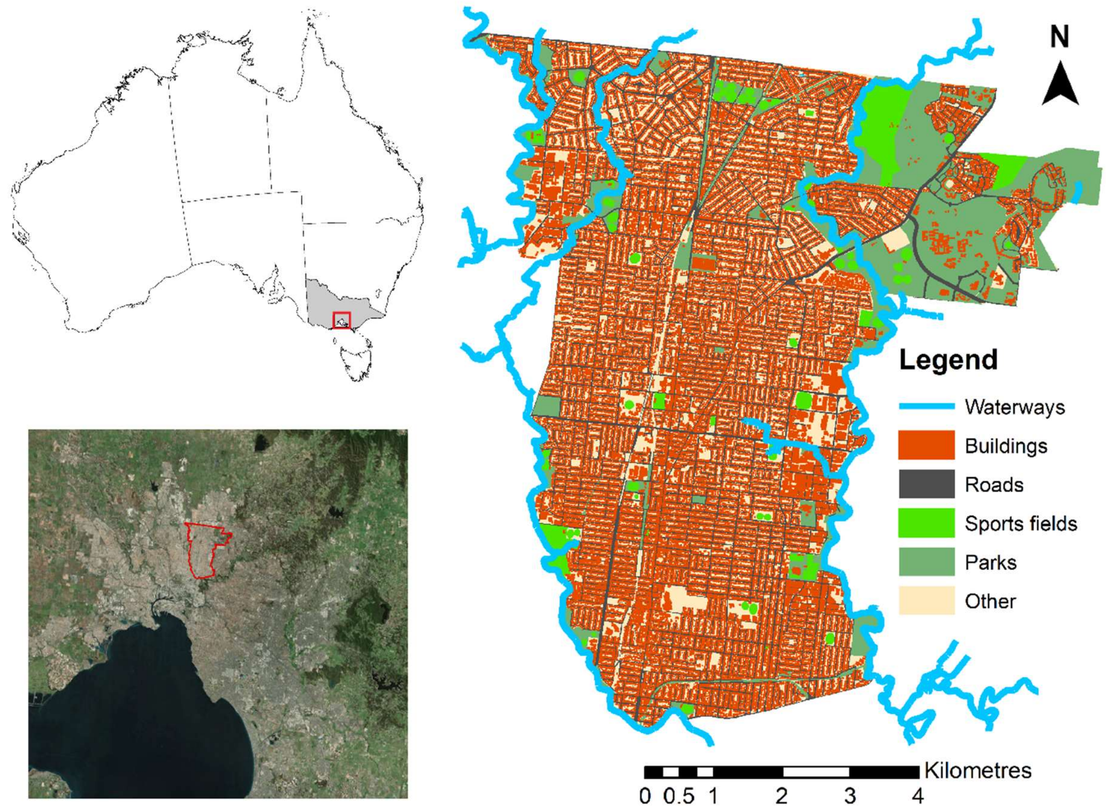

Figure 4: Darebin municipality as situated in Metropolitan Melbourne, Australia. *(Sources: ABS, DELWP, Esri, DigitalGlobe, GeoEye, Earthstar Geographics, ONES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)*

2.3.2 Validation data

Melbourne-based WSUD consultancy E2DesignLab performed a spatial prioritisation study for Darebin in 2017 (Roberts et al., 2017), for two cases: (1) street-scale systems such as small rain gardens and tree pits, and (2) precinct-scale WSUD options such as wetlands, rain gardens and stormwater harvesting schemes that treat moderate to large catchments (from 10 ha to over 100 ha). In the first case, values from 4 spatial datasets (all part of 'Needs') were assigned a suitability score between 1 (least suitable) and 3 (most suitable). The scored maps were then overlaid by adding the suitability scores, to generate a final vector-based suitability map with scores between 4 and 12. This created a coarse suitability map without mask, intended as a high-level aid to decision-makers for streetscape system planning. For the purpose of testing, this map was first normalised to represent scores from 0-100, and subsequently rasterised.

In the second case, 68 priority sites (available as a polygon shapefile) were manually identified as opportunities to retrofit precinct-scale systems (hereafter called: 'E2D priority sites'). E2D priority sites were identified through a manual prioritisation exercise, using E2DesignLab's experience with planning for green stormwater infrastructure combined with spatial data from 12 criteria and additional local knowledge. More detail about the selection process can be found in the supplementary materials as well as Roberts et al. (2017). It should be noted that E2D priority sites were created using detailed information about the urban context as well as tacit knowledge of the urban planner and political motivations, all of which are not always available or reflected in the form of spatial datasets.

2.3.3 Tool setup

A total of seven model runs were performed to validate and test SSANTO, as presented in Table 2. One model run analyses suitability for street-scale systems, using identical weighting and value scales as E2DesignLab (S-Case-Expert). Six model runs analyse suitability for precinct-scale systems, using two sets of criteria ('case-limited' and 'full') and three different weighting methods ('equal', 'expert' and 'entropy'). The case-limited criterion set is a selection of criteria as used in the study by E2DesignLab, while the full criteria set includes all relevant criteria as defined by Kuller et al. (2017) for which data was available. A complete overview of these criteria is presented in Table 3. Weighting method 'equal' refers to a model run where all criteria have equal weight, while for 'expert', weights were provided by E2DesignLab. The 'entropy' weights are calculated from the variability of data within a criterion, as explained in section 2.2.4.

Table 2: Overview of model runs performed for testing.

WSUD type	Criteria Set	Weighting method	Model run
Street-scale	Case-limited	Expert1	S-Case-Expert
Precinct-scale	Case-limited	Equal	P-Case-Equal
		Expert	P-Case-Expert
		Entropy	P-Case-Entropy
	Full	Equal	P-Full-Equal
		Expert	P-Full-Expert
		Entropy	P-Full-Entropy

[1]Both weighting and value scales used by E2DesignLab were also applied for this model run. The value scales can be found in Table 4S of the supplementary materials.

More information about the criteria from Table 3 and all other criteria used by SSANTO for other WSUD types, their data sources, as well as value scales applied to each criterion and WSUD type can be found in the supplementary materials (Table 1S and Table 2S respectively). Expert value scales for model run S-Case-Expert as well as expert weights for precinct-scale systems can be found in the supplementary materials (Table 3S and 4S respectively).

Table 3: Criteria used for testing.

	Category	Criterion	System1	Mask (threshold)
WSUD needs a place (Opportunities)	Biophysical	Slope	S, P	✓ (S: 15%, P: 5.5%)
		Building footprints	S, P	✓
		Pre-human wetland structure	S, P	-
		(Distance to) landfill sites	S, P	-
		Sports fields	S, P	✓
	Socio-Economic	Education level	S, P	-
		Sense of community	S, P	-
		Environmental awareness	S, P	-
	Planning & Governance	Distance to drainage infrastructure	S, P	-
		Utility infrastructure	S, P	-
		Land value	S, P	-
		Street width/type	S	✓
		Lot Size	P	-
		Land ownership	S, P	-
		Cultural Heritage	S, P	-
		Geological Heritage	S, P	-
		Natural Heritage	S, P	-
		Distance to airports	P	✓ (P: 1000m)
A place needs WSUD (Needs)	Provisioning	Irrigation demand	S, P	-
	Regulating	Effective imperviousness2	S, P	-
		Total imperviousness	S, P	-
		Current WSUD	S, P	-
		Heat vulnerability	S, P	-
		Flood risk	S, P	-
	Cultural	Visibility	S, P	-
		Social cohesion	S, P	-
		Green cover	S, P	-
		Recreation	P	-

[1]S: street-scale systems such as tree pits and rain gardens, P: precinct-scale systems such as constructed wetlands and large bioretention. In bold are the criteria used by E2DesignLab and applied in the 'case-limited' model runs.
[2]Effective imperviousness was excluded from the evaluation for the Darebin case study, as this fully developed area has homogeneously high rates of effective imperviousness, far above the threshold for which WSUD could improve water quality.

2.3.4 Comparing SSANTO's outputs to suitability results generated by E2DesignLab

The normalised suitability map from E2DesignLab (E2D) was compared to SSANTO's output suitability map on a cell-by-cell basis, without masking. However, the E2D priority sites from the second case cannot be directly compared to SSANTO's suitability map. To assess whether the outputs of SSANTO reflect E2D suitability site selection, SSANTO's calculated suitability at E2D priority sites was compared to the average calculated suitability for Darebin. Thus, SSANTO's performance was tested for all six model runs presented in Table 2. The suitability maps for the three weighting methods are assessed in greater detail for model runs using full criteria. Finally, the output for 'Opportunities' and 'Needs' are compared for model run P-Full-Expert by comparing their suitability values on a cell-by-cell basis.

3. Results

3.1 Street-scale systems

There was a 96.7% match for street-scale systems (identical cell values between the output generated by SSANTO compared to E2DesignLab), 2.65% of area had a deviation of 1, and only 0.61% deviated more than 1 (Figure 4). While the deviation of 1 can be attributed to rounding errors, deviations above 1 are likely due to misalignment of cells resulting from the transformation of vector data to raster data. The close match between the modelled output and the output from E2DesignLab is promising, as it demonstrates that SSANTO can reproduce the practical steps and thinking required to undertake this analysis.

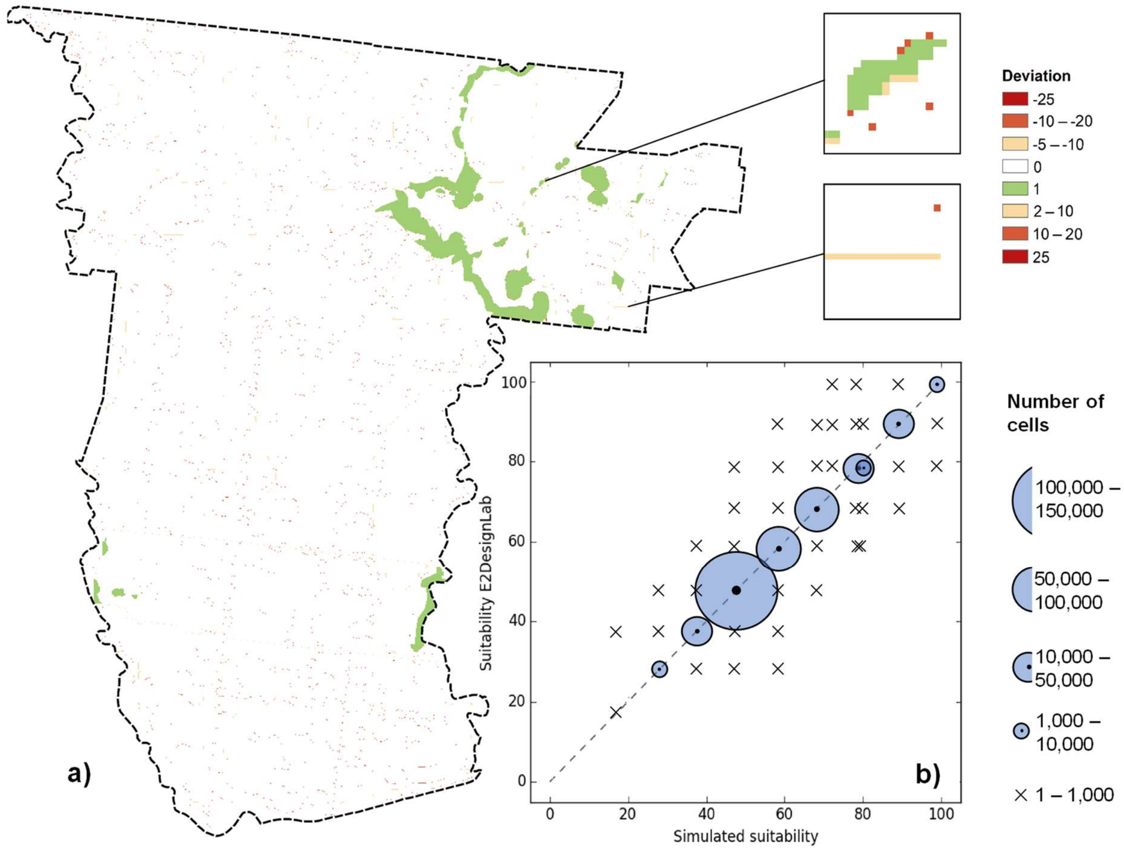

Figure 5 a) Map showing deviations in suitability values between the suitability result for streetscape systems from E2DesignLab and SSANTO's results for S-Case-Expert, using identical value scales and criteria weights. b) Same results, shown in a bubble-weighted scatter plot.

3.2 Precinct-scale systems

Results of the model run using full criteria and expert weights as provided by E2DesignLab are shown in Figure 5. In total, 72% of the case-study area is masked out. SSANTO's suitability scores are relatively higher at E2D priority sites with a mean of 69, compared to 64 elsewhere (Figure 5c). This difference is greater for 'Opportunities' (62 vs. 55) than for 'Needs' (79 vs. 78). This suggests that the 'Opportunities' side of suitability was more important in the selection of E2D priority sites than the 'Needs' side.

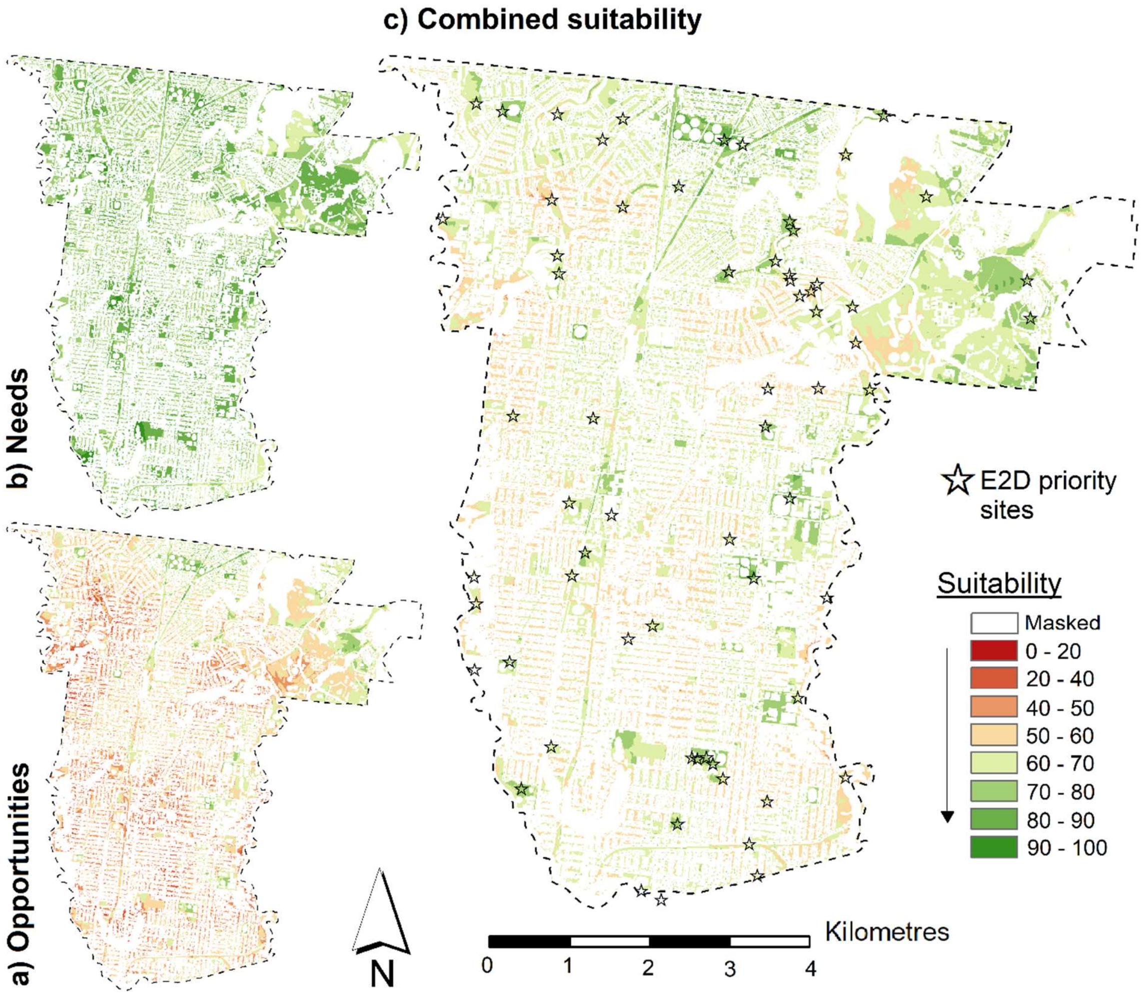

Figure 6: Output maps for model run P-Full-Expert. a) suitability map for the 'Opportunities' side of the suitability framework, b) suitability map for the 'Needs' side of the suitability framework, c) suitability map of 'Opportunities' and 'Needs' combined, overlaid by E2D priority sites and optional sites (stars).

Figure 6 presents the performance of all six model runs, through a full comparison of the suitability distributions. Model runs using full criteria result in a higher positive difference in mean between E2D priority sites and Darebin average than model runs using limited criteria (mirroring E2DesignLab's analysis). This suggests that E2DesignLab and the City of Darebin implicitly used more information than the indicators they reported to inform their E2D priority site selection, including some of the information that SSANTO uses. Thus, some of the tacit knowledge used for E2D priority site selection may be captured by SSANTO's full criteria set.

For the case-limited set of criteria, expert and entropy weighting perform better than equal weighting. For model runs using the full criteria set, entropy weighting results in a significantly better fit than the other weighting sets, while expert weighting results in a slightly better fit than equal weighting.

The full comparison of key suitability summary statistics between E2D priority sites and Darebin average for 'Needs', 'Opportunities' and combined suitability for all scenarios is presented in the supplementary materials (Table 5S). From Table 5S we observe that 'Needs' fitted E2D priority sites better than 'Opportunities', suggesting those criteria from the case-limited set were more closely considered. This order is reversed in tool runs with a full set of criteria, where the fit for 'Needs' is lower than that for 'Opportunities'.

The outperformance of expert weighting by entropy weighting for the full criteria set is notable, considering experts weights were elicited from the same people who selected the E2D priority sites. It highlights the complexity of accurate weight elicitation as it suggests the underestimation of the importance of some, and overestimation of other criteria in the planning process. It furthermore points to the potential strength of entropy weighting, as P-Full-Entropy was found to be the best performing model run. For a full comparison between expert- and entropy weights, refer to the supplementary materials (Table 3S).

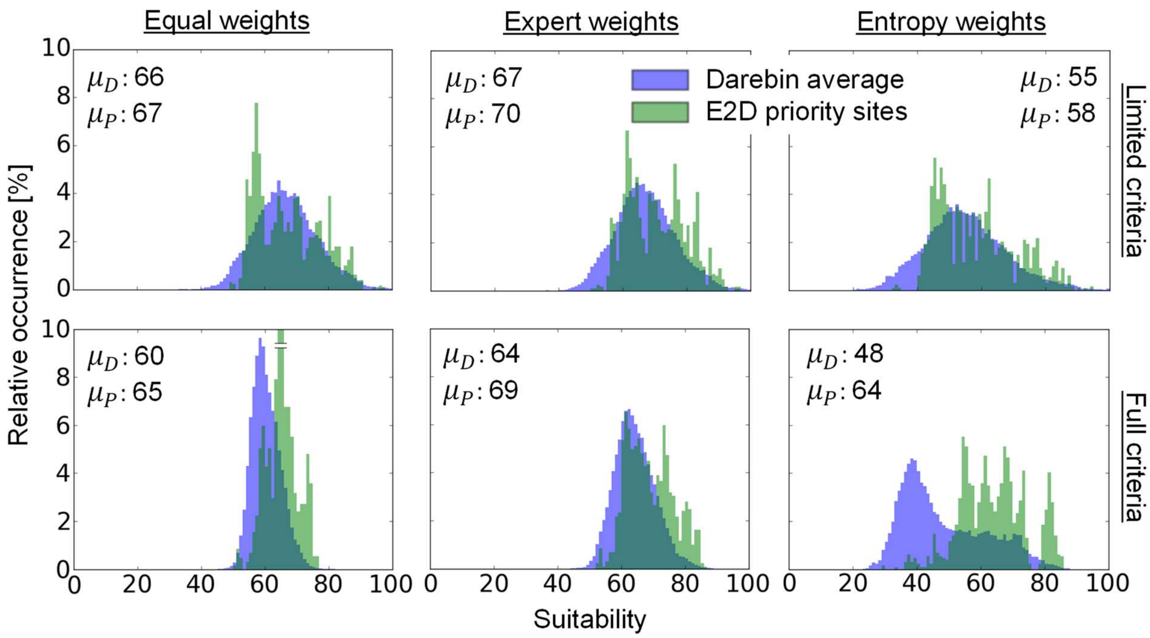

Figure 7: Comparison of distribution of suitability between Darebin average (blue) and E2D priority sites (green) for all precinct-scale scenarios. μ_D: mean suitability for Darebin, μ_P: mean suitability at priority sites. Greater positive difference between μ_P and μ_D indicates better performance.

Figure 7 compares the results for expert (b) with equal (a) and entropy weighting (c). While suitability values vary between the three outputs for certain locations, other locations appear more stable (Figure 6S supplementary material). The spread of suitability values across Darebin is highest for entropy weighting and lowest for equal weighting, where 97.7% of suitability values lie between 50 and 70 (see also: Figure 6). The small number of criteria that dominate the suitability result for entropy weights (refer to Table 3S of the supplementary materials) could explain the high spread compared to expert and equal weighting, where suitability results are evened out by a greater number of influential criteria.

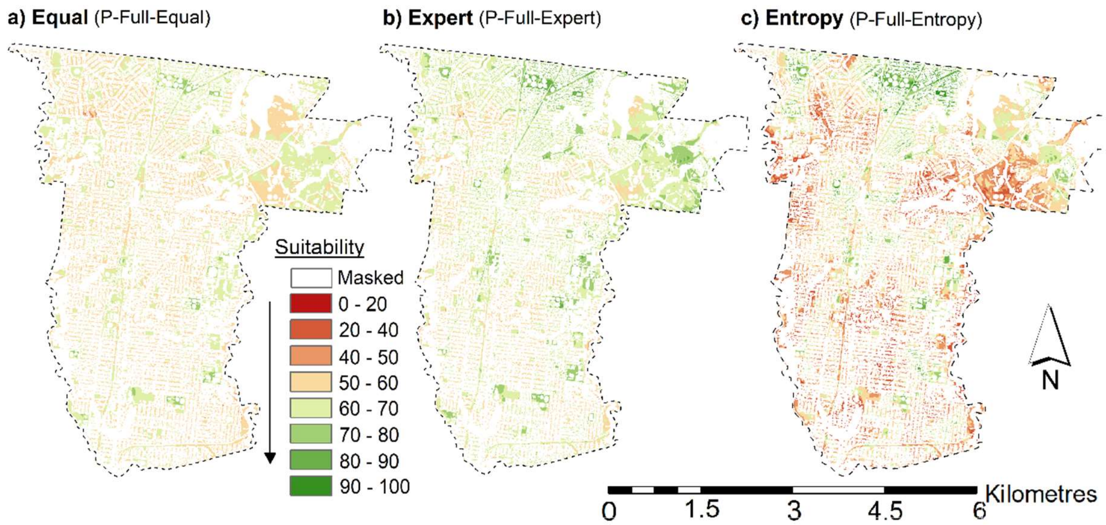

Figure 8: Comparing SSANTO results for different weighting methods for large systems using full criteria. a) Equal weights, b) expert weights, and c) entropy weights.

Finally, it is notable that in most locations, the score for 'Needs' is higher than that for 'Opportunities' (Figure 8). This could indicate that either (i) there is a bias towards 'Needs' in value scales or (ii) green infrastructure is needed in more locations than it can be implemented.

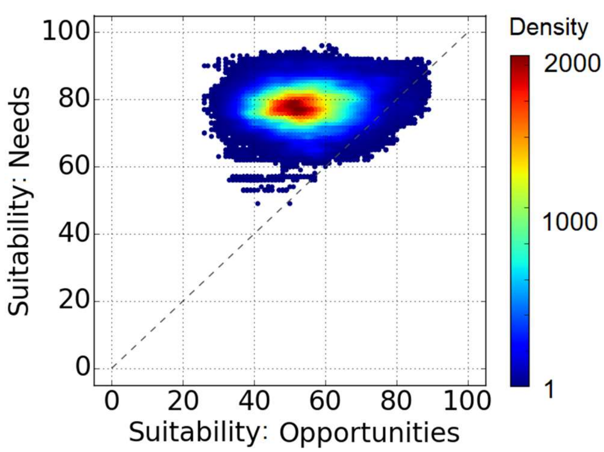

Figure 9: Scatter plot of a cell-by-cell comparison between suitability score for 'Needs' and 'Opportunities' output produced by SSANTO for scenario P-Full-Expert (refer to Figure 5a, b).

4. Discussion

4.1 Operation of SSANTO

As is inherent to many types of models and tools, the availability, quality and format of input data are fundamental to SSANTO's operation. This principle is often referred to as "garbage in, garbage out" (Eysenck, 1978). The most important data-related issues include:

- data quantity: many criteria and related datasets are required, including biophysical, socio-economic and planning-related data (Alexander, 1989);
- data quality, accuracy and collection date (how recent the data are);
- fuzziness of the relation between data/indicator and decision criterion (Chen et al., 2011; Malczewski, 1999);
- high variety of data formats and resolutions related to the different types of data (Openshaw, 1983).

The nature of data inputs, i.e. socio-economic and urban form data, make SSANTO specifically applicable to infill development modelling. Sufficient biophysical data in combination with detailed statutory planning data can warrant SSANTO useful for greenfield developments as well. In cases where master plans are detailed enough, certain 'virtual' datasets can serve as criteria in the *planning & governance, provision, regulating, cultural* and *habitat* categories. Limitations related to data are described in greater detail in the supplementary materials.

Different weighting methods are associated with different advantages, biases and limitations, as described in section 2.1. Varying data formats were found to have an impact on entropy weights, potentially compromising their validity. Further discussion on the power of entropy-based weights to remove biases associated with user-based weighting (Boroushaki, 2017) as well as the limitations related to data formats can be found in the discussion section of the supplementary materials. Clear communication of uncertainties relating to data and weighting is essential to enable appropriate, mindful interpretation and application of the outputs (Walker et al., 2003). Because user-defined weights are a reflection of preferences and expertise, suitability is a human concept, which is not objectively measurable, as mentioned in section 2.3.

Given that suitability is a human concept, caution is required when concluding that model run P-Full-Entropy is better at modelling suitability. More accurately, it 'performs better' in mirroring the outcome of human decision-making processes. Therefore, just as important as validity, is a tool's usefulness: the ability to reduce the cost while increasing the speed and rigour of decision-making processes and enhance the quality of decision outcomes. Usefulness also depends on a tool's user experience, such as user-friendliness, flexibility and relevance to planning problems (Lee Jr, 1973). All of these issues were found crucial in WSUD planning practice (Kuller et al., 2018b).

Tested performance (difference between suitability of E2D priority sites vs. Darebin average) is compromised by E2DesignLab's access to 'inside information' for the selection of E2D priority sites, which is not reflected in input data. Notable example is the location of an E2D priority site at a golf course soon to be decommissioned. Sports fields such as golf courses are identified as highly unsuitable by SSANTO, which has no information about its temporary status. Such discrepancies highlight SSANTO's, and any tool or model's role as supporting (rather than replacing) planning, used in conjunction with other tools, models and, most importantly, the human decision-making processes.

4.2 Application of SSANTO in practice

SSANTO was designed to foster stakeholder collaboration through its rapid generation of preference-based suitability outcomes. It enables users to compare and discuss individual model runs to gain deeper understanding of the underlaying context and preferences of suitability for WSUD. Thus, SSANTO can support more robust decisions. It is, however, not meant to replace human judgement (Reed and Kasprzyk, 2009), and should never be used in isolation. Rather, it should be considered a support tool in a wider decision-making context, which also includes other tools and models as well as human decision-making. The place of SSANTO in such iterative decision-making processes is depicted in Figure 9. Preliminary discussions with planning professionals suggest that SSANTO would provide a valuable addition to their work. SSANTO was developed in response to the urgent need of WSUD planning practitioners for spatial decision analysis (Kuller et al., 2018b).

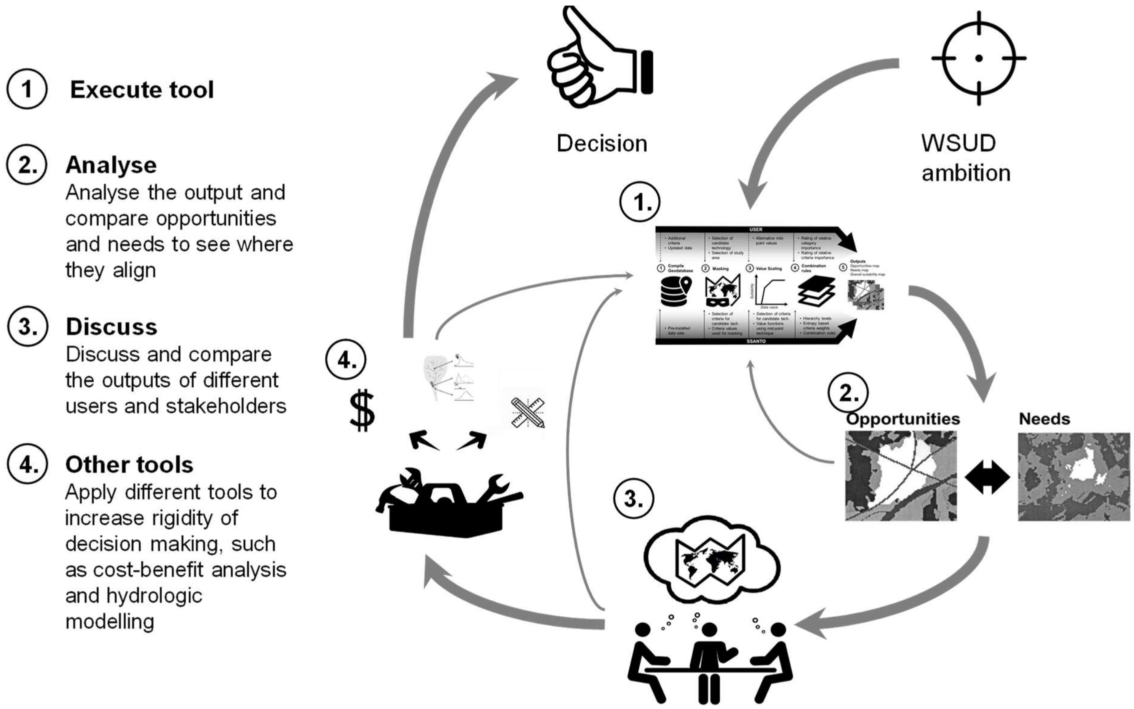

Figure 10: WSUD planning and decision-making cycle with SSANTO.

4.3 Further research

Future work should extensively focus on qualitatively testing and validating SSANTO through workshops with practitioners. Furthermore, quantitative validation will include thorough comparisons with multiple suitability analyses previously undertaken in Melbourne as well as in cities outside Australia, and in-depth sensitivity analysis to gain deeper understanding of the identified biases and uncertainties (Delgado and Sendra, 2004). Also, future work includes the addition of more advanced functionality for weight elicitation such as SWING (Edwards and von Winterfeldt, 1986), which could improve user experience as well as weight consistency, and has previously been implemented in urban water management research (Scholten et al., 2015). As currently the value scales are set in SSANTO, future work should include the option for users to define their own value scales, as these can be (to a certain extent) preference dependent and may change with progressive insights in WSUD placement. Finally, user experience as well as coupling and integration with other models could be achieved by migration of SSANTO to open-source-, standalone- and online platforms.

5. Conclusions

This paper presents a methodology and associated software tool called SSANTO, developed to rapidly assess spatial suitability for the planning and implementation of green and distributed urban stormwater infrastructure, using GIS-MCDA techniques. SSANTO allows suitability mapping for seven different system types including rain gardens and constructed wetlands. The tool allows for diverse criteria sets to be included such as biophysical, environmental, socio-economic and planning related data. For the first time, the two sides of suitability for a broad range of system types are incorporated, applying principles from ecosystem services. The tool's architecture was designed to facilitate the application of various weighting methods, combination techniques and parameter settings, tailored to the user's preferences. Rapid analyses of 'Opportunities' and 'Needs' are presented using an intuitive, spatially explicit way through colour-coded maps.

Running SSANTO with inputs data, value scales and weight assignment identical to those used by an WSUD consultancy demonstrated its ability to replicate the outcomes of manual suitability mapping, confirming the construct- and internal validity of the algorithms used. Further testing demonstrated that SSANTO can reflect human decision-making processes by successfully calculating relatively higher suitability values for selected priority locations from a decision-process by an WSUD consultancy.

It was found that using the most comprehensive set of criteria, SSANTO was more successful to reflect the outcomes of a human decision-making process than using only the selection of criteria used for that human decision-making process. This suggests that SSANTO can capture some of the tacit knowledge that planning practitioners use for WSUD placement. Furthermore, entropy weighting performed better than expert weighting and equal weighting. However, caution should be used as entropy weighting is associated with certain methodological limitations. Throughout our study area, 'Needs' for green infrastructure is consistently higher than the 'Opportunities' for them.

The development of SSANTO aimed for a simple and user-friendly interface and workflow. The aim is to enable experts in sustainable urban water management and planning, as well as lay people, to undertake thorough spatial analysis without the need to invest high amounts of time and resources, associated with manual processes. SSANTO's rapid suitability analysis aimed at facilitating the assessment of multiple scenarios, increasing our understanding of the interaction between urban planning decisions and our urban context. By comparing the outcomes of iterative application by multiple stakeholders, SSANTO should promote discussion, collaborative planning and a deeper understanding of the variation of stakeholder preferences and their impacts on decision-making. In doing so, SSANTO has the potential to bridge the gap between perceived need for planning support and low utilisation levels of models and tools and improve the outcomes of planning for sustainable urban water management.

6. Acknowledgements

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5.3 SSANTO AND THE PLANNING PRACTICE

The ad-hoc and opportunistic planning practices associated with WSUD can have long term effects on its feasibility and limit the benefits derived from WSUD. GIS-MCDA has great potential to improve planning practices, however is generally costly and time consuming (Marttunen et al. 2018). Constrained resources of stakeholders responsible for WSUD planning prevent a wider uptake of GIS-MCDA. SSANTO makes such advanced spatial analysis methods available to planning practitioners through its fast and user-friendly, but rigorous suitability assessment. Such methods have recognised potential to overcome ad-hoc and opportunistic planning processes and improve planning outcomes (Geertman and Stillwell 2012, Klosterman 1997). SSANTO's development was informed through close collaboration with the end-user to ensure that its design responds to their needs.

SSANTO can support the exploration of WSUD layout options in a given area by allowing rapid yet thorough suitability assessment. Outputs and their underlying causes are explored in detail by viewing the summary statistics as well as using the graph method, which present an overview of suitability distribution across the entire case-study. Most important feature, however, is the 'explain' tool, shown in Figure 5S of the supplementary materials. This function allows the user to click anywhere on the suitability map to get a summary of suitability at the clicked location: suitability value, highest to lowers criteria values, and highest to lowest impact of criteria (i.e. a metric considering value, weight and difference with average suitability). Output maps can be overlaid with base maps, such as satellite data, as shown in Figures 7S (street-scale) and 8S (precinct-scale) of the supplementary materials. Such a process deepens the understanding of the local context for WSUD planning.

Using the output maps and other output data for 'opportunities' and 'needs' separately, rather than the combined overall suitability map, is preferred. Separately, these maps provide the user with targeted information about where we could, and where we should place WSUD. Combining these suitability sides together, this nuanced information is lost as in the combined suitability map, a location with average suitability can mean three different things: (1) high opportunity but no need for WSUD, (2) high need, but no opportunity for WSUD or (3) medium need and opportunity for WSUD. Each of these scenarios may lead to very different decisions from urban planners.

5.4 FINAL REMARKS

This chapter brings together all knowledge and insights gained during the research presented in Chapters 2-4 by building a PSS for strategic WSUD planning called SSANTO. Through the automation of methods from GIS-MCDA, the WSUD suitability framework is operationalised. Insights in the needs of planning practice guided the architecture of SSANTO. Testing showed the construct validity and internal validity of its algorithms. It is able to reflect manual strategic decision-making on the prioritisation of locations for WSUD placement in a case-study in Melbourne. In doing so, SSANTO is rapid and flexible, responding to user preferences and expertise. Thus, SSANTO enables decision-makers to enhance the rigour of their decisions without requiring high levels of expertise or investments in time or money. Ultimately, this could lead to improved outcomes of WSUD planning for urban communities in terms of environmental quality, liveability and flood safety. In the following chapter, the Indonesian (WSUD) planning practice will be discussed and the need for, and useability of SSANTO will be tested for the case study of Bogor, Indonesia.

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CHAPTER 6

SSANTO IN THE INDONESIAN PLANNING CONTEXT

Als er geen water meer is, kent men de waarde van de put

"When the water runs out, the value of the well is known"

6.1 INTRODUCTION

In this chapter, the need for and applicability of the newly developed planning support system called SSANTO is evaluated for the Indonesian urban planning context. Firstly, this context is described using the cases of Bogor (West Java) and Surabaya (East Java). Then, the applicability of the tool is tested for the case of Bogor. Background, methodology, results, discussion and conclusions of this work will be submitted for publication in *Cities* and are presented in section 6.2. This research was approved by the Monash ethics committee (Appendix B).

This work responds to the fifth objective of this PhD: **"Test the tool for a developed (i.e. Australia) and developing (i.e. Indonesia) context through case studies"**, focussing on the second part. To this end, this section seeks to answer research question RQ5: *What is the need for, and applicability of a tool such as the one mentioned in H4 in the planning context of urban Indonesia?*

To answer this research question, the following hypothesis was tested:
H5: Planning support in the form of a GIS-MCDA is needed to improve the relatively young planning processes in Indonesia, but will be challenged by the difficulty to acquire quality input data.

Testing of this hypothesis was conducted using qualitative research methods including semi-structured in-depth interviews and demonstration sessions followed by questionnaires (for interview protocol and questionnaire, refer to Appendix E). Research participants included government officials, planning consultants and academics as well as students in the field of urban planning and water management.

6.2 SSANTO IN THE INDONESIAN PLANNING CONTEXT

Planning support for distributed green stormwater infrastructure in a developing context: the case of Indonesia

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Abstract: Water Sensitive Urban Design (WSUD) is increasingly being used around to world as a sustainable stormwater management strategy to improve water quality, reduce urban flood risk and generate a suite of amenity benefits to urban communities. Although predominantly developed and implemented in western countries, WSUD is increasingly applied in developing countries as well, as a response to rapid urban growth and climate impacts. Developing countries have the potential to 'leapfrog' towards more sustainable urban water management practices. As an integral part of the urban landscape, WSUD requires strategic implementation. Planning Support Systems (PSS), such as spatial modelling software, can assist urban planning to achieve this. This study explores current planning practices, the role of tools and models and the potential for the adoption of a specific spatial tool in an Indonesian urban context. Using in-depth interviews and workshops, we elicit the tacit knowledge and experiences of planning practitioners including government officials, planning consultancies and academics. Planning processes were generally found to have improved over the past decades. However, significant barriers to strategic planning exist, including inadequate collaboration between planning actors, insufficient capacity and resources at the local government level. Perhaps the most important barrier highlighted was the lack of access to high-quality spatial data. Although tools and models are used for planning, their application is limited to academia and planning consultancies, who conduct the bulk of planning tasks. Most important considerations for PSS adoption are data needs, alignment with planning needs and user friendliness. The tool tested in this study shows potential for adoption considering the enthusiasm for uptake of novel and innovative spatial methodologies. However, collection and sharing of spatial information is paramount if WSUD is to be successfully implemented in Indonesian cities going forward.

Keywords: Water Sensitive Urban Design; Low Impact Development; Planning Support Systems; Urban Planning; Strategic Planning; Developing Context; Leapfrogging

1. Introduction

Nature-based solutions to urban water management have been applied for several decades to mitigate the negative impacts of increased urbanisation, such as degraded waterways and urban flooding, which are the result of increased runoff from impervious areas. Urban design with incorporated nature-based solutions, in Australia known as water sensitive urban design (WSUD), such as rain gardens, constructed wetlands and bioswales, has been implemented in the US (low impact development – LID) and Europe (sustainable urban drainage systems – SUDS) (Fletcher et al., 2014). Also in Asia there is an increasing interest in similar approaches, as evident from Malaysia (e.g. Liew et al., 2014; Quan et al., 2014), the "sponge city" project in China (MUHORD, 2014) and the ABC Waters programme in Singapore (PUB, 2018).

Less has been published about the uptake of WSUD in the developing world context of Indonesia. However, cities in Indonesia, including the greater Jakarta region, suffer from increasingly frequent and severe flooding as well as waterway degradation because of ongoing urban development and increased imperviousness (Padawangi and Douglass, 2015). Nature-based solutions are well-positioned to manage these growing challenges in Indonesian cities (e.g. Putra and Ridwan, 2016).

WSUD planning and the use of Planning Support Systems

Western nations have had over two decades of experience with planning for WSUD; yet strategic approaches to WSUD implementation remain largely absent, resulting in ad-hoc placement of infrastructure (see e.g. Eckart et al., 2017; Kuller et al., 2018a). Appropriate planning is critical, as we are unlikely to capitalise on the multiple benefits (i.e. ecosystem services, water quality, flood protection) associated with WSUD without its strategic siting. This can also potentially result in failed infrastructure. To support planning processes, Planning Support Systems (PSS) have been developed explicitly to assist urban planners with improving their decision-making process and outcomes (Klosterman, 1997). Indeed, a plethora of PSS were developed to this end (Kuller et al., 2017; Lerer et al., 2015), ranging from high-level visioning (e.g. the societal transitions workbench by De Haan et al. (2011)) to detailed WSUD design tools (e.g. MUSIC by eWater (2011)). Despite the identified need for and promotion of PSS in academic literature (e.g. Geertman and Stillwell, 2012; Klosterman, 1997; te Brömmelstroet, 2013), their application in urban planning practice remains limited.

Academic scholarship on WSUD planning and PSS has focussed mainly on a developed-world context. However, developing contexts present a promising environment for sustainable developments such as WSUD, for their urban infrastructure is still largely undeveloped (UN-HABITAT, 2016). Thus, in the absence of a 'lock-in' into unsustainable practices of grey infrastructure that many developed cities currently face, developing cities have the potential to 'leapfrog' towards more sustainable practices such as WSUD (e.g. Barron et al., 2017; Binz et al., 2012; Poustie et al., 2016). The potential of nature-based solutions in developing cities has been suggested in literature (Mguni et al., 2016), and interest in WSUD is emerging in countries such as South Africa and Indonesia (e.g. Armitage et al., 2013; Faradilla, 2017; Lottering et al., 2015). Improved planning support is called for to support this growing interest. Only few studies have focussed on development and application of PSS for sustainable urban water management in developing contexts (e.g. Galvis et al., 2014; Montangero and Belevi, 2008; Poustie and Deletic, 2014). Urban planning in developing countries differs in a number of aspects, including processes, social structures, institutional capacity, data availability and quality and human as well as monetary resources (Armitage, 2011; Fisher-Jeffes et al., 2012; Mguni et al., 2016). As such, the effects of these aspects on transferability of PSS for WSUD planning remain largely unknown.

SSANTO: A planning support tool for WSUD implementation

Spatial Suitability ANalysis TOol (SSANTO) is a PSS aimed to support urban planners to take a more strategic approach to WSUD implementation (Kuller et al., under review). SSANTO was developed for application across different contexts. It focussing specifically on application in Australia and Indonesia, utilising Australian experience to assist leapfrogging of Indonesian practice (see also: Barron et al., 2017). SSANTO allows rigorous and spatially explicit analysis of opportunities as well as needs for the implantation of WSUD in a selected area of interest. To date, it is the tool that mimics closest the in-depth multi-faceted and multi-criteria decision-making process surrounding the implementation and suitability of WSUD.

SSANTO uses Geo-Information Systems (GIS) based Multi-Criteria Decision Analysis (MCDA), a process that normally requires significant investment of time and expertise. SSANTO follows a 4-step process of GIS-MCDA (Figure 1):

1. Compiling geodatabase: gathering and pre-processing all relevant spatial data;
2. Masking: removing all areas from the analysis where WSUD implementation is constrained;
3. Value scaling: translating raw data into suitability values for each criterion; and
4. Combining: overlaying all datasets based on user-defined criteria.

During each step, the user is asked for inputs, including user-defined weighting of criteria (step 4). Until now, the applicability and capacity of SSANTO was only studied in an Australian context (Kuller et al., under review; Kuller et al., 2018b). SSANTO's simple interface is integrated in the widely used ArcMap software, for use by experts and lay people (Figure 2).

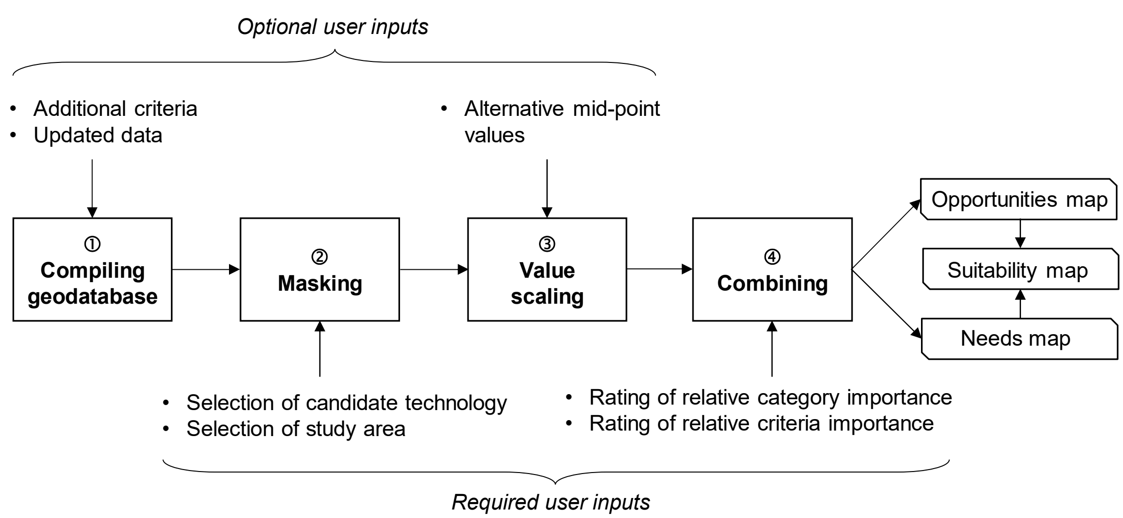

Figure 11 Workflow of SSANTO with user inputs for each of 4 steps (adapted from Kuller et al., for submission)

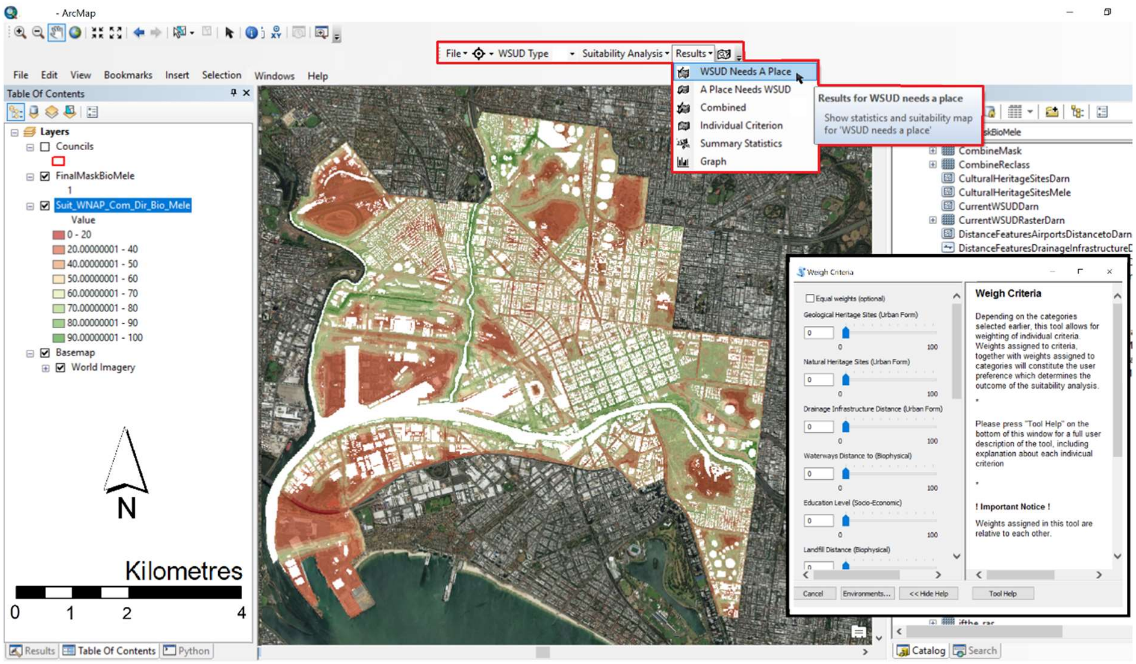

Figure 12 User interface of SSANTO in the ArcMap environment showing the output of the *opportunities* assessment for Melbourne City Council. Red lining: SSANTO's toolbar and results dropdown menu. Black lining: pop-up window for criteria weighting.

Research aim

This study explores the tacit experiences of urban planning professionals in Indonesia to understand: (i) the level of use, if any, of existing PSS and (ii) to what extent a proposed PSS might be useful in day-to-day decision-making processes. Practitioners' perceptions and knowledge were elicited using in-depth semi-structured interviews and workshops. Thus, the study responds to the paucity of academic insights regarding WSUD planning and PSS uptake in a developing context. For the first time, this study seeks to systematic gain insight into planning practice and the current and potential role for PSS in Indonesia. Such knowledge could assist in the ambition to leapfrog towards more sustainable practices by promoting greater and more strategic uptake of WSUD practices in urban areas in developing contexts.

2. Research approach

2.1 Methodology

This work involved unpacking the core roles and responsibilities for urban planning in Bogor, West Java as the primary case-study location, supplemented by data from Surabaya, West Java. Bogor is densely urbanised and increasingly suffers from pluvial flooding (e.g. Ramdhan et al., 2018) and water quality issues (Padawangi and Douglass, 2015). Public disturbance resulting from urban floods and deteriorating water quality combined with an ambition for higher levels of urban green space have led to a recent increase in interest for the implementation of WSUD (e.g. Putra and Ridwan, 2016; Ramdhan et al., 2018). The drive towards sustainable management of urban water systems is reflected in the selection of Bogor as one of the main study locations for a greater research collaboration known as the 'Urban Water Cluster', funded and coordinated by the Australia-Indonesia Centre (AIC). The program involves three Australian and three Indonesian universities, as well as industry partners from government and the private sector. As part of this research project, this study leverages on this network connecting professionals involved in the urban water and urban planning sectors.

To elicit practitioner tacit experiences and to generate a deeper understanding of contemporary planning practices the research was undertaken over two key stages (Table 1). The first stage involved semi-structured, in-depth interviews with 14 practitioners directly involved in urban planning and management, including government officials, planning consultants and academics. Interviews were conducted by the lead author either in English, or with the help of a simultaneous translator in Bahasa Indonesia, depending on the interviewees' preference. Interviewees were asked a series of questions related to their experiences of the current planning system and broadened to inquire about whether PSS were currently being used or considered for future use. Further questions addressed key challenges and opportunities to advance PSS uptake. Stage two involved workshops where SSANTO was showcased, and its utility outlined. This was done through a step-by-step live demonstration of the software. The demonstration was followed by a series of questions collated in a questionnaire, whereby practitioners and students were able to provide feedback on the presented tool, and potential opportunities or constraints regarding adopting such a tool in their planning context.

Table 4 Summary of qualitative research design, stages of research, stakeholder involvement and key research topics

	Who?	How many?	Research topics
Stage 1: Interviews	Government officials, academics and planning consultants	10 interviews of 14 professionals (Bogor: 12, Surabaya: 2)	Current planning practices, strengths and weaknesses, role of PSS
Stage 2: Workshops	Government officials, academics, planning consultants and students	28 professionals and students from 2 workshops. 16 questionnaires returned	Demonstration of tool and discussion of the potential of such tool, specific aspects of the tool and potential barriers for uptake in Indonesian context.

For analysis, all Indonesian recordings of interviews were transcribed and translated to English by an independent professional service. The answers to interview questions were coded and then grouped into emerging themes across the interviews following an iterative analysis process. A similar approach was taken for the analysis of the questionnaires, first translating the answers into English and grouping them into emerging themes where relevant.

2.2 Case study description

Bogor is one of five urban centres in the greater Jakarta urban agglomeration known as Jabodetabek, furthest away from Jakarta city centre in West Java, Indonesia. In the most recent national census, Bogor's population was just under 1 million (BPS, 2010). The densely populated city is located about 50km south of Jakarta city centre (Figure 3). Situated in the tropical rainforest climate zone, Bogor experiences very high rainfall up to 5,000 mm/year and is prone to flooding (Pravitasari et al., 2014). Two main rivers, Cisadane and Ciliwung, flow across Bogor on either side of the city centre. Both rivers pass through greater Jakarta before entering the ocean. The application of WSUD for urban water management is a relatively new phenomenon in Bogor and, particularly, its potential for flood management has been recognised (e.g. Putra and Ridwan, 2016). Recent and future high-end urban developments are adopting WSUD principles and infrastructure in their urban design (e.g. BAPPEDA Cibinong, 2016; Faradilla, 2017).

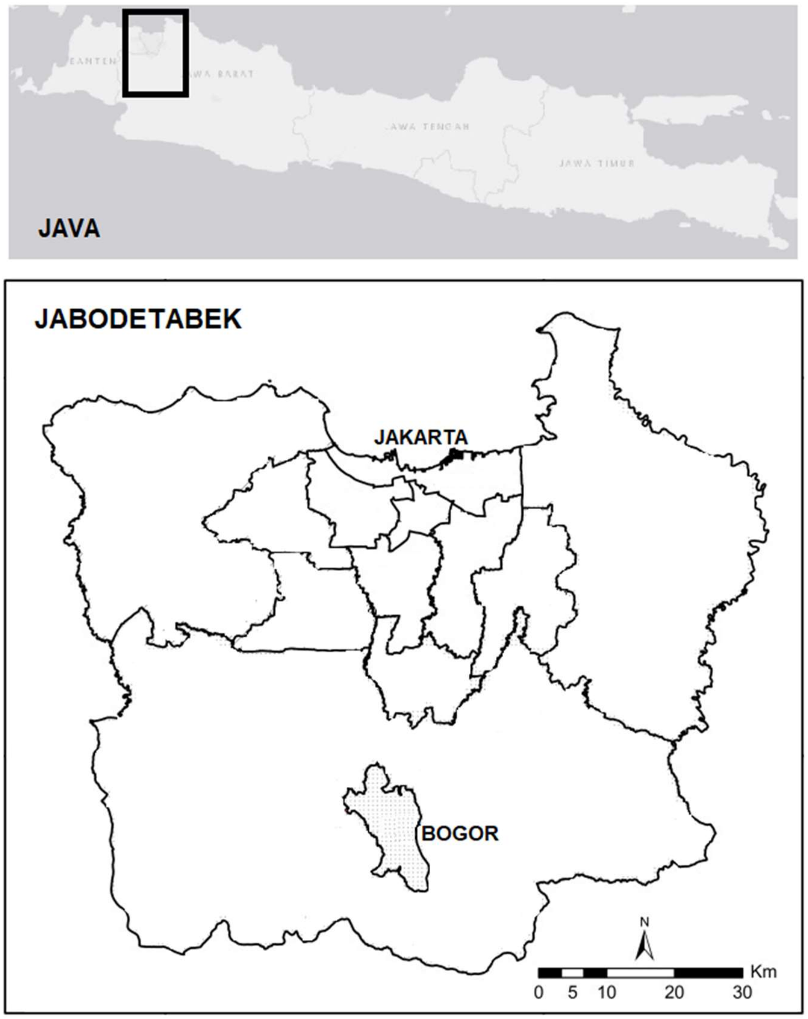

Figure 3 Geographic situation of the case-study area. *Sources: Java: Esri, HERE, DeLorne, MapmyIndia, Open StreetMap contributors and the GIS user community. Jabodetabek: adapted from Pribadi and Pauleit (2015).*

3. Urban planning and WSUD implementation in Indonesia

3.1 Organisation of urban planning

A formal structure for urban planning is a recent phenomenon in Indonesia. Figure 4 gives an overview of the main components of urban planning as inferred from the interviews. Although cities such as Surabaya have had master plans dating back to as early as the 70's (e.g. Surabaya City

Government, 2016), the first national planning law came into force in 1992. The most recent planning law (i.e. Law 26) dates from 2007 and introduces the requirement for zoning. On a national level, *Badan Perencanaan Pembangunan Nasional* (BAPPENAS) is responsible for urban planning and policy making. Since 2004, municipal planning authorities (i.e. *Badan Perencana Pembangunan Daerah* - BAPPEDA) are formally placed at the centre of the planning. BAPPEDA is responsible for the implementation of Law 26 and other relevant national laws, through the production of short-, medium- and long term (master) plans. Drafting of these plans is generally conducted by planning consultants, guided and pending approval from BAPPEDA as well as the senate in the case of master plans. These plans form the context in which developers and other private actors can shape the city. From the interviews, no formal role for the provincial government was inferred. An absence of involvement on a regional scale, such as the provincial scale, may lead to problems with strategic alignment of planning between municipalities. Such alignment can be important for catchment-scale water management.

Instrumental to the promotion of green infrastructure, this law contains a regulation on the provision of urban green space, known as the 30-20-10 rule. This regulation prescribes cities to provide their inhabitants with 30% green open space, of which 20% in public, and 10% in private areas. Further relevant regulations for developments include regulations on maximum impervious space, peak runoff and water quality as well as the requirement for public participation during all phases of the planning process, through so called ‘focus group discussions’.

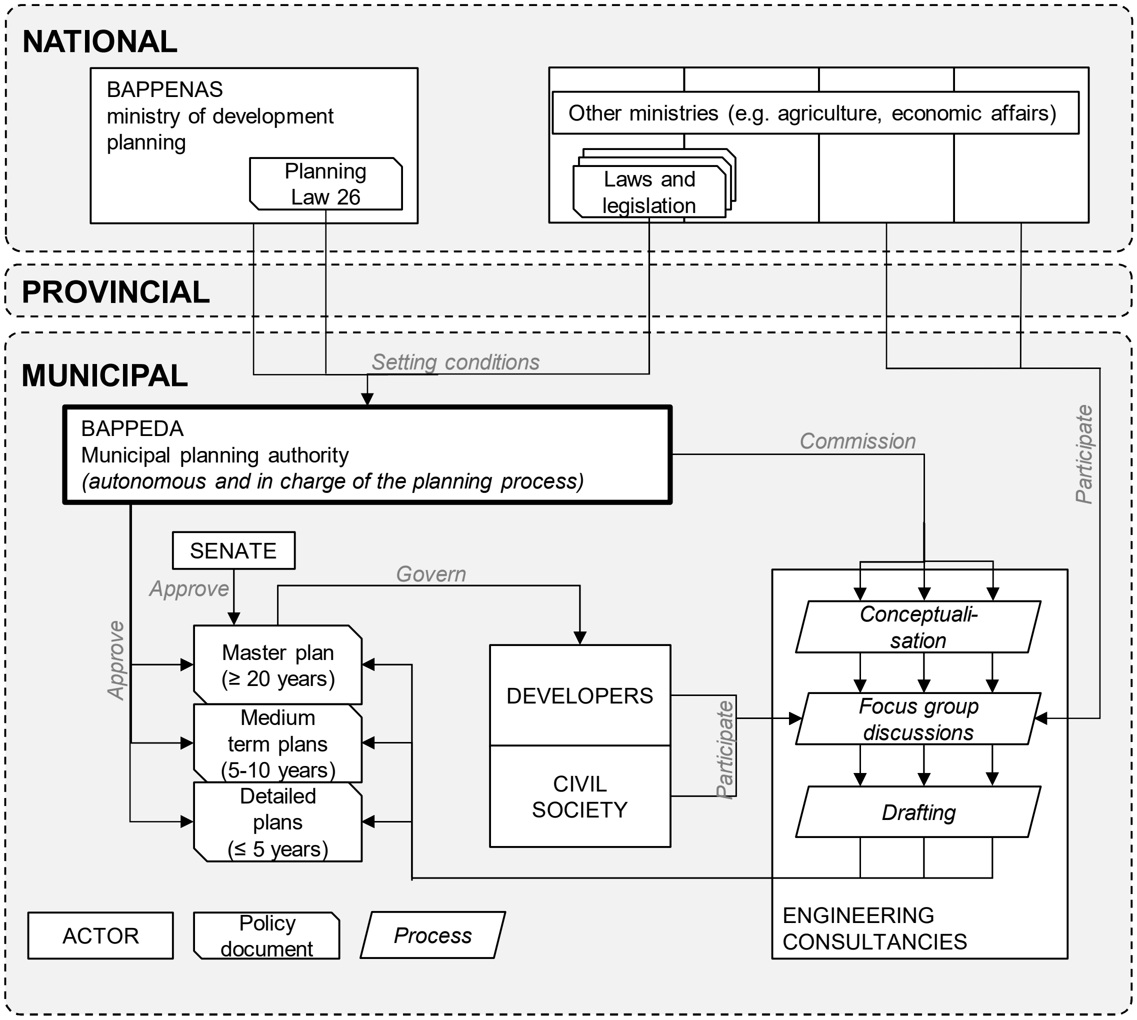

Figure 4 Overview of the organisation of spatial planning in Indonesia as derived from the interview data.

3.2 Planning for success?

The increasing formalisation and regulation of urban planning is generally perceived as an improvement. In particular, the fact that a single organisation (BAPPEDA) is responsible for the entire process was regarded to strengthen the coordination and collaboration between relevant stakeholders, as illustrated by the following quote from a planning consultant: *"What is good is the coordination between stakeholders. Local government has full authority in their municipality to decide. So, if the central government says build the road here, if the local government doesn't want it, it goes as they want. So coordination between stakeholders is quite good."*

However, a lot of criticism was expressed by practitioners as well. Despite the top-down organisation, targets for on-site stormwater retention and green open space are not being met (Bogor only has 13% of green open space, while Surabaya performs better at 22%). Although the formalised collaboration was deemed positive, the practice of the FDG's leaves room for improvement. Several interviewees note that involvement of stakeholders was limited, centred around governmental actors and lacking the representation of local communities. Especially for private development, the involvement of stakeholders is normally at a minimum and public consultation absent. Advancement of urban water management requires a holistic vision and approach of the urban water systems, however, *"it's [urban planning] egocentric, agencies have their own ego. It is hard to combine. We're talking about the budget, that is planned by national and local level. It is all about money and political will."* (academic respondent). This attitude from agencies is further reflected in the lack of data sharing, as noted by several professionals: *"For example, you have data from different sources, they tend to have constraints sharing it all in one database. Because of bureaucracy, mentality."* (urban planning professional). A lack of coordination is a real threat to strategic WSUD planning, which is interdisciplinary by nature.

National regulation prescribes planning documents to be drafted by non-governmental parties, such as engineering consultancies. In practice, conceptualisation and even the organisation of focus group discussions are conducted by consultancies. Both academic as well as governmental respondents pointed to the lack of capacity and skill at governmental level (BAPPEDA) that resulted from this policy. This was perceived to compromise public interest as well as to be unnecessarily costly. Local government therefore relies on the capacities of consultants and developers in terms of integrated urban water management. Although governmental respondents indicated their interest in upskilling themselves and the organisation, this was hindered by the national regulation as well as a lack of resources. One government official noted that *"…if we need training, they think we don't need to. Even if by doing so it would push us in the right direction. […] When the regulation budget proposal* *comes out, there's nothing left for us to get training."* (government official). As integration of WSUD in developments often incurs extra costs, its implementation by the private sector can be compromised. Plans for public development of green infrastructure are often halted due to high land prices and insufficient funds. Instead, as one academic respondent highlighted, *"Economy always wins over ecology. But in my opinion that is not good. In Bogor, there are many shopping malls, CBD [central business district] always gets bigger and bigger. But it comes at the cost of degrading farmland and degrading green space."* (academic respondent).

The most frequently mentioned barrier to strategic urban planning was the limited access to good quality spatial data: *"Data availability is a problem. In developed countries they are using big data in planning. This is a weakness in our process. Data driven policy making is very weak"* (planning consultant). Several causes for this drawback were identified including dispersed sources of data and limited sharing between stakeholders, the absence of a centrally coordinated shared data platform and a lack of resources for data collection. Data availability varies between cities, as a significant amount of spatial data was available for Surabaya, part of which is publicly accessible through an online platform (BAPPEDA Surabaya, 2018). Respondents from Bogor emphasised the need for such a platform, as spatial data availability was very limited. The lack of data often leads to lengthy process of drafting urban plans, caused by the need for local data collection. This is highlighted by one planning consultant: *"That's what makes one year an insufficient amount of time, […] data should already be provided […], for example the map of geology data should be at the geology office."*.

Finally, illegal development from both formal (developers) and informal (slums) sectors create a discrepancy between well-defined urban plans and physical reality. Occasionally mentioned in the interviews, the informal settlements and high-end urban developments regularly take place within riparian zones, where urban development is officially prohibited. Such tendencies, which are extensively described by the academic scholarship, seriously jeopardise sustainable urban water management and put residents in constant danger of floods in Indonesian cities (e.g. Vollmer and

Grêt-Regamey, 2013) as well as developing cities around the world (e.g. Kundzewicz and Schellnhuber, 2004; Tanner et al., 2009).

3.3 The role of PSS

Government's constrained capacity and resources are also reflected in the use of tools and models, which is mostly limited to academia, for research purposes, and consultancy, for urban planning. The local planning agency (BAPPEDA) and other government representatives would require, as part of an urban planning task commissioned to an engineering consultancy, specific tool and model outputs to be part of the planning report. The production of such outputs is often prescribed by national policy. Mostly in hard-copy format, government officials indicated they were able to interpret these outputs, but unable to 'play around' with them independently from the organisation who produced them.

Participants from academia and consultancies reported a widespread familiarity and application of spatial and design software. Most commonly mentioned were ArcMap (Esri, 2018) and AutoCAD (Autodesk, 2018), but also open-source counterparts such as QGIS (QGIS, 2018) and SketchUp (Trimble, 2018). Furthermore, statistical tools such as SPSS are widely applied, while the use of economic tools such as Cost-Benefit Analysis is reported to a lesser degree. Advanced urban planning tools and methodologies such as SUSTAIN-EPA (Lee et al., 2012) and manual suitability analysis using GIS-MCDA were only applied in academia. To date, such methodologies do not seem to be applied in real-world planning practice. Similarly, the use of hydrological and hydraulic tools used for urban water management, such as SWMM (Rossman, 2010), are strictly limited to academia.

When asked for the most important considerations for the adoption of tools and models, practitioners put most emphasis on the data requirements and the extent to which tools and models are flexible to application for their specific purposes (Table 2). Furthermore, user-friendliness and the type and quality of the output were deemed important factors. Especially spatial outputs in the shape of maps were considered helpful in the planning process. Transparency and cost appeared to be less of a decisive factor in tool application. Such findings are in line with an earlier study undertaken in different planning contexts (Kuller et al., 2018b). Contrary to earlier findings however, whether or not tools were an industry convention did not seem to play a role for our Indonesian planning professionals. Respondents seemed eager to try novel and innovative methodologies that are not (yet) commonly used around the world.

4. Potential and evaluation of SSANTO: a GIS-MCDA approach

In this section, the applicability of a GIS-MCDA tool (SSANTO) is tested, in response to the second objective of this study. Practitioners' opinions were elicited using questionnaires during a workshop setting, where SSANTO was demonstrated.

After demonstration, SSANTO was met with enthusiasm from workshop participants. The processing steps to be followed by the user to produce SSANTO's outputs were intuitive enough to warrant a majority of workshop participants (9/15) confident enough to use the tool already after a brief demonstration. Its ArcMap environment was familiar to nearly all participants, who indicated that the built-in support was clear and helpful. The only improvement suggested to the interface was language, as SSANTO is currently only available in English.

A great majority (13/16) of questionnaire respondents indicated that SSANTO would be a welcome addition to planning practice and that they would use it if available to them. One government official wrote: *"Yes, because it [SSANTO] increases knowledge and provides ease to the planning from a spatial angle."*. Most practitioners (7/10) explained that manual GIS-MCDA techniques are already applied in practice, either by simply overlaying maps or more sophisticated methodologies including analytical hierarchy process: *"Similar [process], but very manual. By overlaying all the data needed using simple GIS tools"* (planning consultant). These respondents indicated that SSANTO would significantly improve this process in terms of time invested, rigour and output quality: *"Yes it [suitability analysis] can be easier with this tool. Because the [SSANTO's] design and operational* *processes are simpler."* (government official). The eagerness to try novel and innovative methodologies, that spoke from the interviews, appears to form fertile ground for the uptake of SSANTO, in particular if the software is free and open source.

Respondents indicated they would need a tool such as SSANTO anywhere between two to ten times a year. Consultants, government officials, academics and students all indicated they were interested in applying SSANTO. When asked to whom the tool would be of greatest benefit, however, most participants pointed to the local planning authority, BAPPEDA. This seems counter intuitive considering the bulk of executive planning tasks are currently conducted by consultancies. However, SSANTO may be well-positioned for application within governmental organisations for two reasons: Firstly, there is an eagerness among government staff to build the executive planning capacity of their organisation, of which the absence was perceived problematic by interview respondents. Secondly, its simple stepwise methodology enables time and resource restrained organisations to conduct rigorous GIS-MCDA without the need for highly skilled staff.

Workshop participants were asked their opinion on strengths and weaknesses of SSANTO. Table 2 compares their answers to the considerations for tool adoption, that resulted from the interviews. Most frequently mentioned strengths were the usefulness (fit-for-purpose) of its core functionality for the planning process and its user-friendly interface and process, as summarised by a government respondent: *"Easy to operate, makes work easier"*. The method was considered innovative and map-based tool outputs were appreciated for their capacity to support planning: *"Displays maps that are easy to understand"* (government official). Most respondents were realistic about the reliability of the outputs, as they recognised the importance of quality input data to generate reliable output maps. Evidence from earlier studies suggests that the level of complexity is an important, yet delicate aspect of a tool's successful uptake (e.g. Gibson et al., 2017; Kuller et al., 2018b). While highly complex tools are considered cumbersome and difficult to use, low complexity may render meaningless outputs. SSANTO was considered well-balanced, scoring a mean of 4.5 on a scale from 1 (too simplistic therefore meaningless) to 7 (too complex and therefore useless), where 4 is the optimum.

Table 5 Practitioners' considerations for the uptake of tools and models, their perceived importance from interviews, and the performance of SSANTO derived from workshop results

Issue	Perceived importance	SSANTO score
Data needs	High	☹
User friendliness	High	☺
Fit-for-purpose	High	☺
Output type and quality	Medium	☺
Transparency	Medium	N/A
Cost	Medium	free: ☺ cheap: 😐 expensive: ☹
Innovative	Medium	☺
Industry convention	Low	☺
Level of complexity	N/A	☺
Weight assignment	N/A	practitioners: ☹ students: ☺

While SSANTO scored well on most aspects that were regarded as important by interviewees, there is one important barrier its uptake: data availability. In the interviews, respondents concluded that the most important consideration for uptake of tools was the need for, and availability of data. Workshop results, as well as the lead author's own experiences in Bogor, suggest that the availability and quality of spatial and other data is limited. Articulated by a consultant, SSANTO is *"Very data-dependent, since the availability of detailed secondary data in Indonesia is very limited"*. In Surabaya, where spatial data is more abundant and partly publicly available, this barrier could prove to be lower. A relatively data-scarce environment such as Bogor can benefit from harnessing open source data platforms such as OpenStreetMap (www.openstreetmap.org), Google Earth (www.google.com/earth), as well as proprietary satellite data such as those from LANDSAT, available through the U.S. Geological Survey (https://earthexplorer.usgs.gov). The future development of SSANTO will include its migration into an online platform, which will enable easy integration of such online data resources.

Although data availability can limit the usefulness of a tool such as SSANTO, the availability of a PSS that is considered to contribute a valuable addition the planning process can also serve as an incentive for better data collection and sharing. Better contextual knowledge, as derived from better data, is considered to benefit the planning process. As such, the role of PSS as a catalyst of data collection might be at least as important as their role in planning support in developing contexts.

Besides the availability of data, the significant amount of data needs gave some respondents the perception that the tool was heavy and required significant computational power. Despite this perception, SSANTO is easy to run on any device that can run ArcMap and doesn't need computation power exceeding that of an average personal computer.

Interestingly, planning professionals seemed highly uncomfortable with performing weight assignment, which is part of MCDA. This is illustrated by a government official who noted that *"In the weighting I think it won't be accurate, because each person has different opinions."*. Most felt that they were not in the position to make this judgement, but that this should be done using expert opinion. Who this expert should be, other than themselves, remained unclear. As local professionals involved in the day-to-day planning and decision-making in their municipality, our workshop participants arguably are well-positioned as experts for weight assignment. The apparent lack of confidence in their own expertise may be a product of the highly hierarchical nature of organisations and work-relations in Indonesia (e.g. Claramita et al., 2013). The lack of training and capacity-building of local government staff could amplify this paucity. Alternatively, the discomfort with weighting may result from a misinterpretation of the function of weighting, and the concept of MCDA. As such, it highlights the need for clear communication and manual accompany implementation of SSANTO. Such communication should include the fact that SSANTO is not an objective decision-making tool, but rather a decision support tool and the final decision-making remains at the discretion and judgement of the decision-maker. Notable was the difference between student respondents and professionals, as the former seemed to have no reservation towards weight assignment. Perhaps this speaks to a cultural origin that is slowly changing and is not as prominently expressed among the younger generation, or the absence of the burden of responsibility that senior decision-makers face.

Judging from the interviews, costs only seemed to play a moderate role in the decision to adopt a tool. However, when workshop participants were asked to indicate whether they would use SSANTO when it was 'free', 'cheap' or 'expensive', the likelihood of adoption was greatly reduced, even if the cost was 'cheap'. Thus, there may be a discrepancy between stated importance of costs and the willingness-to-pay in practice. These findings suggest that free and open source software has the greatest potential in the developing world context of Indonesia, which is faced with relatively constrained budgets of governmental organisations.

5. Conclusion

Developing countries have been recognised for their potential to 'leapfrog' towards more sustainable environmental management practices such as urban water management, because of the absence of the technological lock-in common to many developed nations. Green infrastructure recently emerged for stormwater management in Indonesian cities. Such management practices require strategic planning for communities to enjoy their multiple benefits. For the first time, this paper systematically explores current planning practices, the role of tools and models and the applicability of a specific strategic planning support tool (SSANTO) for the Indonesian urban context. It draws on the tacit knowledge and experiences from planning practitioners in Bogor and Surabaya.

Although practitioners acknowledged that urban planning developed a lot over the past decades, they point to a number of important shortcomings. While the organisation of urban planning promotes collaboration among governmental stakeholders, as well as between government and a broader set of actors, actual collaboration was perceived to be insufficient. In a system where the executive part of planning is primarily conducted by consultancy firms, practitioners recognised the inadequate capacity and resources in government. But perhaps the greatest barrier to strategic planning is the lack of high quality spatial data. While in many cases datasets simply do not exist, their accessibility is low when they do exist, as data sharing practices are largely non-existent.

As WSUD practices are introduced, strategic planning processes are needed to guide their implementation. PSS can play a crucial role to improve strategic planning of WSUD assets. Although some PSS are currently being used, they are limited to consultants and academia. Important considerations for PSS adoption are input data needs, their ability to respond to specific needs in the planning process and user-friendliness.

For the first time, a spatial MCDA method called SSANTO was tested in a developing context. Indonesian practice was shown to provide opportunities for the application of tools such as SSANTO. Practitioners indicated to already use similar methodologies, albeit manually, and perceive a tool to enhance their current practices. SSANTO scored high on most considerations that were deemed important in the uptake of PSS in Indonesia, including SSANTO to be user-friendly and fit-for-purpose. The tool was valued for its innovation, and the visual map-based outputs were deemed to provide strategic guidance in decision-making. In line with general shortcomings of urban planning in Indonesia, the greatest hurdle towards uptake of SSANTO is the availability of data.

The willingness of practitioners to adopt novel and innovative approaches to urban planning in Indonesia warrants a potential for the uptake of tools such as SSANTO. Such a trend could enhance strategic planning, but also critically empower capacity- and resource-limited local governments in urban centres. To achieve the strategic planning needed to guide the ambition to leapfrog towards more sustainable water management practices, attention and investment should be geared towards the collection and sharing of high-quality spatial data. Without such efforts, progress in urban planning and sustainable urban water management is unlikely to occur.

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6.3 AUSTRALIAN VS INDONESIAN CONTEXT

6.3.1 Planning process and context

Urban planning is organised differently in every country, and even within countries there can be different laws, regulations and practices. At a high level, Australia and Indonesia have a similar structure of governance and planning, being democracies with a hierarchically organised government, including national, provincial/state and municipal levels. National laws set the boundaries for urban planning and development, while the executive responsibilities lay mostly with lower tiers of government. One of the most important instruments used to guide urban development in both countries is zoning (see also: 6.2. subsection 3), although Australia has a longer history with this practice (Gurran, 2011). Both countries have specific regulations to promote green space, reduce impervious areas and manage peak runoff quantity and quality.

Important contrast in the planning process is the fact that Indonesian government is not involved in the execution of urban planning, as a result of national regulation against this. Therefore, all urban plans are effectively developed and drafted by the private sector, commissioned by BAPPEDA and approved by the senate (for master plans). Although in Australia, many parts of urban planning are often outsourced to private consultancies, the strict separation we see between commissioning and approval (government) and execution (private sector) of planning tasks is absent. As a result, governmental departments and agencies in Indonesia have much lower capacity than their Australian counterparts.

Apart from the formal organisation of planning, preliminary findings of this study suggest that there are some differences in planning culture between Australia and Indonesia. Indonesia has a much shorter history of formalised urban planning (section 6.2) and experience is therefore lower than in Australia. This could be one cause of the observed discomfort of Indonesian planning practitioners with the manual weighting step that is part of SSANTO, a discomfort that was not observed among their Australian counterparts. Another cause may be the higher apparent importance of hierarchy in Indonesian organisations, illustrated by the delegates sent to focus group discussions and interviews held for this and other studies that were part of the overarching water cluster project of the Australia-Indonesia Centre. In the majority of cases, these delegates were the leaders of departments, rather than the (lower ranked) experts on the topic at hand. This hierarchical culture is confirmed in a limited body of academic literature (e.g. Claramita et al., 2013).

Probably the most important difference, however, is found in the planning context between the two countries. Both the urban fabric and the socio-economic composition of cities differ greatly. Residential areas tend to be much denser in Indonesia compared to Australia, and official and unofficial use of open spaces much higher. Green strips, sidewalks and parks are intensively used by small business (mainly food trucks) as well as residents to rest and socialise in. This intensive use of space has significant consequences for WSUD planning, as entry to green infrastructure such as rain gardens can result in damage and failure of these systems. Furthermore, differences in wealth between the countries impact on the reality of planning outcomes. Very low-income informal settlements as well as high-income illegal settlements are common features of the Indonesian context, and virtually non-existent in Australia. Therefore, the physical outcome of urban development follows urban plans to a lesser degree in the Indonesian context. Finally, the difference in quality and quantity of the available spatial data differs greatly. While the Australian government provides a wealth of data free of charge via online platforms, the scarce data available in Indonesia is often difficult to access.

6.3.2 PSS use and requirements

In both countries, consultancies and academia are familiar with using spatial PSS. Also, other types of tools are being used, although the diversity seems slightly higher in Australia. The greatest difference however, is the use of PSS by the government sector. As a result of the stringent rules around the execution of planning in Indonesia, the use of tools and models in government is practically non-existent. While government requires plans to contain AutoCAD designs and GIS maps, they only deal with the hard-copy outputs. In Australia, consultancy and academia generally are the most common users as well. However, local and state government usually have in-house GIS capacity and often use hydrological and economic tools. The difference in data availability between the countries may be another important cause of the discrepancy in PSS application.

There are strong similarities in characteristics that are considered important in the decision to use tools and models. User-friendliness, data requirements and output types are among the most important considerations in both countries. Whether or not a tool is industry convention was an important consideration in Australia, but had little significance for Indonesian practitioners.

Indonesian government respondents placed more emphasis on novelty and innovation than their Australian counterparts, who appeared more conservative in this regard. This technological positivism could also explain the discomfort of workshop participants in Indonesia with user-defined weighting. Their view seemed to be more deterministically focused, relying on a model to take a decision for them, rather than using a model to help them take the decision. Cost seemed to play a much bigger role in Indonesia, with the reported likelihood for using SSANTO decreasing significantly with increasing user fees.

6.3.3 Transferability of SSANTO in Indonesia

Different approaches to introducing SSANTO are called for as a result of the differences in planning and PSS use between Indonesia and Australia. For example, an ArcMap plugin is apt for the Indonesian context, where Esri software is universally used. In Australia, an online platform or standalone software is preferred, as GIS software use varies greatly between stakeholders. Open-source software is more likely to gain ground in Indonesia, while Australian actors happily pay for proprietary software that suits their needs.

No fundamental barriers to the uptake of SSANTO were identified in the Australian case. Contrarily, an important barrier currently complicates the wider uptake of SSANTO in Indonesia: availability of sufficient spatial data. Despite the flexibility of the suitability framework to substitute missing indicators, the current lack of data and data sharing prevents meaningful application of SSANTO. This issue extends beyond the application of SSANTO and affects the quality of urban planning in general. Indeed, this has been recognised to be one of the main barriers to planning in Indonesia and other developing countries alike (e.g. Kirono et al., 2014; Larson and Larson, 2007). Furthermore, one of the objectives of SSANTO is to empower government actors in particular, to make planning more strategic. Therefore, the current Indonesian regulation against execution of planning being done by government party's forms another important barrier to a wider uptake of SSANTO.

Once these barriers are overcome, the potential for adoption of SSANTO is expected to be high, provided it remains open source. Enthusiasm from stakeholders observed during workshop sessions, a willingness from government staff to develop their skills combined with a need to improve strategic planning, create a high receptivity for SSANTO. A clear user-manual which explains the rationale behind user-defined weighting is instrumental and will be required. Furthermore, alternatives to manual weight assignment, such as pre-programmed expert weighting and entropy weighting, may further help the uptake in Indonesia. Furthermore, an online version of SSANTO would take away any issues with limited available computational power (even when the tool is currently relatively light) and help circumvent data sharing issues.

6.4 Final remarks

This chapter tested hypothesis H5: Planning support in the form of a GIS-MCDA is needed to improve the relatively young planning processes in Indonesia, but will be challenged by the difficulty to acquire quality input data. The organisation of present-day urban planning in Indonesia finds its origin in the 1970s. Incorporation of WSUD principles in urban planning is a very recent phenomenon in Bogor. It was found that GIS-MCDA has great perceived potential to aid planning in Bogor, similar to our findings for Melbourne. The greatest challenge for the uptake of SSANTO is the lack of available high-quality input data, in line with the hypothesis. Further research is needed to test the application of SSANTO in a data-scarce environment to see if meaningful outputs can be generated to support the planning and implementation of WSUD.

The next and final chapter will revisit the main findings from this PhD and suggests several future research avenues.

6.5 References

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CHAPTER 7
CONCLUSION

Het staat als een paal boven water

"It stands, like a pole above water"

--It is beyond all doubt--

7.1 INTRODUCTION

In this final chapter of the thesis, a synthesis of all the work is presented. The chapter starts with a review of all research outcomes that resulted from the testing of our hypotheses. Then, the strengths and weaknesses of the evidence are discussed. The implications of this work for planning practice and PSS development are reviewed, and an outline of proposed further work is presented at the end.

7.2 RESEARCH OUTCOMES

Preparation, development and testing of SSANTO, a PSS for WSUD planning, was described throughout this thesis. Testing of the hypotheses following the research questions as outlined in Chapter 2 resulted in a number of key outcomes. These outcomes all contribute to two overarching themes: (1) WSUD planning & support and (2) modelling WSUD suitability. The first theme relates to current processes of planning and the state of adoption of WSUD planning support, while the second theme relates to the development and assessment of SSANTO.

7.2.1 WSUD planning & support

PSS for urban water management are plentiful and diverse and WSUD planning can greatly benefit from their application. A critical review of tools and models resulted in a typology that organises existing PSS into three categories that vary in functionality from high level vision, strategy and conceptualisation to lower level planning, design and implementation. From high to low level, these tools include those that approach (1) WSUD as part of water governance, (2) WSUD as part of the urban form and (3) WSUD as part of the urban water cycle.

Despite the existence of the PSS described above, the outcomes of WSUD planner in Melbourne can be described as ad-hoc and opportunistic. Two types of analysis were done during model preparation to confirm this finding: a spatial analysis of current distribution of WSUD systems in Melbourne and qualitative analysis of current planning processes.

The spatial analysis uncovered that:

- WSUD placement was correlated with biophysical factors;
- High occurrence of WSUD away from the city centre resulted in an overrepresentation of WSUD in communities of low socio-economic status, low environmental awareness and low sense of community;
- While strong correlations existed between WSUD locations and socio-economic factors, these seemed to be an unintended result of the high occurrence away from the city centre;
- Size of the WSUD system increases with the distance to city centre, where space is less constraining;
- WSUD is strongly overrepresented in streetscapes, where systems can be implemented opportunistically during road renewal works.

The ad-hoc and opportunistic planning apparent from the distribution of WSUD in Melbourne was confirmed by qualitative research, which further showed that:

- More internal and external collaboration is needed from relevant organisations;
- Planners face a difficulty to build a business case for WSUD;
- Clear legislation and water strategies are needed;
- PSS are recognised to support with some of the aforementioned issues, and their uptake is moderate;
- Most ingredients for an 'implementation gap' are present in WSUD planning;
- A number of issues need to be considered when developing new PSS including Relevance to current processes and practices of planning; user-friendliness of PSS and time required for training; simplicity, only adding complexity where strictly needed; and delivering ongoing support, enabling PSS to become industry convention.

Such issues can only be addressed through meaningful engagement between developers and urban planning practitioners throughout PSS development.

7.2.2 Modelling WSUD suitability

The key outcomes described in section 7.2.1 critically informed the development of SSANTO. At the centre of SSANTO's functionality lies a WSUD suitability framework developed as part of the current study. This framework defines suitability from two angles: *WSUD needs a place* (opportunities) and *A place needs WSUD* (needs). The holistic framework integrates biophysical, socio-economic and governance factors with ecosystem services to provide a comprehensive definition of spatial suitability. This definition implies that urban planners, faced with the task of implementing WSUD in their city, can approach the task from either or both two defined angles. It is up to everyone involved in the planning process to reach consensus on which angle(s) to choose and how to weigh different aspects of the urban context. In doing so, they consciously move away from ad-hoc practices as they start considering a broad set of relevant spatial data. The suitability framework is operationalised through measurable indicators for each criterion, specifically linked to the different types of WSUD infrastructure.

Application of this framework was achieved through the development of SSANTO, a Python-based GIS-MCDA tool in the Esri environment of ArcMap. We were able to rapidly replicate the outcomes of a manual GIS-MCDA exercise conducted by an engineering consultancy, using SSANTO's algorithms. Furthermore, application of SSANTO for a case-study in Melbourne demonstrated its capability to reflect outcomes of a manual prioritisation of sites for WSUD implementation. The generated results fitted the manual planning outcomes best for a scenario using a full set of criteria and entropy weighting.

Qualitative testing of SSANTO in Bogor, Indonesia, suggested great potential for its application in this developing context. Receptiveness among local stakeholders was high, particularly among government stakeholders. SSANTO's combination of simplicity and rigour was recognised for its aptitude to assist in assisting in an environment lacking of governmental planning actors which lack capacity and currently fully rely on private consultants for the execution of planning tasks. Major barrier to the uptake of SSANTO or any other PSS in Indonesia is the low availability of spatial data. Gathering high quality data should be the prime focus in this context to help urban planning become more strategic in the future.

7.3 STRENGTHS AND WEAKNESSES OF THE EVIDENCE

The process of developing SSANTO encompassed four distinct stages: (1) definition of suitability, (2) model preparation, (3) model building and (4) model testing. Strengths and weaknesses of the evidence are described for each of these development stages.

An important strength of the overall research project is that the work was able to harness the interdisciplinary nature of the problem. SSANTO was developed using different academic approaches and guided by insights from across these disciplines including civil engineering, urban planning/architecture and social sciences. Such an interdisciplinary approach is critical, considering the inherently complex and multi-dimensional nature of WSUD planning and implementation.

7.3.1 Definition of suitability

Unlike many existing PSS, which have focussed on one aspect of suitability only (e.g. biophysical suitability), SSANTO adopts a holistic lens towards suitability as outlined in section 7.2.2. Thus, it enables urban planners to make conscious decisions about the trade-offs between aspects inherent to spatial planning. Although significant effort was invested to make this framework relevant for developing as well as developed urban contexts around the world, details of the framework may change depending on geographic location.

As WSUD systems vary in terms of shape, size, function and operation, planning considerations are different for each WSUD type. One of the strengths of the suitability framework is that it is specifically aligned to a broad selection of WSUD types. While SSANTO implements the most important WSUD types, not all WSUD types from the suitability framework were included in SSANTO. However, SSANTO's flexible architecture allows for easy integration of any new types of green infrastructure, decentralised wastewater management and even beyond urban water management.

7.3.2 Model preparation

We were fortunate to have access to a unique spatial database containing WSUD systems throughout metropolitan Melbourne from the Melbourne Water authority (Chapter 3). Although quite extensive, there were considerable data missing from this database, including existing systems, system sizes and exact locations. Significant effort was invested into infilling these data gaps by cross-checking with councils, data cleaning and field analysis. Despite these efforts, we weren't able to rectify all data issues. For example, we managed to reduce missing data on system sizes from 50% to below 10%. Remaining missing systems sizes had to be estimated using the information on comparable systems in comparable urban context. Furthermore, the spatial analysis is limited to one side of suitability: *WSUD needs a place*. However, some interesting results could be achieved by correlating WSUD locations with factors from *A place needs WSUD*.

For the spatial analysis, suitable spatial correlation methods were limited. Therefore, other statistical analysis methods needed to be used. However, the validity of these methods for application to spatial analysis is unknown. For robustness, mix of three statistical methods were applied. All three methods yielded similar results, which speaks to the validity of the outcomes. Despite this, drawing causal relationships from such analyses is problematic. Therefore, planning process and considerations that drive WSUD placement were also investigated using qualitative methods (Chapter 4).

This study has benefited from continuous and structured interaction with WSUD planning practice throughout the development of SSANTO, both in Australia (Chapter 4) as well as Indonesia (Chapter 6), using qualitative research methods. This responds to the hypothesis in literature that the key cause for the implementation gap is inadequate interaction between PSS developers and planning practitioners (e.g. te Brömmelstroet, 2013).

This study is one of the few studies that empirically tests the hypothesised causes for the implementation gap (Chapter 4). Although conclusions can be drawn from the qualitative work regarding the potential existence of the implementation gap, this study has focussed only on planning practice in Melbourne. To generalise these findings, data gathering needs to be undertaken in other urban contexts around the world. Unfortunately, such data gathering fell outside the scope of this PhD.

7.3.3 Model building

The initiation of SSANTO's development resulted from a deep understanding of the current PSS landscape for WSUD planning and the main gaps, provided by the critical review and typology of WSUD-PSS (Chapter 2). This knowledge was complemented by structured engagement with planning practice (Chapter 4), which confirmed SSANTO's relevance to practice.

Models, by definition, are an abstract representation of reality. Therefore, model building is inevitably associated with making simplifications and assumptions. The most important simplifications and assumptions are related to model structure, data inputs and value scaling and are discussed in this section.

Choices related to model structure include data structure, weight elicitation, aggregation methods and value scaling (separately discussed). All these choices impact on the final model outputs. SSANTO was designed using simple and transparent GIS-MCDA techniques, but allows for future addition of other techniques, if deemed to add to SSANTO's structural validity.

The key strength of SSANTO is in its ability to rapidly generate spatial suitability outputs using a broad set of criteria. Its conceptual simplicity makes the techniques understandable for lay-people, thus building trust in its outputs. The speed enables iterative modelling and scenario analysis, providing deep insights into spatial contexts and the impact of varying preferences. The extensive base of criteria adds to the rigour of the outputs. Weakness of such approach, however, is the high data requirements. Data gathering is a very lengthy process and is further complicated by the diverse nature of the data coming from scattered sources. To facilitate a straightforward process for the user, SSANTO was set-up for Melbourne with datasets pre-installed. Although comprehensive and diverse data were acquired to run SSANTO, certain datasets are still missing. For example, metropolitan-wide flood (risk) data is not currently part of SSANTO. For testing purposes, case-specific flood maps were therefore used.

Perhaps the most crucial step in the generation of suitability maps is value scaling. Each system type and criterion have a unique value scale, as suitability is highly context specific. Value scales were preferably determined using evidence-based information from academic and grey literature. Furthermore, two workshops were organised to elicit knowledge from experts, the outcomes of which are subsequently used for value scaling. However, for a limited number of cases, information was neither available in the literature, nor from experts. In such cases, value scales had to be estimated using the best available knowledge. Furthermore, there is currently no option for user-defined value scales in SSANTO, which would allow decision-makers to include their preferences into the value scales.

Suitability values, as a human construct, don't inherently bear an absolute meaning. Rather, they are used to compare sites to each other. Comparing suitability values for different criteria can therefore be somewhat problematic. For example, the interpretation of a suitability value of 100 (maximum) for 'slope' indicates slope is not limiting WSUD implementation in any way. A suitability value of 100 for 'irrigation demand' indicates high vicinity to locations where irrigation water is used, such as sport fields. These different interpretations of data values are hard to compare on an absolute level. Especially with a large variety and quantity of criteria, as used by SSANTO, the meaning of the absolute value of suitability becomes somewhat diluted. However, relative importance of criteria, or how suitability 100 for 'slope' compares to 100 for 'irrigation demand', is determined by the user, providing them with control over the final impact of a criterion on suitability outcomes. Furthermore, the impact of each individual criterion on the final suitability can be reviewed for any given location using the 'explain' tool.

Important tool design aspects that are a direct result of the engagement with practitioners include its spatially explicit outputs, simplicity of the process and speed. However, not all recommendations could be implemented in SSANTO. For example, the preference for stand-alone or open-source software among WSUD practitioners in Melbourne was welcomed, but not considered due to the time constraints of this PhD. SSANTO was developed within the Esri environment of ArcMap, which is the most widely used GIS software worldwide, and particularly in Indonesia. ArcMap was considered an efficient platform as it has all necessary libraries for spatial data processing, presentation and organisation. In line with the broader research context of this PhD, the candidate wanted to ensure transferability to developing contexts. Although SSANTO is easily adaptable, the migration of SSANTO into open-source spatial software such as QGIS, or development of a stand-alone or online software package were outside the scope of this PhD.

7.3.4 Model testing

Direct model validation is problematic for SSANTO, as it deals with the abstract phenomenon 'suitability', which is not objectively measurable in the field. Results of SSANTO thus cannot be compared to 'real' suitability. Therefore, validity testing was conducted by comparing to current practice used for spatial prioritisation for WSUD which is based on expert opinion (i.e. consultants are usually employed for decision-making without comprehensive modelling). Such studies are occasionally undertaken in Melbourne, usually commissioned by municipalities trying to improve strategic implementation of WSUD systems.

As discussed in section 7.3.3, most value scales were evidence based. For value scales without an evidence base in literature or expert knowledge, simple sensitivity analysis was conducted to check that changing value scales didn't impact the tool's outputs excessively. Deeper sensitivity analysis of the impact of varying value scales as well as weight assignment and combination techniques were not part of the scope of this PhD. However, the impact of including different sets of criteria, different weighting regimes and different system types was conducted as part of tool testing, and provided some insightful clues about sensitivity to inputs, methods and validity of outputs.

One of the weakest points of the study is the fact that SSANTO was tested for the developed context of Melbourne. Although the original intention was for application in the developing context of Bogor or Surabaya as well, this was severely hampered by the lack of available, or accessible data. Especially for Bogor this proved to be a challenge, as several months of attempts by local partners did not result in the acquisition of a single dataset. Therefore, instead of testing the tool directly, the applicability of SSANTO was evaluated using tool demonstration workshops with planning practitioners in Bogor. These workshops have provided the best possible insights into the usefulness of, and barriers to SSANTO's application in a developing context.

7.4 RESEARCH IMPLICATIONS TO PRACTICE

This section discusses how the above findings could be used to advance the organisation and substance of WSUD planning. It also includes a practical example of the application of the research outcomes for the Melbourne Water authority (this project was conducted by the global engineering consultancy firm Jacobs, with the candidate's substantial involvement).

7.4.1 Organisation of planning

WSUD distribution was found to be very uneven and inequitable across metropolitan Melbourne. Depending on the decision-maker's goals, better harmonisation can be accomplished through better coordination and collaboration between stakeholders and organisations from all involved geographies and jurisdictions. The use of PSS could assist collaborative efforts

A good example of this coordination and collaboration are the 'Integrated Water Forums' that were recently initiated by the Department of Environment, Land, Water and Planning in Melbourne (DELWP, 2016). These forums bring together all actors from an entire urban catchment on a regular basis to build better and more integrated urban water strategies together. PSS can play a crucial role on such platforms by visualising ideas, communicating preferences and exploring scenarios. Furthermore, such platforms can be a vehicle for the engagement of PSS developers with practice to stimulate the creation of PSS that better connect to the needs of urban planners.

SSANTO is particularly well-positioned for use in collaborative settings. By rapidly producing interactive and visual map-based outputs that depend on user preferences and insights, it facilitates group learning (Chapter 4). Iterative model runs by diverse stakeholders can uncover diverging insights and priorities and build deeper understanding of opportunities and needs. SSANTO's ability to translate stakeholders' priorities into concrete spatial outcomes enables meaningful interaction that lead to concrete planning outcomes. Furthermore, SSANTO can enhance the capacity of local government to conduct strategic planning, especially in developing contexts such as Indonesia.

7.4.2 Substance of planning

The findings of this work can directly impact on WSUD planning to create better strategies on a local level. The suitability framework gives explicit guidance how to include a wider pallet of considerations to decision-making. Beyond simply urging the incorporation of a wider array of criteria, the framework also guides planners with *how* to do this, by providing measurable indicators specific to the WSUD type under consideration. For data-poor situations, often encountered in developing countries such as Indonesia, this framework can serve as a starting point for data collection and the construction of a geo-database.

Keeping a complete and up-to-date asset inventory is important for asset management, which was currently found to be a shortcoming. The inequitable distribution of WSUD in Melbourne can be reversed by using the outcomes of the spatial analysis that was part of the current study. More emphasis could be placed on those communities with high environmental awareness and high sense of community, inner-city communities that have so far been largely overlooked when it comes to WSUD implementation.

Although SSANTO is not an economic tool, it can provide better insight into the diverse benefits of WSUD in a visual format that is easy to understand (needs map). In doing so, we it provides at least part of the justification for investment in WSUD.

7.4.3 Real-world application of the research outcomes

The WSUD suitability framework that underpins SSANTO was applied in the 'Feasibility of Stormwater Management Actions' (FOSMA) project, undertaken with engineering consultant Jacobs for Melbourne Water. The aim of the project, proposed in May 2017, was to *"develop a decision / planning support system to assess the technical feasibility and cost-effectiveness of various approaches to stormwater control in order to optimise investment in enhancing waterway health in Port Phillip Bay and Western Port as well as the social values that the waterways provide."* (Jacobs, 2017). As the timeline for the project delivery was very tight, Jacobs decided to collaborate with the candidate to use the WSUD suitability framework as the basis for this work.

The suitability framework was adapted to the specific needs of the client, following discussion sessions during of workshops organised with key stakeholders in Melbourne. The resulting 'feasibility assessment framework' and its associated database toolkit were the primary output of the work undertaken by the candidate and Jacobs. The toolkit has three components and is closely connected to another PSS used by Melbourne Water called the 'Area of Interest' tool (Figure 7-1).

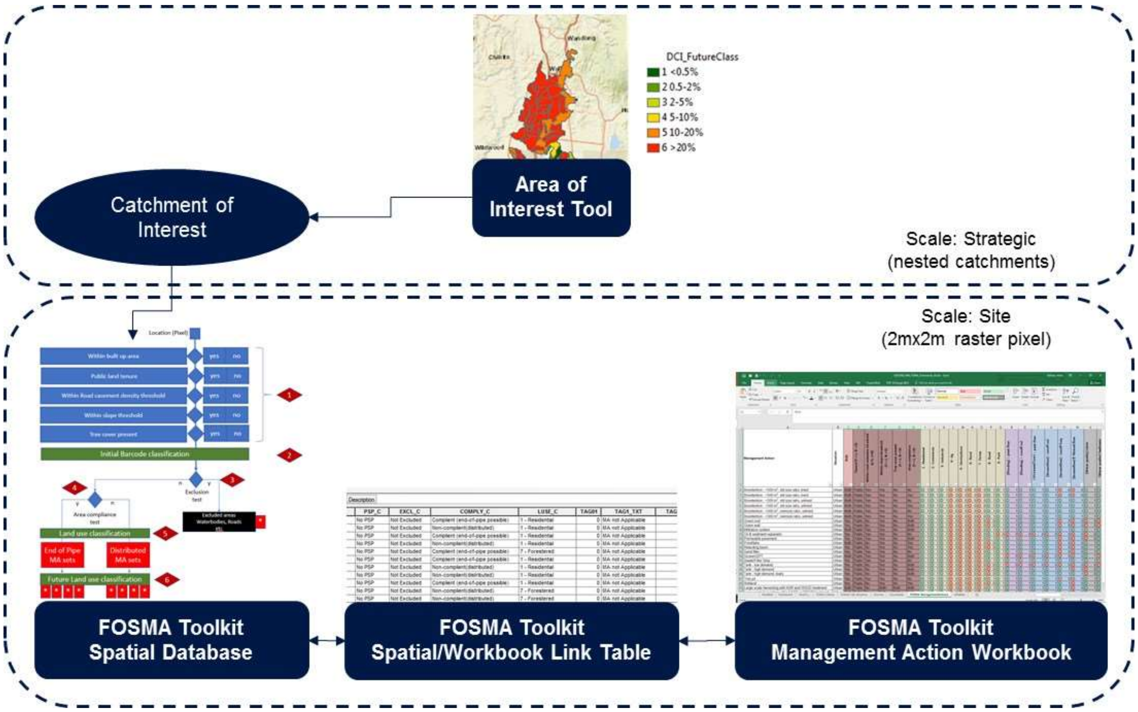
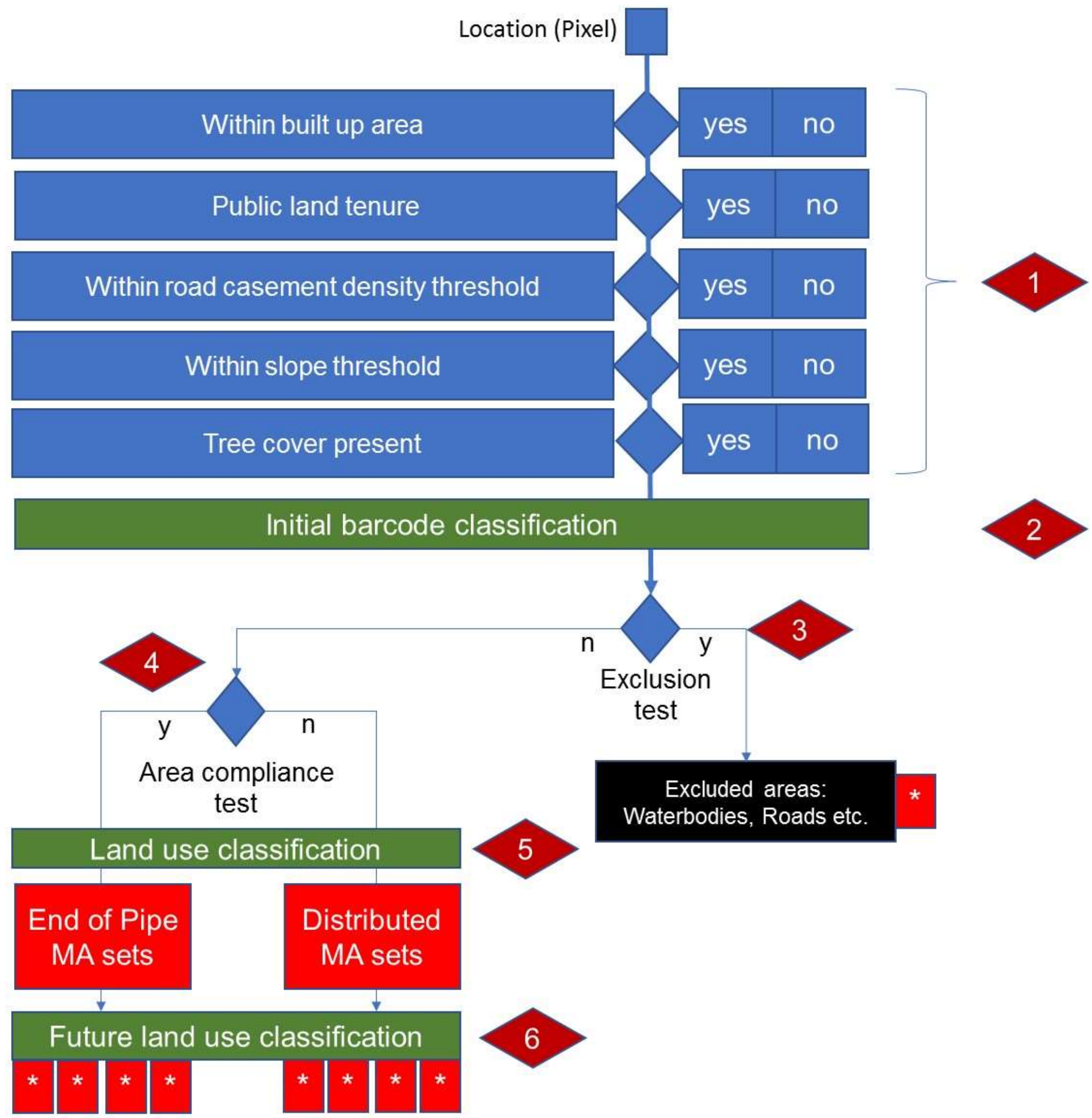


Figure 7-1 Components of the FOSMA toolkit. Note that this schematic also illustrates how the FOSMA toolkit can be used in conjunction with the Areas of Interest tool. *Source: Jacobs (2018)*

Most important part of the toolkit is the decision tree, which allows the user to choose a suitable management action for a given locale. The decision tree was based on the *WSUD needs a place* side of the WSUD suitability framework and is illustrated in Figure 7-2. Detailed information about the datasets included, management action considered, and recommendations made can be found in the FOSMA final report (Jacobs, 2018). This work was finalised in May 2018.

The project benefited from the holistic nature of the suitability framework, by including a wide array of criteria for the decision tool. Even though these criteria are linked to a spatial database, Jacob's tool lacks spatial explicitness and spatial modelling capabilities. Furthermore, it does not provide a user-friendly, logical interface, which was found to be so important for user uptake (Chapter 4).



1 Area of Interest barcoding process produces a unique combination of y/n combinations for the 5 key binary criteria – this process splits up the area of interest into a initial classification of management regimes

2 Barcode assign to each location (pixel) ready for next phase in the decision process. Barcodes are of the form *11110 = built up + public land + meets road casement threshold + meets slope threshold + no tree canopy*

3 This decision point removes excluded areas from the analysis process (converts to "null") prior to area compliance decision point. Excluded areas are waterbodies and roads – that is, areas where no action can occur.
Assign to barcode classification from step 2

4 Using a defined area threshold (area required for feasible management options), determine the ratio of available area to threshold area (percentage compliance) and set a compliance threshold for binary classification (i.e. meets or fails area threshold / requirement) – add compliance status to barcoded classification from step 3

5 Assign current land-use classification to barcode classification from step 4

6 Assign future land-use classification (areas to be developed) to barcode classification from step 5

* This decision logic produces a combination of unique site characteristics that is used to identify a suite of possible management actions, each of which is scored in terms of their relative effectiveness at achieving desired stormwater management outcomes (quality and quantity control) as well as their relative cost

Figure 7-2 Decision tree for identifying runoff management options at a site / sub-catchment. *Source: Jacobs (2018)*

7.5 FURTHER WORK

SSANTO is part of an ongoing development process of refinement, extension and testing. Furthermore, insights into the processes and results of WSUD planning around the world are critical to improve strategic planning. Three avenues for future work are thus suggested: (1) WSUD planning practice, (2) Model improvement and (3) Model testing and application.

7.5.1 WSUD planning practice

The absence of strategic WSUD planning and the existence of an implementation gap are likely to occur in cities around the world, however, there is currently no empirical research to confirm this. Future research should focus on spatial- as well as qualitative analysis of WSUD planning in urban contexts of Europe, Asia and North America where WSUD planning has an established history like in Australia, such as Portland in the United States (Netusil et al., 2014). Furthermore, inclusion of additional correlation factors in the spatial analysis, especially from the *A place needs WSUD* perspective could create interesting insights.

In addition to such extended spatial analysis, the results of SSANTO could be compared to current locations of WSUD. This would give us a more detailed insight in the performance of opportunistic planning practices in terms of strategic outcomes. Combining such desktop analysis with site visits to assess WSUD performance as well as social and contextual integration would add further rigour to this work.

7.5.2

The strengths and weaknesses discussed in section 7.3.3 give rise to a number of model improvements for future work. Firstly, despite the greatest efforts to collect all relevant data, there are still gaps in SSANTO's database for Melbourne. Especially knowledge and data on suitability from an ecological perspective (category 'habitat'), are needed. Authors who specialise in landscape ecology and urban design, such as Ahern (2013) and Forman (1995), have emphasised the importance of urban ecological networks, connectivity, redundancy and other design principles that can promote ecological diversity. SSANTO, as a raster-based MCDA analysis tool, is ill-equipped to support network analysis necessary for ecological design. Although spatial MCDA analysis can help to locate suitable locations for ecological development, the spatial cohesion is overlooked. Therefore, SSANTO's result should be linked to ecological models, or interpreted by experts in urban ecology to add such level of consideration.

Leaving the core architecture intact, SSANTO's general spatial analysis can be adapted to support any other spatial planning tasks. Urban examples include transport planning, site selection for infrastructure ranging from urban parks to schools. Rural examples include nature and ecological management, agricultural planning and site selection for infrastructures such as solar- and wind parks for electricity generation. The potential applications are endless, and only requires the implementation of tailored suitability frameworks and value scales.

The functionality of SSANTO can be expanded to include an 'optimisation mode', which identifies the 'top locations' for the implementation of a specific WSUD system for a given preference set. The identification of such locations should not only depend on the highest ranking in terms of suitability score, but also consider amount of highly suitable uninterrupted space in relation to average size of the system type under assessment. Such an optimisation mode could further highlight the most significant contrasts between preferences.

SSANTO's GIS-MCDA techniques could be further expanded and refined in the future by adding non-additive and non-compensatory techniques such as ideal point methods (Zeleny, 1982) and outranking methods like ELECTRE (Brans and Vincke, 1985) and PROMETHEE (Benayoun et al., 1966). Providing users with the option to choose between different approaches enables them to better reflect their preferences as well as to get a deeper understanding of the drivers behind suitability. Also, weight elicitation techniques can be expanded. Preference stability, consistency and reliability of methods has been shown to vary greatly depending on circumstances (Lienert et al., 2016). Alternatives to the currently implemented ranking method may be preferred, such as SWING (e.g. Scholten et al., 2015). Finally, user defined value scales can be included to tailor SSANTO further to the preferences and judgement of the decision-maker.

SSANTO can be coupled to complementary PSS that assist with other aspects or stages of the planning process (e.g. water quality and hydrology), such as the highly used MUSIC (eWater, 2011) and SWMM (Rossman, 2010). Knowledge concerning the design of treatment trains and catchment-wide WSUD layout strategies could be generated by coupling SSANTO to planning simulators such as UrbanBEATS (Bach, 2014). UrbanBEATS currently assumes suitable sites simply as areas classified as open space and considers stakeholder preferences towards the use of specific WSUD technologies only. Outputs generated by SSANTO could significantly improve the representation of suitability in this model and better reflecting user preferences at the same time.

A last model improvement suggestion would be migration to open-source GIS software or even development as a stand-alone tool would make SSANTO more widely accessible to people from different disciplinary backgrounds as well as enabling its use without ArcMap's licensed software. Another possibility is the development of an online platform, that can be a vehicle for coupling and integration of SSANTO with other tools as discussed earlier in this section.

7.5.3 Model testing and application

SSANTO could benefit from an in-depth sensitivity analysis to test the impact of changing value scales, weight assignment and combination rules. Notable example for weight assignment is the case of entropy weighting and its impact on absolute suitability values. Entropy weighting reduces the impact of homogeneous datasets on the final output, which increases variation of suitability outcomes and thus increases the distinction between alternatives. Despite its capacity to increase the ability to make distinctions between locations, entropy weighting decreases the accuracy of absolute suitability. The extent and implications of this reduction in information could be tested using sensitivity analysis. Furthermore, sensitivity of cross-correlations between input criteria should be investigated, to optimise the selection of complementary criteria and avoid inclusion of criteria that do not add enough extra information.

The validity of SSANTO can further be tested by repeating the comparison of its output to manual suitability analyses conducted for different case studies around the world, as this has currently only been conducted in Melbourne. Of particular interest would be testing tool application for contexts with limited data availability, such as developing contexts.

Finally, the role and usefulness of SSANTO in WSUD planning could be tested using qualitative research methods. On a high level, SSANTO should be tested against the 'seven sins of large scale models' as identified by Lee Jr (1973) and referred to in Chapter 1.1.3, including its performance in terms of data availability, output relevance, transparency, flexibility and complexity. Application and reporting by practitioners in a real-life case study and testing of SSANTO in a workshop setting with diverse stakeholders from government, consultancies, utilities and water authorities will provide valuable information on tool usability and relevance. This type of qualitative study should be repeated for case studies in both developed and developing world contexts, to ensure SSANTO's wider applicability.

7.6 FINAL REMARKS

WSUD has great potential to increase resilience, preserve environmental quality and improve liveability of our cities, which are under increasing pressure of continuing urban growth and climate change. However, its reciprocal relationship with the physical and non-physical urban context necessitates highly strategic placement of WSUD. PSS are well positioned to provide the required assistance with urban planning.

The present thesis examined current planning practices the role of PSS in Melbourne. It describes the development of a novel PSS for spatial suitability analysis called SSANTO. Insights that were gained on the limitations and needs of planning practices and PSS informed the design of SSANTO, which was applied for a Melbourne case-study and qualitatively tested in Bogor, Indonesia.

Current planning of WSUD was found to be ad-hoc and opportunistic, resulting in unintended and sub-optimal outcomes. Spatial suitability tools were found highly capable to respond to these challenges, provided that they were fast, user friendly and simple yet thorough. Such planning support was found to be unavailable to practitioners.

SSANTO responds to the need for rapid and automated spatial suitability analysis. The tool was successful at simulating suitability and regarded intuitive and easy to use. Provided data availability is sufficient, it has the ability to improve strategic planning and optimise water quality, flood protection and amenity benefits derived from WSUD.

Much work remains to be done both in academia and practice, to improve the implementation of WSUD worldwide. However, the present thesis provided important progress in the understanding of strategic planning as well as direct technical planning support through the development of SSANTO.

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APPENDICES

Het water loopt altijd naar de zee

"Water always flows towards the sea"

--The rich always get richer--

Appendix A

Introduction

This appendix contains a non-first authored peer reviewed journal paper about the interdisciplinary research context of this PhD.

Citation of the journal article presented in this chapter:

Barron, N., Kuller, M., Yasmin, T., Castonguay, A., Copa, V., Duncan-Horner, E., Gimelli, F., Jamali, B., Nielsen, J., Ng, K., 2017. Towards water sensitive cities in Asia: an interdisciplinary journey. Water Science and Technology, doi:wst2017287.

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Towards water sensitive cities in Asia: an interdisciplinary journey

N. J. Barron, M. Kuller, T. Yasmin, A. C. Castonguay, V. Copa, E. Duncan-Horner, F. M. Gimelli, B. Jamali, J. S. Nielsen, K. Ng, W. Novalia, P. F. Shen, R. J. Conn, R. R. Brown and A. Deletic

ABSTRACT

Rapid urbanisation, population growth and the effects of climate change drive the need for sustainable urban water management (SUWM) in Asian cities. The complexity of this challenge calls for the integration of knowledge from different disciplines and collaborative approaches. This paper identifies key issues and sets the stage for interdisciplinary research on SUWM in Asia. It reports on the initial stages of a SUWM research programme being undertaken at Monash University, Australia, and proposes a framework to guide the process of interdisciplinary research in urban water management. Three key themes are identified: (1) Technology and Innovation, (2) Urban Planning and Design, and (3) Governance and Society. Within these themes 12 research projects are being undertaken across Indonesia, China, India and Bangladesh. This outward-looking, interdisciplinary approach guides our research in an effort to transgress single-discipline solutions and contribute on-ground impact to SUWM practices in Asia.

Key words | developing cities, integrated water management, sustainable development, sustainable urban water management

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INTRODUCTION

Rapid urbanisation as a worldwide phenomenon is most prominent in Asia. With Asia accounting for 65% of global urban expansion since the start of the century, the 21st century is shaping up to be the 'Asian Urban Century' (UN-Habitat 2013). This transformation exerts tremendous pressure on urban water systems, which is further aggravated by the effects of global climate change. Many Asian cities are ill-equipped to respond to these pressures, as they face a host of social, institutional, technological and economic barriers to establishing 'sustainable urban water management' (SUWM) practices (UNW-DPAC 2010). Examples of such barriers include resistance to change, poverty and marginalisation, fragmented responsibilities, lack of institutional capacity and legislative mandate, insufficient engineering standards and guidelines, uncertainties in performance and cost of potential solutions, and lack of funding and effective market incentives (Roy *et al.* 2008; Goff & Crow 2014).

SUWM is advocated by an increasing number of scholars as an alternative paradigm to traditional water infrastructure and approaches, which can address the complex challenges facing urban water management (Pahl-Wostl *et al.* 2008; Brown *et al.* 2009; Crow-Miller *et al.* 2016). SUWM is an umbrella concept which encapsulates the concepts of 'integrated urban water management' and 'water sensitive urban design' (WSUD) (Mitchell 2006; Fletcher *et al.* 2015). A 'water sensitive city' (WSC) integrates normative SUWM values of environmental protection, equity, rehabilitation and sustainability with essential water services, including supply security, flood control, and public health, but also additional benefits such as food security, energy savings, amenity and resilience of cities to

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climate change (Wong & Brown 2009). Furthermore, it has acquired diverse, adaptive, multi-functional technologies and infrastructure, with urban design features that reinforce water sensitive behaviours and practices, underpinned by a flexible institutional regime (Brown *et al.* 2009).

Theoretically, a WSC state can be achieved, in part, through cumulative change in socio-political drivers and service delivery functions that fully operationalise the principles of SUWM (Brown *et al.* 2009). Figure 1 shows the urban water transitions framework which can be used to demonstrate the continuum 'states' a developed city may pass through towards a WSC state. An emerging line of inquiry in urban water transitions research is whether developing countries can 'leapfrog' this traditional pathway and directly execute SUWM (Binz *et al.* 2012).

Stemming from earlier work in transitions and systems innovation, Binz *et al.* (2012) define leapfrogging as 'a situation in which a newly industrialised country learns from the mistakes of developed countries and directly implements more sustainable systems of production and consumption, based on innovative and ecologically more efficient technology' (p.156). In short, leapfrogging theory proposes that developing countries may be able to leapfrog older versions of technology and avoid developed countries' path to industrialisation with its environmentally degrading legacy. By leapfrogging straight to a cleaner (sustainable) production, developing countries may also be able to avoid the socio-technical 'lock-in' that many industrialised economies are currently experiencing (Unruh & Carrillo-Hermosilla 2006; Maassen 2012). This difference in socio-technical contexts (between industrialised and developing) is an important element in the process of leapfrogging. The focus is not on how existing methods of production can be transferred from industrialised countries, but instead what solutions are available that meet the contextual conditions and allow the normative goals of sustainability to be achieved. Taken together, this presents an opportunity for developing cities to 'leapfrog' towards a WSC state.

The United Nations (UN) recently released 17 'sustainable development goals' (UN 2015), of which Goal 6 – Clean water and sanitation, Goal 9 – Industry, innovation and infrastructure, and Goal 11 – Sustainable cities and communities align closely with the concept of WSCs. Each of these goals relates future prosperity to the provision of clean water, sanitation, community engagement, smart infrastructure and technological innovation. While these goals are specifically related, SUWM relates to most of the other goals, such as ending poverty, ending hunger, equity and protection of ecosystems. Because of these complex interdependencies, uncertainty of future drivers and lack of consensus on solutions, the obstacles related to SUWM can be classified as 'wicked problems' (Rittel & Webber 1973). It is this 'wicked' nature of SUWM that calls for an interdisciplinary approach, as solutions from any one discipline are not fit to address this complexity (Brown *et al.* 2015; Larson *et al.* 2015).

In our research programme, researchers from different disciplines are working together to address complex

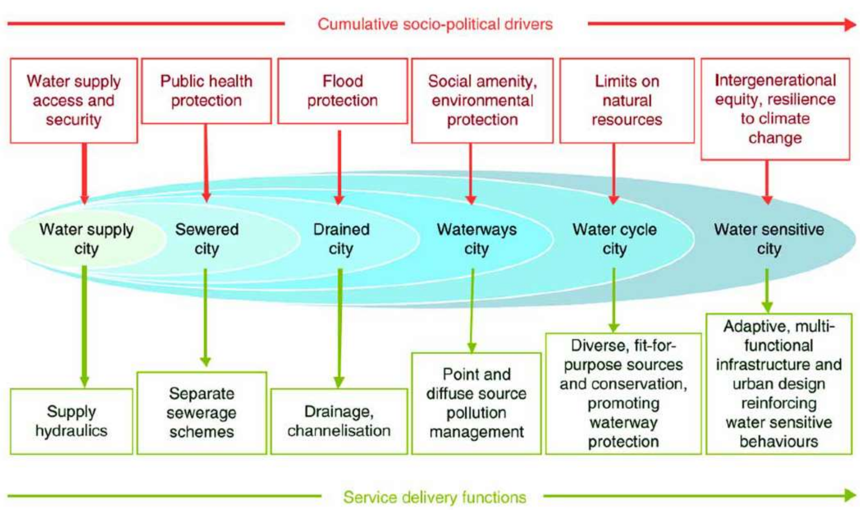

Figure 1 | Urban water transitions framework (Brown *et al.* 2009, p. 850).

SUWM challenges from both a biophysical and social perspective. Each researcher employs their own discipline-specific base (Rosenfield 1992), but also actively shares and synthesises their knowledge across the single disciplinary silos in order to develop a holistic understanding of SUWM in developing Asian cities. Although complexity poses a challenge, there is a range of opportunities to achieve research impact and facilitate real-world transformation in this space. First and foremost, our approach seeks to create impact through interdisciplinary research that defines emerging urban water problems and advances novel SUWM solutions in Asian cities – a context where such a research programme is, to date, yet to transpire.

While it is not at the core of our approach, the involvement of a variety of stakeholders beyond the academic actors (Massey *et al.* 2006), or the so-called transdisciplinary approach, serves as an important background to many of the research activities. We envisage that our research activities will create opportunities for bridging the interface between academic theory, policy-making and application. This paper is primarily focussed on the journey the researchers are undertaking as part of the interdisciplinary team. We will discuss the role of interdisciplinary researchers in bridging research, policy, and practice, where suitable (Brown *et al.* 2015).

MATERIAL AND METHODS

Traditionally urban water management solutions and innovations emerge from, and are sought after, within strictly separated disciplinary silos, most prominently social sciences and natural sciences/engineering. An interdisciplinary approach requires breaking down the barriers between these silos. Therefore, our research integrates the knowledge and expertise from both civil engineering and social science. Collaboration is the backbone to this approach. An integral but not core part of our research is engagement with industry, governments and non-governmental organisations (NGOs) in the process. Again, collaboration is the underpinning theme in our research programme, both between academics from different disciplines and between academia, decision-makers and implementing stakeholders.

Brown *et al.* (2015) identify five fundamental principles for interdisciplinary research in SUWM: (1) a shared mission, (2) 'T-shaped' researchers, (3) constructive dialogue, (4) institutional support and (5) bridging research, policy and practice. Following these principles, 12 researchers from five continents and diverse cultural backgrounds are working together at Monash University to tackle the complexity of SUWM in Asian cities. While six of these researchers are based in the Department of Civil Engineering and six from the School of Social Sciences, educational training and professional expertise included civil engineering, environmental engineering, environmental science, sustainability, international relations, international development, economics, geography, resource management, psychology, religious studies and landscape architecture.

RESULTS AND DISCUSSION

Research framework and outcomes

We developed a research framework that breaks down the disciplinary boundaries (see Figure 2). Three key themes or 'angles' are identified to cover a broad spectrum of the issues identified when implementing SUWM in a developing Asian context. The framework serves as a heuristic model, and boundaries between the angles are necessarily porous. As discussed below, these angles are: (1) Technology and Innovation, (2) Urban Planning and Design, and (3) Governance and Society.

The outcomes of this interdisciplinary programme span the spectrum of urban water management, from technological innovation (low level, focussing on local implementation) up to vision and strategy (high level, focussing on metropolitan strategies) (see Figure 2). These outcomes emerge on the interface of the three research angles. All outcomes are based on a fundamental knowledge and understanding of the urban water system in the broadest sense. In order for this knowledge and understanding to have the anticipated impact in the real world – a transition towards SUWM – it must be operationalised. This operationalisation is achieved through the development of a diverse set of 'tools', which should empower policy makers, urban planners, developers and civil society to drive the envisioned transition.

As shown in Figure 2, these tools are broadly categorised into four groups:

1. The development and testing of technological innovations in infrastructure design, to effectively capture, treat, control and monitor urban runoff, both stormwater and wastewater. These technologies are designed in the context of developing Asian cities, to generate multiple

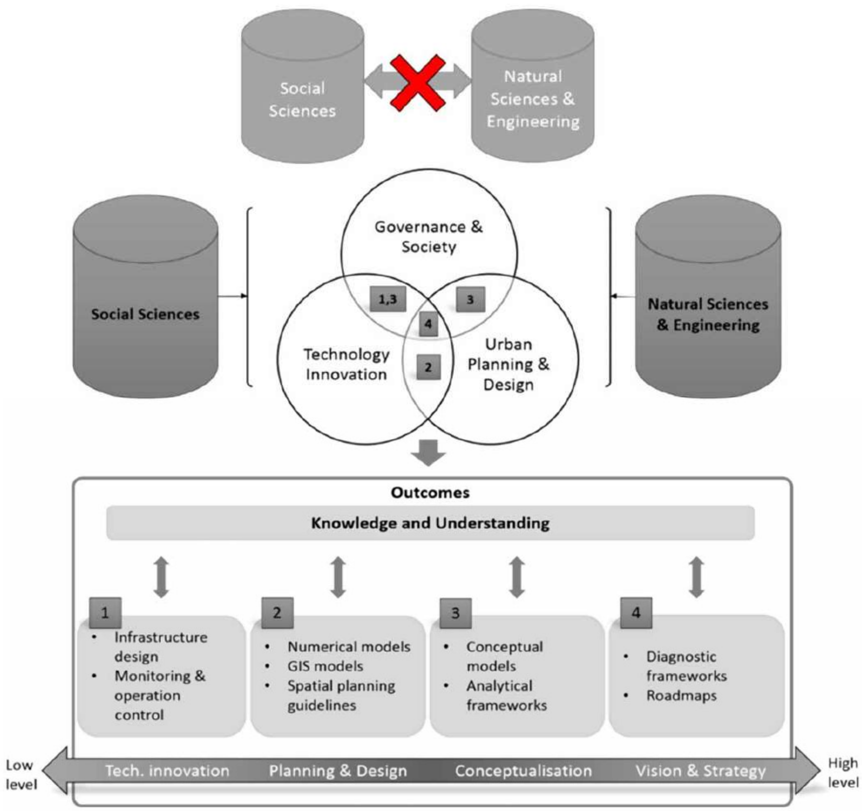

Figure 2 | Breaking the wall between disciplinary silos in urban water management: our interdisciplinary research model and its outcomes.

benefits, such as water treatment, fit-for-purpose water supply, flood mitigation, food production and the provision of green space in dense cities.

2. The development of computer tools and models which can simulate different scenarios of urbanisation, calculate impacts and optimise the localisation of SUWM measures. These tools support the implementation of distributed, local-scale technological innovations, in combination with centralised water infrastructure. This combination is important as careful urban planning and design is required to ensure sustained operation and maximisation of acquired benefits.
3. The development of conceptual models and analytical frameworks that describe systems of stakeholders and their roles, capacities and relations with respect to urban water and sanitation. These frameworks and models inform and enable good governance practices and support urban planning and design, which needs to be based on solid concepts of socio-technical urban water systems.
4. Overarching visions and strategies are required to inspire and enable change. We support these visions and strategies by developing diagnostic frameworks and roadmaps towards water sensitivity. Tools in this group promote adaptive governance and identify strategies for cities to leapfrog to more effective, sustainable and just urban water management.

Technology and Innovation

There are genuine opportunities for sustainable technologies to be adopted in developing Asian cities, as urban water infrastructure has yet to be formalised. While centralised systems for water supply and wastewater treatment, along with large underground drainage networks for stormwater management, are associated with a number of benefits (e.g. securing a clean water supply, improvements in health through the disposal of contaminated wastewater and mitigating flood impacts), they also come with a number of costs (Brown *et al.* 2009). These include but are not limited to locked-in technology that is expensive to maintain, centralised systems that are difficult to upgrade, environmental degradation of local waterways due to discharging of polluted wastewater, impacts on the hydrological cycle and system vulnerability to climate change. Consequently, alternatives are being sought, including technology that is adaptable, multi-functional, cheaper and greener (Wong & Brown 2009).

Four researchers work primarily within the Technology and Innovation theme and have identified the following research topics: (1) the design of small-scale green technology for the on-site management of stormwater and greywater, (2) development of a stormwater biofiltration system for the simultaneous treatment of stormwater and irrigation of urban agriculture, (3) the control and optimisation of WSUD systems to allow real-time adaptation to different operational conditions, and (4) exploring the emergence and uptake of innovations in sanitation and how to leverage this at the community scale. These topics are explored in two different contexts: Indonesia and China (see Figure 3). Conducting studies in two different contexts will allow us to compare and contrast the success of novel technology (e.g. adaptions required in design due to climate) and community engagement in the uptake of innovation.

Urban Planning and Design

Rigorous planning and functional design of the urban landscape are instrumental to facilitating growth and adapting to climate change. Planning and design is foundational to the physical exponent of the WSC. It requires a deep understanding of the local spatial, demographic and social context (Bach *et al.* 2015). In this angle, this understanding is combined with innovative green technologies such as raingardens, ponds and wetlands, which are aimed at stormwater retention, treatment and harvesting.

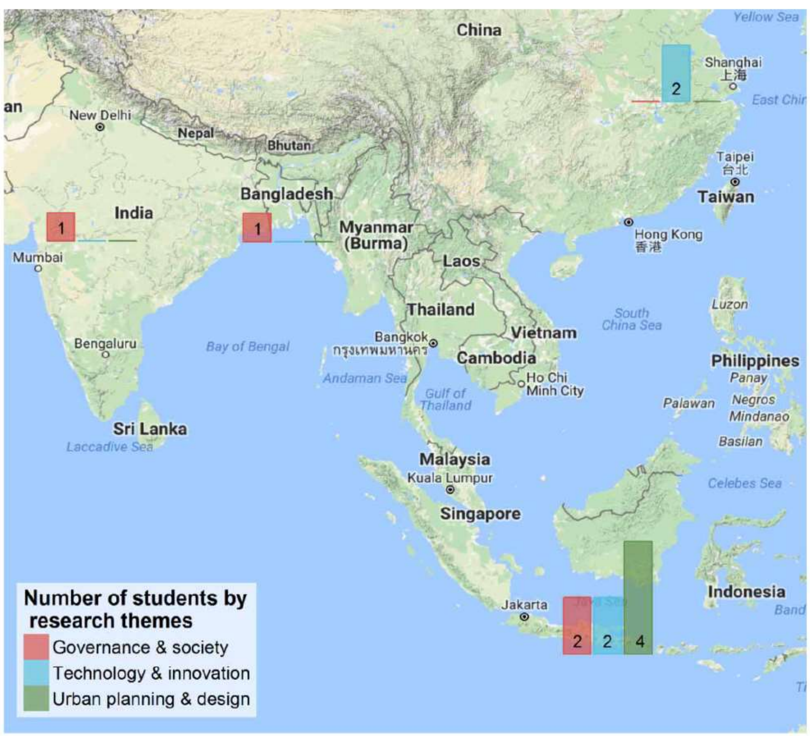

Figure 3 | Map of SUWM research projects across Asia (Google Base Map 2016).

Four researchers work primarily within the Urban Planning and Design theme and have identified the following research topics: (1) developing an integrated urban water modelling tool to investigate the multiple benefits of WSUD elements, (2) the development of a spatial suitability assessment method and computer application for the placement of WSUD elements, (3) modelling the impact of different policies on the transition from traditional infrastructure to green infrastructure adoption, and (4) assessing the influence of the physical built environment on sustainability transitions to inform strategic action towards SUWM. These topics are explored in Indonesia (see Figure 3). Conducting all these studies in Indonesia allows for comprehensive data gathering (e.g. topography, existing water infrastructure), which is required to inform the models and assessments.

Governance and Society

We begin with a hypothesis that governance strategies are needed to facilitate progressive policies and institutional change for implementing SUWM in developing contexts. When faced with uncertainty and complex choices, conventional water institutions tend to go into inertia which sustains less-than-effective governance structures and societal processes, such as organisational fragmentation, poor political processes, lack of accountability, bureaucratic complexity, ad hoc decision-making, entrenched inequality, and risk-averse attitude, among others (Brown 2005). In contrast, studies have shown that new governance attributes (e.g. adaptive learning and experimentations, multi-stakeholder decision-making, accountable and transparent process, just and equitable outcomes) need to be introduced in order to facilitate complex societal transformations as required by SUWM (Van de Meene *et al.* 2011; Finewood & Holifield 2015).

Four researchers work primarily within the Governance and Society theme and have identified the following research topics: (1) identifying socio-political drivers and the enabling contexts for leapfrogging towards SUWM, (2) diagnosing capacity for strategic action to accelerate SUWM adoption, (3) assessing adaptive capacity to overcome institutional barriers for SUWM, and (4) developing a justice framework to empower marginalised communities towards SUWM. These topics are explored in three different contexts: Indonesia, Bangladesh and India (see Figure 3). Conducting studies in three different contexts will allow us to compare and contrast governmental structures and alternative practices, which promote or hinder the implementation of SUWM in a developing context.

Interconnections

While each researcher sits within one of the above mentioned research angles it is important to note that as a cohort we span the spectrum from pure engineering to social science research, with a number of researchers also working on individual interdisciplinary projects. Of the 12 projects, this roughly equates to: two pure engineering projects, one each from Technology and Innovation and Urban Planning and Design; two pure social science projects, both from Governance and Society; and eight interdisciplinary projects, two from Society and Governance, three from Technology and Innovation and three from Urban Planning and Design. Regular meetings, conversations and presentations are organised to facilitate dialogue and ideas among the group.

Linkages

As stated previously, while not at the core of our programme, the involvement of a variety of stakeholders beyond academic actors serves as an important background to our research activities. In all four countries various professionals from the government involved in the water and sanitation sector will be interviewed as they play a key role in the decision-making, implementation and enforcement of SUWM. For example, in Indonesia, individuals from the Department of Planning, Environmental Agency and Department of Public Works will be engaged via interviews and focus groups. The results of these encounters are expected to provide us with insights on current water management approaches and their receptiveness towards SUWM. Additionally, these interactions will allow us to understand the various current government structures, their workings and effectiveness in delivering current water management goals and hence their ability to move towards SUWM.

In addition to governmental organisations and agencies, NGOs will also be involved. These NGOs may be industry partners or charities involved in the water sector, such as WorldVision. Their involvement is essential as it recognises the influence that NGOs have in engaging with the community and their role in various community-led movements, particularly in the areas of sanitation and ensuring equitable urban water development. In contrast to governmental agencies and private organisations, NGOs are more involved in bottom-up instead of top-down approaches. They provide a different perspective that can be used to inform the development of SUWM initiatives, such as consideration to the needs and wants of communities and the contextual suitability of projects. Additionally, there will be other industry partners, such as consultants and developers, involved in the design, construction and implementation of water systems who will be engaged through interviews. They play an important role in determining the capacity for the implementation and adoption of SUWM.

While governmental and NGOs play a large role in decision-making and the implementation of various strategies, there is a need to include the community whose lives are impacted by these approaches and their social and environmental outcomes. This is particularly the case for WSUD elements delivered as part of SUWM, where placement is within the vicinity of local communities. SUWM is also a relatively new concept in developing countries and will give rise to different perceived risks and uncertainty. As such, it is intended that select local communities in all four countries will be involved through surveys and focus group discussions to obtain their insights on the current water system, their understanding of SUWM and their receptiveness to this approach.

Finally, in developing cities where there is underdeveloped infrastructure and institutional capacity, there is a need to look at the role and strategies used in alternative practices emerging outside formal institutions (Bauler *et al.* 2017). Among these are social innovations and social entrepreneurship, which are gaining tangible traction for their ability to tackle complex and persistent social and environmental problems while contributing to environmental sustainability and socio-economic development of poor and marginalised citizens (Bonifacio 2014). Therefore, social entrepreneurs in the water and sanitation realm will also be engaged as part of our research programme.

Interdisciplinary research: initial thoughts

Interdisciplinary research has a more holistic view in solving complex problems in comparison to traditional silo research; however, it comes with both rewards and challenges. The biggest challenge we have found to date is that it requires more time, more patience, more effort, more support and more money, than traditional projects we have worked on. The biggest incentive of interdisciplinary research is that approaching problems from different angles and thinking about them through different disciplinary lenses can result in non-conventional ideas and solutions. Besides this advantage, the process of doing interdisciplinary research has several personal rewards. In the journey so far, it has provided a good opportunity for individual researchers to gain or improve communication and team work skills. It has enabled and facilitated learning about other disciplines. Through the increased communication with each other, we have learnt to understand the lexicon of other disciplines, conversing across academic boundaries and beginning to speak a common language. With time this should lead to T-shaped professionals who can quickly collaborate across different disciplines, even in entirely new teams and contexts for future projects (Brown *et al.* 2015). Arguably, T-shaped professionals possess transferable skills and capacity to effectively bridge communication and collaboration across various stakeholders (beyond the academic actors). After all, the task of tackling complex challenges cannot be delivered only through the ivory tower of research academia. Nonetheless, we contend that by starting the journey early and intently, interdisciplinary researchers can complement the broader transdisciplinary agenda to bridge research with policy and practice more effectively.

CONCLUSIONS

SUWM is facing complex challenges in developing cities, such as rapid urbanisation, population growth and climate change. However, there are also substantive opportunities to promote SUWM in this context, with urban water systems yet to be formalised and minimal lock-in to conventional approaches. Utilising an interdisciplinary approach and bridging the interface between the biophysical and social science disciplines, researchers are working together to aid 'leapfrogging' of Asian cities to WSC futures. Three key research angles have been identified in this process; (1) Technology and Innovation, (2) Urban Planning and Design, and (3) Governance and Society. Within these research angles 12 research projects are being undertaken across Indonesia, China, India and Bangladesh. This outward-looking, interdisciplinary approach guides our research in an effort to transgress single-discipline solutions and contribute on-ground impact to SUWM practices in Asia.

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APPENDIX B

Introduction

This appendix contains the Human Ethics Certificate of Approval for our qualitative research conducted in Australia and Indonesia presented in Chapter 4 and Chapter 6, respectively.

Human Ethics Certificate of Approval

MONASH University

Monash University Human Research Ethics Committee (MUHREC)
Research Office

Human Ethics Certificate of Approval

This is to certify that the project below was considered by the Monash University Human Research Ethics Committee. The Committee was satisfied that the proposal meets the requirements of the *National Statement on Ethical Conduct in Human Research* and has granted approval.

Project Number: CF16/730 - 2016000357

Project Title: Urban Planning for Water Sensitive Urban Design

Chief Investigator: Prof Ana Deletic

Approved: **From:** 14 April 2016 **To:** 14 April 2021

Terms of approval - ***Failure to comply with the terms below is in breach of your approval and the Australian Code for the Responsible Conduct of Research.***

1. The Chief investigator is responsible for ensuring that permission letters are obtained, if relevant, before any data collection can occur at the specified organisation.
2. Approval is only valid whilst you hold a position at Monash University.
3. It is the responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval and to ensure the project is conducted as approved by MUHREC.
4. You should notify MUHREC immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.
5. The Explanatory Statement must be on Monash University letterhead and the Monash University complaints clause must include your project number.
6. **Amendments to the approved project (including changes in personnel):** Require the submission of a Request for Amendment form to MUHREC and must not begin without written approval from MUHREC. Substantial variations may require a new application.
7. **Future correspondence:** Please quote the project number and project title above in any further correspondence.
8. **Annual reports:** Continued approval of this project is dependent on the submission of an Annual Report. This is determined by the date of your letter of approval.
9. **Final report:** A Final Report should be provided at the conclusion of the project. MUHREC should be notified if the project is discontinued before the expected date of completion.
10. **Monitoring:** Projects may be subject to an audit or any other form of monitoring by MUHREC at any time.
11. **Retention and storage of data:** The Chief Investigator is responsible for the storage and retention of original data pertaining to a project for a minimum period of five years.

Professor Nip Thomson
Chair, MUHREC

cc: Mr Martijn Kuller

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ABN 12 377 614 012 CRICOS Provider #00008C

APPENDIX C

Introduction

This appendix contains the interview protocol used for the qualitative research of Chapter 4.

Interview protocol

Time of interview:

Date:

Place:

Interviewee:

Position of Interviewee:

Consent form and explanatory statement explained and signed:

Brief explanation of the purpose and the research.

Recording

Theme 1: Planning processes

1. What is your role in the organisation? What type of projects do you work on? *(Are you in charge of WSUD/green space planning and implementation?)*
2. Please explain the planning process you follow for WSUD implementation. When you plan WSUD items, which are the things you consider and why?
3. Problems in the planning process?
4. What should be done/changed to improve the processes and outcomes? *(justification, money, time, opportunism, collaboration, innovativeness, is it improving?)*

Theme 2: Tools and models to support planning

5. What methods and tools do you use to aid your processes? *(CBA, MCA, hydrological, water balance, spatial, spreadsheets?)*
6. Who decides to use PST(s)? *(Own choice, superiors/other organisation, industry convention)*
7. When are they used? *(communication/participation, decision-making, decision-support, conceptualisation, visioning, design, scenario analysis, story-telling)*

8 Are there other parts of the process that PST could be helpful with? *(communication/participation, decision-making, decision-support, conceptualisation, visioning, design, scenario analysis, story-telling)*
9 Could you name some good points about the PST you use?
10 What do you not like about the PSTs that you use? Why are they not used more?

Concluding questions

11 Do you have any other comments?
12 Could you give me names of other people you advise me to contact?
13 Is it OK if I contact you in the future for clarification and verification of answers?

APPENDIX D

Introduction

This appendix contains the supplementary materials for the development and testing of SSANTO, as described in Chapter 5.

Supplementary Materials

Detailed methodology of priority site selection for precinct-scale systems

The focus of E2DesignLab's study, over 100 WSUD sites (polygon shapefile) were manually identified as opportunities to retrofit large scale WSUD assets. E2Designlab used their experience with planning of green stormwater infrastructure design combined with spatial analysis. The spatial assessment 'masks' unsuitable areas and identifies desirable areas based on assessment of land ownership, slope, proximity to drainage, catchment, available space, reuse opportunities, potential land use conflicts and the presence of existing systems. The study focussed solely on municipal or public land, so no sites were identified in private land. Once sites had been identified, they were ranked based on a preliminary assessment of project costs (capital and operational), treatment performance and alternative water use. The treatment and reuse potential of each site was estimated using unit model results. The highest priority sites were presented to a broad group of internal municipal stakeholders for review and refinement. This process resulted in a prioritised shortlist of sixty-eight (68) sites. The shortlisted sites were subjected to a detailed assessment which included estimates of treatment performance, storage size, reuse volume and reuse reliability from the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) v6.2 (eWater 2011). The benefit cost ratio (BCR) for each site was calculated based on net present value (NPV) of potable water savings (benefit) and total nitrogen abatement (benefit) and lifecycle cost, including capital, operational/maintenance and renewal (cost). The sixty-eight (68) sites were prioritised based on their BCR (high BCR = high priority). In addition, qualitative data risk and opportunity was collected for each site based on consultation with the municipality and GIS mapping of landfill sites, cultural heritage, natural heritage, biodiversity, geological sites and flooding (1% AEP). The prioritisation led to selection of priority sites which progressed to concept or more detailed design.

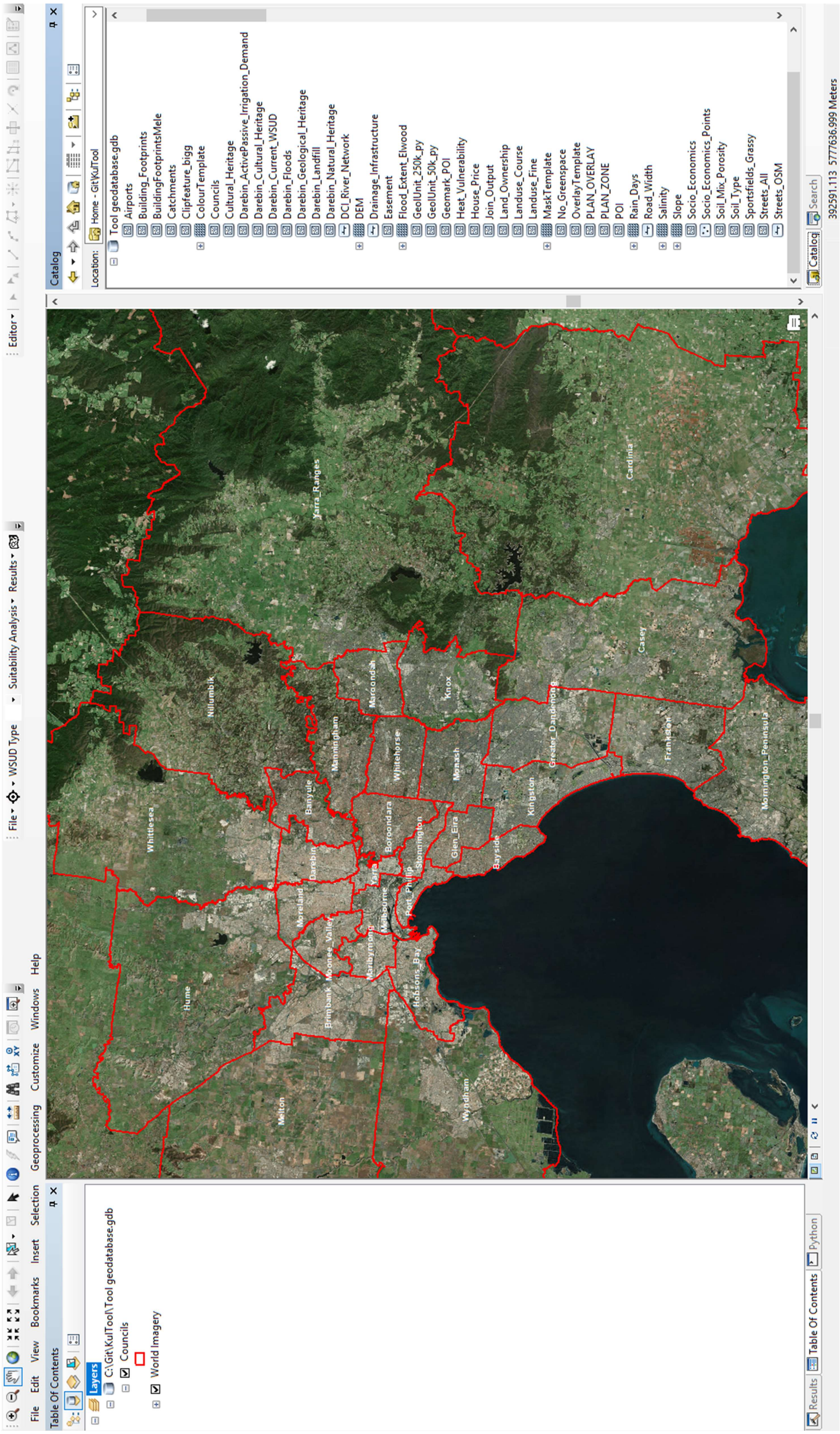

Figure 3S Start window within ArcGIS, with on top in the middle the toolbar of the tool.

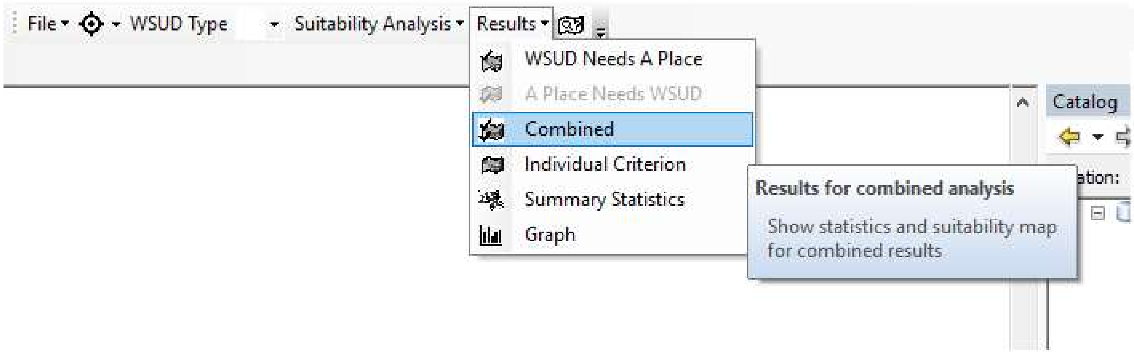

Figure 4S Close-up of the toolbar with the results drop-down.

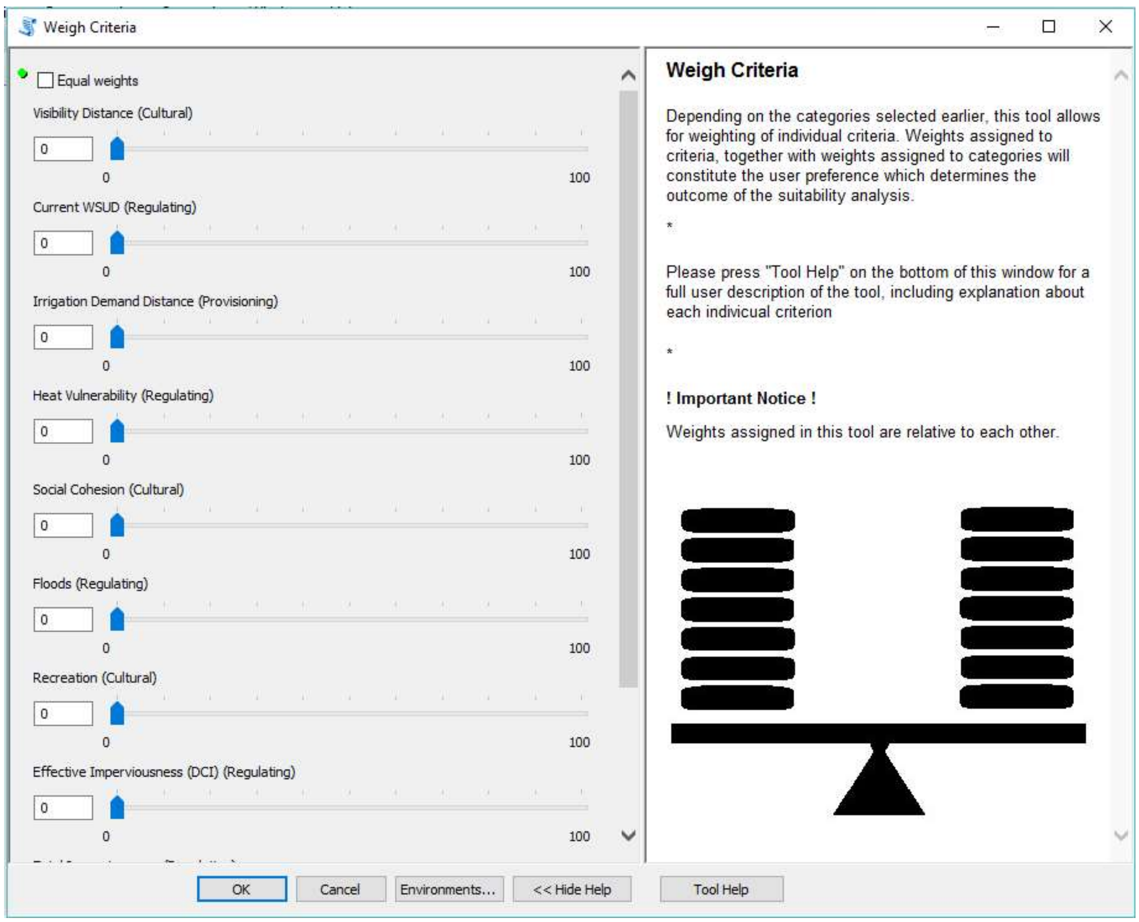

Figure 5S Wizard for criteria weighting, developed as a python toolbox.

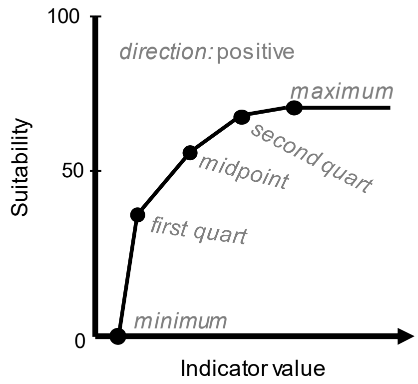

Figure 4S Hypothetical example of piecewise linear value function as generated from 6 parameters (grey).

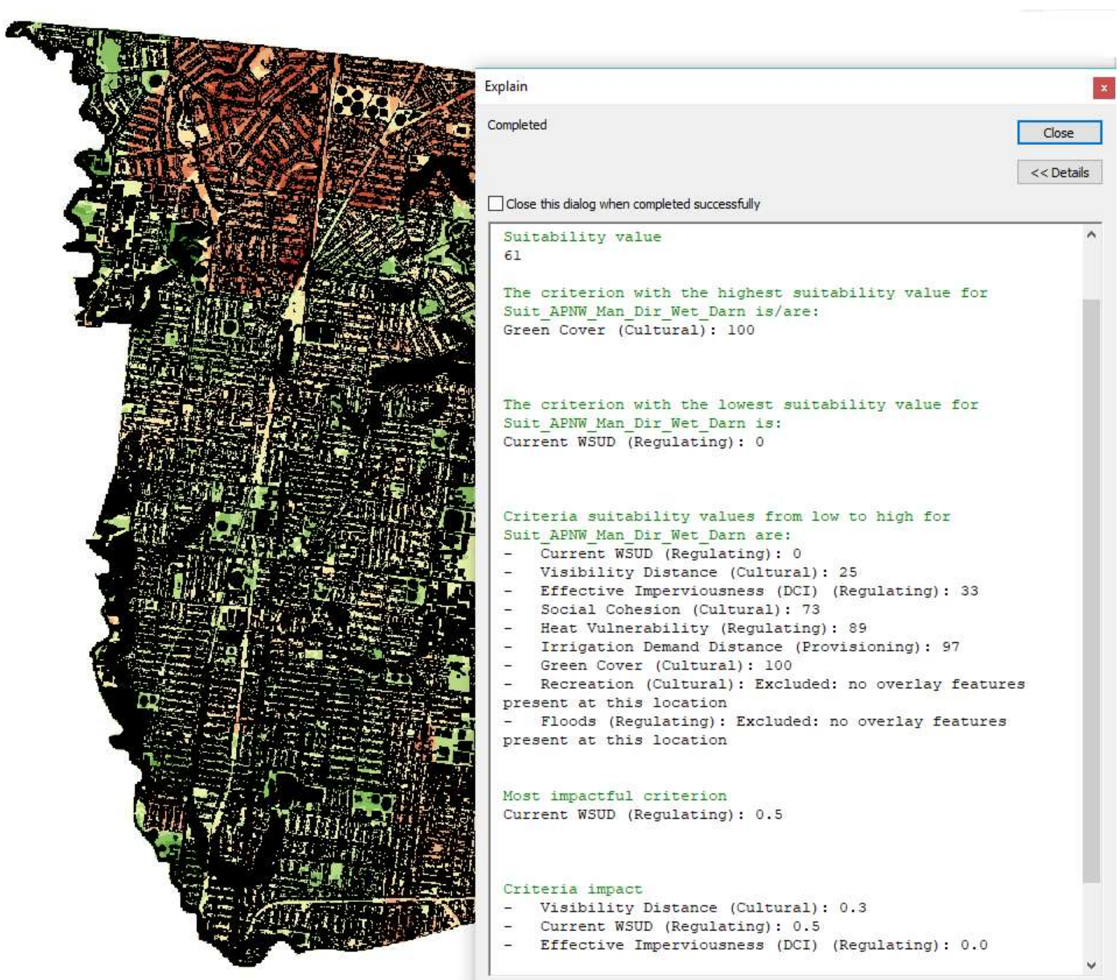

Figure 5S Output window of the "Explain" function, where the user can click anywhere on the map and the tool produces a numerical explanation of the reason behind the suitability score at the clicked location.

Table 6S Datasets in the geodatabase and their corresponding indicators.

Indicator	Dataset	Data type	Proxy	Comments	Source*
Soil salinity	Soil salinity	Raster			VVG
Storage capacity	Groundwater table	Raster			VVG
Contamination	Landfill Sites	Features	√	Only part of potentially contaminates soils	Council
Slope	Digital Elevation Model (DEM)	Raster		Slope percentages are calculated from the DEM	DELWP
Rainfall	Rain days	Raster		The average number of days per year that the total rainfall exceeds 1mm.	BOM
Topography (drainage channels)	Surface water	Features		Used to calculate distance to waterways.	Melbourne Water
Surface water	Water bodies	Features		Selected all features with an attribute related to surface water.	DELWP
Ecosystem structure	Pre-European wetland structure	Overlay		Wetland systems before they were altered by human intervention	DELWP
Education level	Bachelor degrees	Aggregated (census tract)	√	PCA results show that percentage of population with a bachelor degree is the best proxy for education level (Kuller et al. Submitted).	ABS
Relative wealth	SEIFA	Aggregated (Census tract)			ABS
Environmental awareness	Election results	Aggregated (Electoral district)	√	Percentage of population with "The Australian Greens" as their first preference vote. (Kuller et al. Submitted).	VEC
Sense of community	Volunteers	Aggregated (Census tract)	√	Percentage of population partaking in volunteering work. Can be used as a proxy (Torgler et al. 2012).	ABS
Building foundations	Building footprints	Features			DELWP
Proximity to airports	Airports	Features		Proximity to airports is evaluated because of bird-plane collision risk.	DELWP
Road renewal	Capital works program	Overlay		Upcoming road renewal projects	Council
Utility infrastructure	Easements	Features		Electricity, gas and water mains	DELWP
Drainage infrastructure	Drainage infrastructure	Features		Rainwater sewer system	??

Street width or type	Street network	Features		Spatial join between the street type from OSM with the street lines from VicRoads	OSM, VicRoads
Cultural Heritage	Cultural Heritage Sites	Overlay			HCV
Geological Heritage	Geological Heritage sites	Overlay		Local, regional, state and national importance	Council
Natural Heritage	Natural Heritage Sites	Overlay		Local, regional, state and national importance	Council
Land value	House price	Aggregated (Suburb)		Median property sales by suburb	DELWP
Land ownership	Cadastre	Features		4 ownership types: public roads, public crown, private single owner, private multiple owners. Overlaid with public open space to get locally owned public land.	DELWP
Lot size	Cadastre	Features			DELWP
Proximity to water demand	POI (Points of Interest)	Features	√	As irrigation of grassy sports fields is the greatest irrigation demand, we use the distance to grassy sports fields as a proxy. Grassy sports fields were extracted from POI.	DELWP
Heat vulnerability	Heat vulnerability	Aggregated (Suburb)			(Loughnan et al. 2012)
Connected impervious area	Directly connected imperviousness (DCI)	Aggregated (catchment)	√	This metric is a proxy for environmental degradation and measures the percentage of the drainage area that is directly discharging into the urban stream	Melbourne Water
Total impervious area	Sealed surfaces	Aggregated (catchment)			Melbourne Water
Current WSUD	Surfaces currently treated by WSUD	Aggregated (catchment)		Catchments from which water is treated by WSUD	Melbourne Water and Council
Floods	Flood extents	Raster		1/100 year underground/natural drain	Council
Visibility	Land-use, POI	Features, Features	√	A combination of distance to POI (such as commercial zones, schools) and land uses (e.g. housing density).	(Bach et al. 2015), DELWP
Greenery	Tree density	Aggregated		Density of woody vegetation in four categories: none, sparse, medium, dense.	DELWP

Recreation	Walkable green public open spaces	Features	√	Areas within 4 minutes walking to public open spaces	VPA
Social cohesion	Volunteering	Aggregated (census tract)	√		ABS

*ASRIS: Australian Soil Resource Information System, CSIRO: Commonwealth Scientific and Industrial Research Organisation, VVG: Visualising Victoria's Groundwater, DELWP: Department of Environment, Land, Water and Planning (Victoria State Government), BOM: Bureau of Meteorology, ABS: Australian Bureau of Statistics, VEC: Victorian Electoral Commission, OSM: Open Street Maps, HCV: Heritage Council Victoria, VPA: Victorian Planning Authority

Table 7S Value scales per WSUD type

WSUD type	Criterion	Source*	Mask	Value Scales					
				Min	Max	Mid	Q1	Q2	Dir
Rain gardens	Slope [%]	L[1]	15	4	15	-	-	-	↓
	Distance to waterway [m]	A	0	0	2397	143	38	421	↓
	Pre-human wetlands	N/A	Yes						↑
	(Distance to) landfill sites	L[3]	0	0	1500	-	-	-	↑
	Building footprints	L[1]	Yes	Boolean					↓
	Education level [%]	D	-	Data dependent					↑
	Environmental awareness [%]	D	-	Data dependent					↑
	Sense of Community [%]	D	-	Data dependent					↑
	Distance to drainage infrastructure	L[4]	-	0	200	-	-	-	↓
	Utility infrastructure	N/A	-	Boolean					↓
	Street type (speed limit) [km/h]	A	-	Void: 101, 10: 100, 15: 100, 20: 100, 25: 100, 30: 100, 40: 100, 50: 50, 60: 0, 70: 0, 80: 0, 90: 0, 100: 0, 110: 0, <Null>: 100					↓
	Cultural Heritage sites	N/A	-	Boolean					↓
	Natural Heritage sites	N/A	-	Boolean					↓
	Geological Heritage sites	N/A	-	Boolean					↓
	Land value (median house price) [$]	D	-	Data dependent					↑
	Land ownership (categorical)	P	-	Void: 50, Private individual: 25, Private multiple owners: 0, Public other: 50, Public roads: 100, Public crown: 75, Public municipal: 100, Public authority land: 100,					
	Distance to grassy sports field [m]	P	-	0	∞	1000	-	-	↓
	Heat vulnerability (custom range)	A	-	1	10	-	-	-	↑
	Effective imperviousness (DCI) [%]	L[1]	-	-2	2	-	-	-	↑
				5	100	10	-	-	↓
	Total imperviousness [%]	P	-	0	100	20	-	-	↑
	Current WSUD (fraction)	A	-	0	1	0.25	-	-	↓
	Flood extents [cm]	N/A	-	Boolean					↑
	Visibility (distance to POI) [m]	A	-	0	300	-	-	-	↓
	(land use type – categorical)	P		Void: 50, Education: 100, Floodway: 0, Heavy industry: 25, High density residential: 75, High density trade: 100, Health and community: 100, Light industry: 25, Low density residential: 25, Low density trade: 25, Medium density residential: 50, Mixed HDR and commercial: 100, Mixed trade and industry: 50, Offices: 75, Parks and gardens: 50, Reserves: 50, Road: 75, Services and utility: 25, Transport: 25, Unclassified: 0,					

				Undeveloped: 0, Very low density residential: 10					
	Greenery (tree density - categorical)	A	-	Void (no trees): 100, Scattered: 75, Medium: 50, Dense: 0					
	Social cohesion (volunteering) [%]	D	-	Data dependent					↓
Infiltration systems	Slope [%]	L[1]	10	0	10	-	-	-	↓
	Groundwater table [m]	L[1]	0.5	0.5	1.5	-	-	-	↑
	Surface water	N/A	Yes						↓
	(Distance to) landfill sites	L[3]	0	0	1500	-	-	-	↑
	Building footprints (distance) [m]	L[1]	4	Boolean					↑
	Education level [%]	D	-	Data dependent					↑
	Environmental awareness [%]	D	-	Data dependent					↑
	Sense of Community [%]	D	-	Data dependent					↑
	Distance to drainage infrastructure	L[4]	-	0	200	-	-	-	↓
	Utility infrastructure	N/A	-	Boolean					↓
	Cultural Heritage sites	N/A	-	Boolean					↓
	Natural Heritage sites	N/A	-	Boolean					↓
	Geological Heritage sites	N/A	-	Boolean					↓
	Land ownership (categorical)	P	-	Void: 50, Private individual: 25, Private multiple owners: 0, Public other: 50, Public roads: 100, Public crown: 75, Public municipal: 100, Public authority land: 100,					
	Heat vulnerability (custom range)	A	-	1	10	-	-	-	↑
	Effective imperviousness (DCI) [%]	L[1]	-	-2	2	-	-	-	↑
				5	100	10	-	-	↓
	Total imperviousness [%]	P	-	0	100	20	-	-	↑
	Current WSUD (fraction)	A	-	0	1	0.25	-	-	↓
	Flood extents [cm]	N/A	-	Boolean					↑
	Visibility (distance to POI) [m]	A	-	0	300	-	-	-	↓
	(land use type – categorical)	P		Void: 50, Education: 100, Floodway: 0, Heavy industry: 25, High density residential: 75, High density trade: 100, Health and community: 100, Light industry: 25, Low density residential: 25, Low density trade: 25, Medium density residential: 50, Mixed HDR and commercial: 100, Mixed trade and industry: 50, Offices: 75, Parks and gardens: 50, Reserves: 50, Road: 75, Services and utility: 25, Transport: 25, Unclassified: 0, Undeveloped: 0, Very low density residential: 10					
	Greenery (tree density - categorical)	A	-	Void (no trees): 100, Scattered: 75, Medium: 50, Dense: 0					
Green roofs	Rain variability (rain days)	A	-	0	365	122	61	183	↑

	Building footprints (distance) [m]	L[1]	Yes	Boolean					↑
	Education level [%]	D	-	Data dependent					↑
	Environmental awareness [%]	D	-	Data dependent					↑
	Distance to drainage infrastructure	L[4]	-	0	200	-	-	-	↓
	Cultural heritage sites	N/A	-	Boolean					↓
	Land value	D	-	Data dependent					↑
	Heat vulnerability (custom range)	A	-	1	10	-	-	-	↑
	Effective imperviousness (DCI) [%]	L[1]	-	-2	2	-	-	-	↑
				5	100	10	-	-	↓
	Total imperviousness [%]	P	-	0	100	20	-	-	↑
	Current WSUD (fraction)	A	-	0	1	0.25	-	-	↓
	Flood extents [cm]	N/A	-	Boolean					↑
	Visibility (distance to POI) [m]	A	-	0	300	-	-	-	↓
	(land use type – categorical)	P		Void: 50, Education: 100, Floodway: 0, Heavy industry: 25, High density residential: 75, High density trade: 100, Health and community: 100, Light industry: 25, Low density residential: 25, Low density trade: 25, Medium density residential: 50, Mixed HDR and commercial: 100, Mixed trade and industry: 50, Offices: 75, Parks and gardens: 50, Reserves: 50, Road: 75, Services and utility: 25, Transport: 25, Unclassified: 0, Undeveloped: 0, Very low density residential: 10					
	Greenery (tree density - categorical)	A	-	Void (no trees): 100, Scattered: 75, Medium: 50, Dense: 0					
Ponds & Lakes	Distance to waterway [m]	A	0	0	2397	143	38	421	↓
	(Distance to) landfill sites	L[3]	0	0	1500	-	-	-	↑
	Pre-human wetlands	N/A	-	Boolean					↑
	Building footprints	L[1]	10	Boolean					↓
	Airports (distance) [km]	L[2]	1	1	13	-	-	-	↑
	Distance to drainage infrastructure	L[4]	-	0	200	-	-	-	↓
	Utility infrastructure	N/A	-	Boolean					↓
	Street type (speed limit) [km/h]	A	10	-	-	-	-	-	↓
	Cultural Heritage sites	N/A	-	Boolean					↓
	Natural Heritage sites	N/A	-	Boolean					↓
	Geological Heritage sites	N/A	-	Boolean					↓
	Land value (median house price) [$]	D	-	Data dependent					↓
	Lot size [1000 m^2]	A	-	0.24	13	1.37	0.57	4.99	↑
	Distance to grassy sports field [m]	P	-	0	∞	1000	-	-	↓
	Heat vulnerability (custom range)	A	-	1	10	-	-	-	↑

	Effective imperviousness (DCI) [%]	L[1]	-	-2	2	-	-	-	↑
				5	100	10	-	-	↓
	Total imperviousness [%]	P	-	0	100	20	-	-	↑
	Current WSUD (fraction)	A	-	0	1	0.25	-	-	↓
	Flood extents [cm]	N/A	-	Boolean					↑
	Visibility (distance to POI) [m]	A	-	0	300	-	-	-	↓
	(land use type – categorical)	P		Void: 50, Education: 100, Floodway: 0, Heavy industry: 25, High density residential: 75, High density trade: 100, Health and community: 100, Light industry: 25, Low density residential: 25, Low density trade: 25, Medium density residential: 50, Mixed HDR and commercial: 100, Mixed trade and industry: 50, Offices: 75, Parks and gardens: 50, Reserves: 50, Road: 75, Services and utility: 25, Transport: 25, Unclassified: 0, Undeveloped: 0, Very low density residential: 10					
	Recreation (absence of urban green/blue space at walking distance)	A	-	Boolean					↑
	Social cohesion (volunteering) [%]	D	-	Data dependent					↓
Swales	Slope [%]	L[1]	8	-0.5	0.5	-	-	-	↑
				2	5	-	-	-	↓
	Distance to waterway [m]	A	0	0	2397	143	38	421	↓
	(Distance to) landfill sites	L[3]	0	0	1500	-	-	-	↑
	Building footprints	P	4	Boolean					↓
	Education level [%]	D	-	Data dependent					↑
	Environmental awareness [%]	D	-	Data dependent					↑
	Sense of Community [%]	D	-	Data dependent					↑
	Distance to drainage infrastructure	L[4]	-	0	200	-	-	-	↓
	Utility infrastructure	N/A	-	Boolean					↓
	Street type (speed limit) [km/h]	A	10	Void: 101, 10: 0, 15: 0, 20: 0, 25: 0, 30: 0, 40: 50, 50: 100, 60: 30, 70: 60, 80: 80, 90: 100, 100: 100, 110: 100, <Null>: 0					
	Cultural Heritage sites	N/A	-	Boolean					↓
	Natural Heritage sites	N/A	-	Boolean					↓
	Geological Heritage sites	N/A	-	Boolean					↓
	Land value (median house price) [$]	D	-	Data dependent					↑
	Land ownership (categorical)	P	-	Void: 50, Private individual: 25, Private multiple owners: 0, Public other: 50, Public roads: 100, Public crown: 75, Public municipal: 100, Public authority land: 100,					
	Heat vulnerability (custom range)	A	-	1	10	-	-	-	↑

	Effective imperviousness (DCI) [%]	L[1]	-	-2	2	-	-	-	↑
				5	100	10	-	-	↓
	Total imperviousness [%]	P	-	0	100	20	-	-	↑
	Current WSUD (fraction)	A	-	0	1	0.25	-	-	↓
	Flood extents [cm]	N/A	-	Boolean					↑
	Visibility (distance to POI) [m]	A	-	0	300	-	-	-	↓
	(land use type – categorical)	P		Void: 50, Education: 100, Floodway: 0, Heavy industry: 25, High density residential: 75, High density trade: 100, Health and community: 100, Light industry: 25, Low density residential: 25, Low density trade: 25, Medium density residential: 50, Mixed HDR and commercial: 100, Mixed trade and industry: 50, Offices: 75, Parks and gardens: 50, Reserves: 50, Road: 75, Services and utility: 25, Transport: 25, Unclassified: 0, Undeveloped: 0, Very low density residential: 10					
	Greenery (tree density - categorical)	A	-	Void (no trees): 100, Scattered: 75, Medium: 50, Dense: 0					
Rain tanks	Rain variability (rain days)	P	0	0	121	-	-	-	↑
					5	-	-	-	↓
	Surface water	N/A	Yes						↓
	Building footprints (distance)[m]	L[1]	-	-	5	-	-	-	↓
	Education level [%]	D	-	Data dependent					↑
	Relative wealth (custom scale)	D	-	Data dependent					↑
	Environmental awareness [%]	D	-	Data dependent					↑
	Distance to grassy sports field [m]	P	-	0	∞	1000	-	-	↓
	Heat vulnerability (custom range)	A	-	1	10	-	-	-	↑
	Effective imperviousness (DCI) [%]	L[1]	-	-2	2	-	-	-	↑
				5	100	10	-	-	↓
	Total imperviousness [%]	P	-	0	100	20	-	-	↑
	Current WSUD (fraction)	A	-	0	1	0.25	-	-	↓
	Flood extents [cm]	N/A	-	Boolean					↑
Wetlands	Slope [%]	L[1]	5.5	0	5.5	1	-	-	↓
	Distance to waterway [m]	A	0	0	2397	143	38	421	↓
	(Distance to) landfill sites	L[3]	0	0	1500	-	-	-	↑
	Pre-human wetlands	N/A	-	Boolean					↑
	Education level [%]	D	-	Data dependent					↑
	Environmental awareness [%]	D	-	Data dependent					↑
	Sense of Community [%]	D	-	Data dependent					↑
	Building footprints	L[1]	20	Boolean					↓
	Airports (distance) [km]	L[2]	1	1	13	-	-	-	↑

Distance to drainage infrastructure	L[4]	-	0	200	-	-	-	↓
Utility infrastructure	N/A	-	Boolean					↓
Street type (speed limit) [km/h]	A	10	-	-	-	-	-	↓
Cultural Heritage sites	N/A	-	Boolean					↓
Natural Heritage sites	N/A	-	Boolean					↓
Geological Heritage sites	N/A	-	Boolean					↓
Land value (median house price) [$]	D	-	Data dependent					↓
Lot size [1000 m²]	A	-	1.07	46.7	6.85	2.78	18.2	↑
Distance to grassy sports field [m]	P	-	0	∞	1000	-	-	↓
Heat vulnerability (custom range)	A	-	1	10	-	-	-	↑
Effective imperviousness (DCI) [%]	L[1]	-	-2	2	-	-	-	↑
			5	100	10	-	-	↓
Total imperviousness [%]	P	-	0	100	20	-	-	↑
Current WSUD (fraction)	A	-	0	1	0.25	-	-	↓
Flood extents [cm]	N/A	-	Boolean					↑
Visibility (distance to POI) [m]	A	-	0	300	-	-	-	↓
(land use type – categorical)	P		Void: 50, Education: 100, Floodway: 0, Heavy industry: 25, High density residential: 75, High density trade: 100, Health and community: 100, Light industry: 25, Low density residential: 25, Low density trade: 25, Medium density residential: 50, Mixed HDR and commercial: 100, Mixed trade and industry: 50, Offices: 75, Parks and gardens: 50, Reserves: 50, Road: 75, Services and utility: 25, Transport: 25, Unclassified: 0, Undeveloped: 0, Very low density residential: 10					
Greenery (tree density - categorical)	A	-	Void (no trees): 100, Scattered: 75, Medium: 50, Dense: 0					
Recreation (absence of urban green/blue space at walking distance)	N/A	-	Boolean					↑
Social cohesion (volunteering) [%]	D	-	Data dependent					↓

*A: author's discretion, D: data dependent, P: expert panel, L: literature.
[1] (Melbourne Water 2005)
[2] (ICAO 2012)
[3](Mor et al. 2006)
[4](Roberts et al. 2017)

Table 8S Weight assignment for expert weighting and entropy weighting (calculated) as used for tool testing. Weights are normalised, relative to each other and dimensionless.

Criterion	Precinct scale	
	Expert weight	Entropy weight
Slope	100	41
Pre-human wetland structure[1]	30	
(Distance to) landfill sites	80	28
Education level	10	7
Sense of community	20	7
Environmental awareness	20	15
Distance to drainage infrastructure	90	1
Utility infrastructure	70	19
Land value	20	5
Street width/type		
Lot Size	50	100
Land ownership	70	30
Cultural Heritage	30	36
Geological Heritage	20	14
Natural Heritage	30	30
Distance to airports	60	3
Irrigation demand	80	12
Effective imperviousness[2]	100	
Total imperviousness	80	25
Current WSUD	90	0
Heat vulnerability	60	11
Flood risk	30	5
Visibility	60	100
Social cohesion	40	37
Green cover	60	20
Recreation	40	4

[1]Pre-human wetland structure was excluded from the analyses as no overlay features are present for the case study location.
[2]Effective imperviousness was excluded from the evaluation for Darebin case study, as this fully developed area has homogeneously high rates of effective imperviousness, far above the threshold under which WSUD could improve water quality.

Table 9S Expert-defined value scales and criterion weights as used in model run S-Case-Expert, normalised for tool application (originally, data values were given a suitability score between 1 and 3 for each criterion).

Criterion	Weight	Value Scales
Current WSUD	1	(Yes: 100), (No: 33)
Heat vulnerability	1	(10: 100), (9: 67), (<9: 33)
Visibility	1	(Yes: 100), (No: 33)
Green cover	1	(High: 100), (Moderate: 67), (Low: 33)

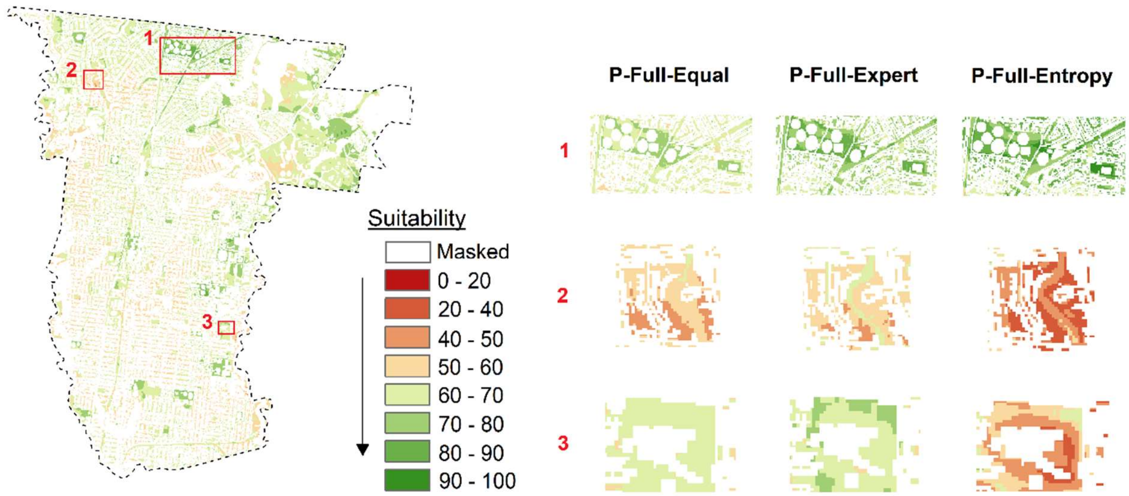

Figure 6S Variability of suitability for precinct scale WSUD using full criteria between different weighting regimes: Equal (P-Full-Equal), Expert (P-Full-Expert) and Entropy (P-Full-Entropy).

Table 5S Comparison of key suitability summary statistics between overall suitability and suitability at priority locations as identified by E2DesignLab. Numbers in bold represent priority sites, while regular font represents all of Darebin.

Model run		High		Low		Mean		Median		Majority		% Above 70		Fit[1]
S-Case-Expert	Opportunities	-		-		-		-		-		-		
	Needs	100		33		69		67		58		42.2		
	Suitability	100		33		69		67		58		42.2		
P-Case-Equal	Opportunities	100	**99**	19	**28**	56	**54**	56	**52**	60	**41**	17.0	**22.0**	
	Needs	100	**100**	39	**75**	90	**96**	91	**97**	92	**100**	100	**100**	
	Suitability	100	**97**	32	**49**	66	**67**	66	**65**	64	**57**	35.7	**38.3**	
P-Case-Expert	Opportunities	100	**99**	18	**29**	56	**59**	56	**58**	56	**46**	15.5	**24.2**	
	Needs	100	**100**	39	**76**	91	**96**	92	**97**	92	**100**	100	**100**	
	Suitability	100	**96**	32	**50**	67	**70**	66	**69**	64	**61**	36.5	**49.6**	
P-Case-Entropy	Opportunities	100	**100**	1	**14**	43	**43**	41	**40**	39	**27**	6.8	**6.7**	
	Needs	100	**100**	49	**51**	82	**92**	83	**95**	100	**100**	82.0	**96.0**	
	Suitability	100	**94**	18	**32**	55	**58**	54	**56**	52	**45**	11.6	**18.9**	
P-Full-Equal	Opportunities	78	**72**	28	**35**	49	**56**	49	**56**	46	**56**	0.2	**0.5**	
	Needs	95	**91**	50	**54**	76	**77**	76	**78**	75	**77**	90.0	**80.3**	
	Suitability	82	**76**	43	**50**	60	**65**	59	**65**	58	**64**	2.8	**17.3**	
P-Full-Expert	Opportunities	89	**84**	26	**38**	55	**62**	54	**60**	55	**55**	6.9	**21.6**	
	Needs	96	**91**	49	**57**	78	**79**	78	**80**	77	**80**	95.5	**85.0**	
	Suitability	90	**86**	42	**52**	64	**69**	63	**68**	62	**61**	18.4	**42.7**	
P-Full-Entropy	Opportunities	92	**85**	8	**16**	39	**60**	33	**60**	24	**56**	5.2	**17.1**	
	Needs	95	**89**	25	**43**	62	**68**	59	**70**	48	**80**	27.8	**50.2**	
	Suitability	89	**85**	21	**29**	48	**64**	44	**63**	38	**54**	9.6	**26.8**	

[1]The number indicates the difference between the mean suitability at priority sites vs Darebin average, while the colour indicates the difference in % above suitability of 70 between priority sites and Darebin average (: below -5, : between -5 and -1, : between 0 and 4, : between 5 and 15, : above 15 dark green: above 15).

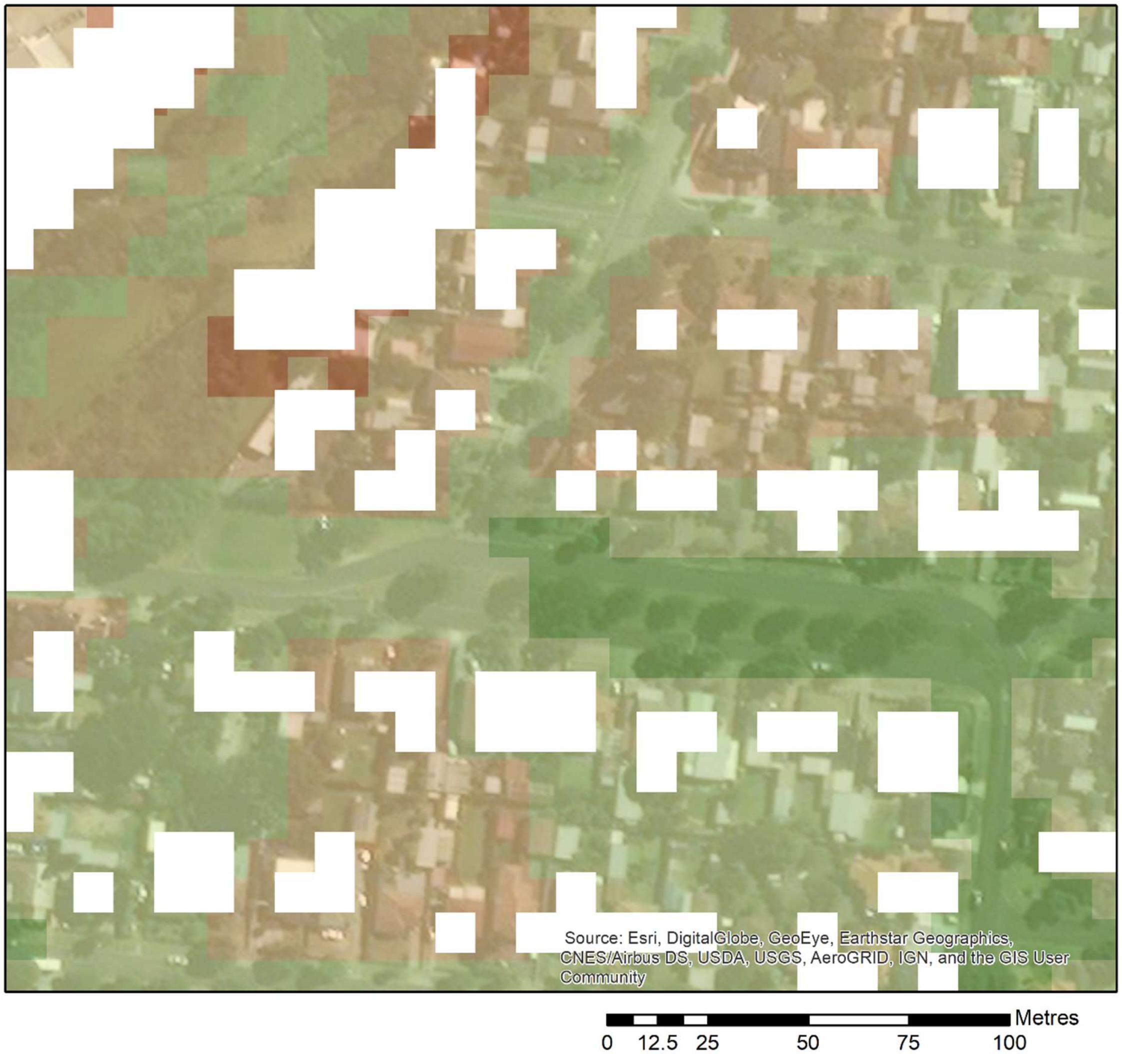

Figure 7S Close-up of satellite image overlain with suitability output for model run S-Case-Expert.

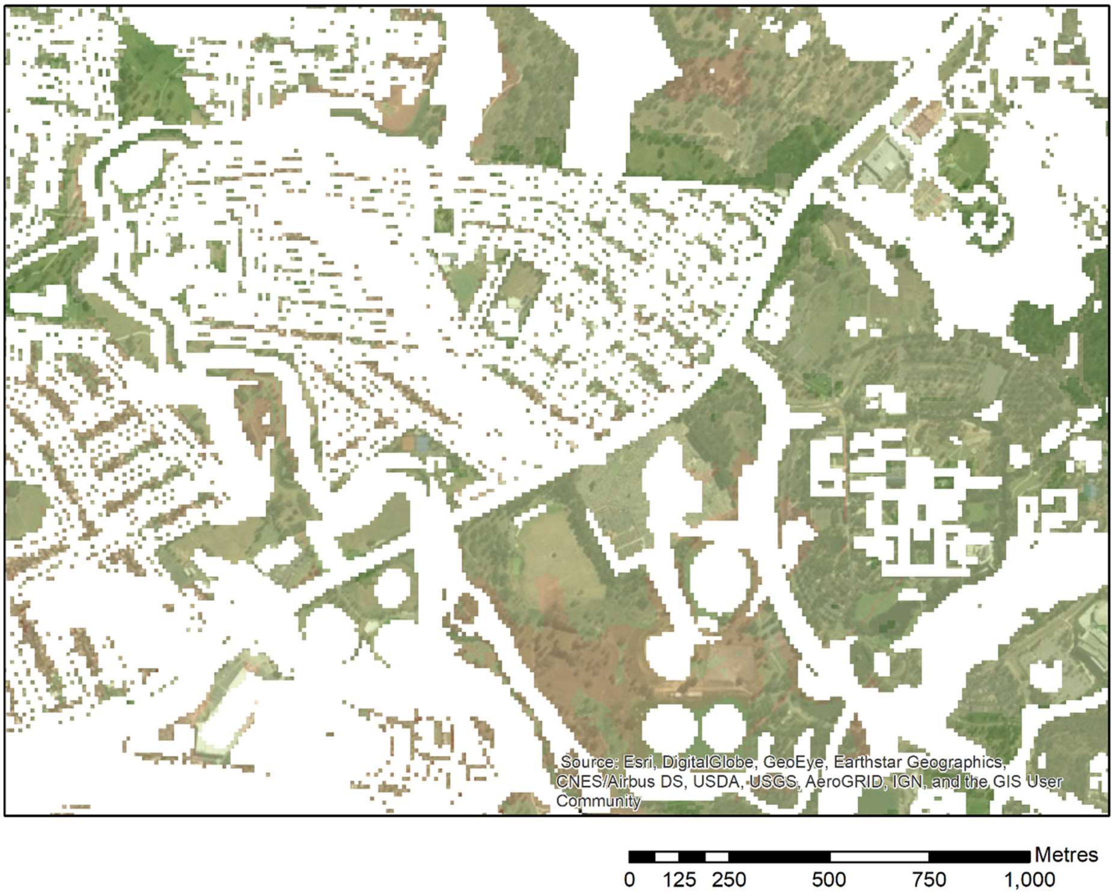

Figure 8S Close-up of satellite image overlain with suitability output for model run P-Full-Expert.

Discussion

Input data

As a MCDA tool, SSANTO is inherently data-hungry (Malczewski and Rinner 2015). The quantity and quality of input data will be directly reflected in the results. The variety of information required (biophysical, socio-demographic, urban form) is reflected in the variety of data formats and resolution. While biophysical data, such as elevation, are often represented as continuous data (raster format), socio-demographic data is always discrete and aggregated over geographic units such as census tracts. While the output resolution should always reflect the highest resolution in the data in order not to lose information, this might create a false sense of accuracy. User awareness of the quality and resolution of the data used is therefore crucial (Walker et al. 2003). Furthermore, it is important to note that overlay maps have a lower impact on map summary statistics than normal criteria, as altered suitability values only occur at the location of overlay features and not elsewhere.

Finally, streamlined value scaling is complicated by the high variety of data types and formats which, in turn, complicates the introduction of user-defined value scales programmatically.

Uncertainties of the output are related to the quantity, quality (accurateness and resolution) and how up-to-date the input data is. SSANTO only considers suitability for the criteria it has input data for, and the output should be treated as such. As many criteria are related to the existing urban context, SSANTO is mostly suited for infill developments. However, if sufficient biophysical data is combined with provisional urban form (master plans) and socio-economic context, it can also inform greenfield developments. Model-induced biases are related to value scaling, weighting and combination rules. They were discussed in detail in section 2.1.

Entropy weighting

The variation in data types poses an extra challenge for entropy weight calculations. Variation in data is naturally higher in continuous datasets. Value scaling and data manipulation related to suitability transformations have great impact on entropy weights. For example, inclusion of distance gradients (e.g. gradually decrease suitability of the criterion 'visibility' with distance to train stations) results in higher entropy weights than discrete distance boundaries. Furthermore, calculating the entropy of overlay maps, which only have a suitability impact at the location of overlay features, is problematic. For example, if all overlay features have the same negative impact on suitability (e.g. cultural heritage sites), the entropy is very high, and the weight of the criterion is near zero. Although this makes sense for most locations (i.e. where these overlay features are absent), at the locations of these features this might be a very important consideration. However, entropy weighting will greatly underestimate this criterion's importance at such locations. All these effects are reflected in the entropy weights as presented in Table 3S of the supplementary material. 'Lot size' dominates the analysis of opportunities, representing nearly a third of the total criteria weight, while 'visibility' represents almost half of total criteria weight for 'needs'.

The purpose of entropy weighting is to decrease the importance of homogeneous data, which are deemed unhelpful for location selection. It thus enhances relative suitability variations (i.e. the difference between suitability of different locations), but disregards absolute suitability (the 'real' suitability of a location). Using entropy weights therefore imposes the risk of poor decisions. This is illustrated with the following example:

consider a case study site that is fully contaminated and has steep slopes throughout but has varying levels of environmental awareness. Entropy weights for contamination and slope will be near zero, as these criteria are spatially homogeneously distributed. On the other hand, full importance will be given to environmental awareness to produce suitability outcomes. Even though the entire site is unsuitable for WSUD implementation, MCDA will show high suitability in locations where environmental awareness is high. Although entropy weighting has been applied in GIS-MCDA sporadically (e.g. Berger 2006), the risks identified above are confirmed by literature on the application of entropy weights in multi-criteria decision making (Jessop 1999). Combining user-defined weights with entropy weighting, as suggested by (Hwang and Yoon 1981), could mitigate some of these risks. This option has therefore been adopted in SSANTO.

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APPENDIX E

Introduction

This appendix contains the interview protocol and the questionnaire used for the qualitative research of Chapter 6. Please note that an Indonesian translated version of the interview protocol and questionnaire was used in Indonesia.

Interview protocol

Introductory questions

1. Could you please explain briefly what your role in the organisation is and what your responsibilities are?
2. Could you please explain how you meet your responsibilities (what do you do on a day to day basis)
3. Do you know what WSUD (Water Sensitive Urban Design) is?
4. What do you know about WSUD in Bogor?
5. Are you in any way involved in WSUD in Bogor?

Theme 1: Planning processes

6. Could you explain more about the process of urban planning in Bogor/Indonesia?
7. Could you please explain more about the process of urban planning that your organisation is involved in?
8. What could make urban planning (the process and outcomes) in Bogor better?

Theme 2: Planning Support Systems

9. Are you familiar with planning support systems such as models, spatial software and economic evaluation?
10. Do you use any tools or models in your planning work?
11. Are you familiar with: Cost-Benefit Analysis, Multi-Criteria Analysis, Life Cycle Analysis, GIS (Geo-Information Systems) such as ArcGIS, hydraulic/hydrological modelling, and integrated modelling.
12. Could you explain why you use them (if they do) or why not (if they don't)?
13. Who decides if you use tools and which tools you use?
14. Can you give me a few characteristics you like about the tools you use (if they don't use any: could you give a few characteristics you are looking for in a tool you would use?)
15. Can you give me a few characteristics you dislike about the tools you use (if they don't use any: could you give a few characteristics you do not like about tools?)
16. For the following characteristics, could you please rank them:

- Input data quality and needs
- User friendliness
- Industry convention
- Type/quality of output
- Costs
- Transparency
- Flexibility

Final questions

17. Do you have any questions or comments?
18. Is there anyone that you know you could recommend me to talk to?

Questionnaire

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Questionnaire

Spatial Planning Tool - Demo, Design and Testing

Section 1

Questions in this section relate to the potential of this tool to support current planning practices in your organisation.

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1. Would you want use this tool? Why (not) and for what purpose (if yes)? Please explain.

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2. Do you use similar processes to inform urban planning decisions as outlined in the tool demonstration? Why (not)? Please briefly explain.

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3. If you answered YES to Question 1: Would this tool make it easier for you? If you answered NO to Question 1: Do you think this process would improve your urban planning decision-making, and would you use this tool to assist? Please briefly explain.

………

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………

4. If you answered YES to Question 1: How often would you use this tool in a year?

………

5. Is there anyone else in your organisation who would use the tool? If yes, please specify (department/division, role, responsibility).

………

………

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Questionnaire

Spatial Planning Tool - Demo, Design and Testing

Section 2

Questions in this section relate to your overall opinion of the tool.

1. Please identify 3 things you like (or find useful) about the tool?

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2. Please identify 3 things you dislike (or found difficult) about the tool?

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3. On a scale of 1-7 where 1 represents 'too simplistic and therefore meaningless', and 7 represents 'too complex and therefore unusable', where would you place the tool (please circle below)?

Too simplistic			Good balance			Too complex
1	2	3	4	5	6	7

4. Do you trust that the outputs of the proposed tool are an accurate representation of reality? Please briefly explain.

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Section 3

Questions in this section focus on the user-friendliness and user interface of the tool.

1. Please provide some feedback on the user interface of the tool, as an integrated toolbar within the ArcMap environment?

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2. Considering the proposed tool, are the steps involved clear and logical to arrive at a useful outcome? Please explain briefly why (not).

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3. Is the guidance provided by pop-up explanation (hovering over button) and within pop-up windows sufficient and clear? Please briefly explain.

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4. Would you be confident to use the tool right now? If not, please briefly explain.

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Questionnaire

Spatial Planning Tool - Demo, Design and Testing

Section 4

Questions in this section focus on specific functionality aspects of the tool.

1. What is your favourite function from this tool and why?

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2. If you could <u>remove</u> one aspect of the tool, what would it be? Please briefly explain.

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3. If you could <u>add</u> one function to the tool, what would it be? Please briefly explain.

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4a. Are the different outputs generated by the tool useful?
4b. How would you use them? Please briefly explain.

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Section 5
Final section - general questions.

1. What do you consider the greatest strength of the tool?

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2. What do you consider the greatest weakness of the tool?

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3. On a scale of 1-7, how likely are you to use this tool if it was:

- *Free (open source):………….*
- *Cheap (comparable to individual Microsoft WORD licence): ………….*
- *Expensive (comparable to full ESRI ArcGIS license):………….*
- *Not (yet) used by any urban planner: ………….*
- *Only used by a small, select number of urban planners:………….*
- *Commonly used by most urban planners in your area:………*

Definitely not			Possibly			Definitely
1	2	3	4	5	6	7

4. Please provide any additional comments and suggestions below.

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