ISBN 978-82-326-7148-9 (printed ver.)
ISBN 978-82-326-7147-2 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (electronic ver.)

NTNU
Norwegian University of Science and Technology

Doctoral thesis

Vincent Pons

Doctoral theses at NTNU, 2023:224

NTNU
Norwegian University of Science and Technology
Thesis for the degree of Philosophiae Doctor
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU

Doctoral theses at NTNU, 2023:224

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Doctoral theses at NTNU, 2023:224

PRINTED IN NORWAY
NO - 1598

NORDIC SWAN ECOLABEL
Printed matter
2041 0731

Printed by Skipnes Kommunikasjon AS

The Future of Green Infrastructure:
From climate data to informed hydrological performance

Pons Vincent

Supervisors:

Prof. Tone Merete Muthanna (NTNU)

Prof. Jean-Luc Bertrand-Krajewski (INSA Lyon)

Dr.Ing. Edvard Sivertsen (SINTEF)

Assessment Committee:

Prof. Alain Mailhot, INRS-Eau, Quebec, Canada

Asc. Prof. Adriana Bruggeman, The Cyprus institute

Prof. Marina Bergen Jensen, København Universitet, Denmark

Asc. Prof. Thomas Meyn, NTNU (Administrator)

Thesis for the Degree of Philosophae Doctor

Realized in Cotutelle between:

Norwegian University of Science and Technology (NTNU),

INSA Lyon, member of the University of Lyon.

NTNU
Faculty of Engineering
Department of Civil
and Environmental Engineering

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

Abstract

The 21st century presents numerous challenges to urban stormwater management, including the impacts of changes in both climate and city morphology. These challenges necessitate rethinking the stormwater management paradigm, particularly in the context of existing and ageing infrastructure. This thesis deals with green infrastructures (GI) considered as decentralized multifunctional infrastructures that utilize evapotranspiration and/or horizontal and vertical infiltration to achieve a hydrological function.

This study evaluates the potential of GI to manage day-to-day rainfall events, attenuate major events, and contribute to the management of extreme events in the context of climate change adaptation. It also aims to provide a framework and tools to realign current GI modelling and design methods with the principles of robust decision-making.

The thesis investigates how to use climate and hydrological present and future data with hydrological GI models to extract relevant information for decision-making under deep uncertainty. The results provide guidelines for i) designing experiments to calibrate reliable hydrological models and ii) using available climate projections together with weather generators for GI performance evaluation. The proposed framework HIDES demonstrates how future downscaled time series can be used to evaluate annual retention distribution and frequency of exceedance, while sampling extreme events allows for estimating both a probability of failure and an indication of the behaviour of GI under failure.

The thesis suggests rethinking the methods for implementing GI at the city scale. The study shows that system-based design outperforms site-scale design through modelling at the roof scale of a neighbourhood, and that lumping GI models at a neighbourhood scale may neglect interactions and fail to estimate performance. The thesis highlights the need to couple GI to achieve challenges in stormwater management.

Résumé

Le 21e siècle présente de nombreux défis en matière de gestion des eaux pluviales urbaines, notamment en ce qui concerne l'impact du changement climatique et de l'évolution des morphologies des villes. Ces défis nécessitent de repenser le paradigme actuel de gestion des eaux pluviales, en particulier dans un contexte d'infrastructures vieillissantes. Les objets d'étude de cette thèse sont les Techniques Alternatives (TA) de gestion eaux pluviales présentées ici comme des infrastructures multifonctionnelles décentralisées. Elles remplissent leur fonction hydrologique au travers de procédés d'évapotranspiration et/ou l'infiltration horizontale et verticale.

Cette étude évalue le potentiel des TA pour gérer les précipitations modérées, atténuer les événements majeurs et contribuer à la gestion des événements extrêmes dans un contexte d'adaptation au changement climatique. Elle vise également à fournir un cadre et des outils pour réaligner les méthodes actuelles de modélisation et de dimensionnement des TA sur les principes de prise de décision robuste.

Cette étude évalue le potentiel d'utilisation de séries climatiques et hydrologiques présentes et futures avec les modèles hydrologiques TA pour extraire des informations pertinentes pour une prise de décision sous incertitude profonde. Les résultats fournissent des lignes directrices pour i) concevoir des stratégies d'expérimentation pour caler des modèles hydrologiques fiables et ii) utiliser les projections climatiques disponibles avec des modèles de génération de séries de pluies synthétiques pour l'évaluation de la performance des TA. Le cadre proposé HIDES démontre comment des séries synthétiques de précipitations futures peuvent être utilisées pour évaluer les distributions de probabilité de fraction de rétention annuelle et la fréquence de dépassement de débits de sortie. La génération d'événements extrêmes synthétiques permet d'estimer à la fois la probabilité de défaillance et de prédire le comportement de TA en cas de défaillance.

À travers la modélisation à l'échelle de la toiture d'un lotissement, il est montré que négliger les interactions entre TA peut entrainer des erreurs importantes dans l'estimation des performances. Il est également montré que prendre en compte les interactions entre les TA lors du dimensionnement peut mener à une amélioration des performances. La thèse suggère alors qu'un dimensionnement à l'échelle du système est plus pertinente qu'une conception à l'échelle du site, et souligne la nécessité de coupler les TA pour relever les défis de la gestion des eaux pluviales.

Preface

This PhD has been completed in a cotutelle between the Norwegian University of Science and Technology (NTNU, Norway) and the National Institute of Applied Science of Lyon (INSA Lyon, France). At NTNU, work has been conducted in the water and wastewater group (va) within the Department of Civil and Environmental Engineering (ibm) of the faculty of engineering (iv). At INSA, part of the University of Lyon UdL, the work has been conducted at the DEEP research group (French acronym for "waste water environment and pollution"), within the frame of the MEGA doctoral school.

The PhD is written as part of the research project Klima 2050, a centre for research-based innovation (SFI). It was funded by the Research Council of Norway and its consortium partners (grant no. 237859/030). Klima 2050 aims at reducing the societal risks associated with climate change, increased precipitation and flood water exposure within the build environment (https://www.klima2050.no/, last access: 06 March 2023). This research was partly performed within the framework of the OTHU (*Observatoire de Terrain en Hydrologie Urbaine* - Field Observatory for Urban Water Management – https://www.graie.org/othu/index.htm, last access: 06 March 2023) and realized within the Graduate School H2O'Lyon (ANR-17-EURE-0018) and Université de Lyon (UdL) as part of the program "Investissement d'Avenir" and by Agence Nationale de la Recherche (ANR).

This work is the result of a three-and-half-year PhD program with 25% of teaching duty and 75% of research. It was supervised by Professor Tone Merete Muthanna (NTNU), Professor Jean-Luc Bertrand Krajewski (INSA), and Dr.ing. Edvard Sivertsen, senior scientist at SINTEF.

In accordance with the requirements of the cotutelle agreement, the current PhD thesis consists of a monograph. The general practice at NTNU is to write a collection of papers which consists of a main text from 20 to 50 pages presenting the topic's main methods, results, discussions, conclusions and making the link between papers. The papers are then given in an appendix. In the frame of the cotutelle agreement between INSA Lyon and NTNU, it was decided to prioritize a monograph. It aims at increasing the readability and explaining the choices made during the PhD by providing a storyline linking the different papers and publications consistently. To some extent, the current PhD thesis can be considered as a hybrid version between a monograph and a collection of papers. Indeed, most of the chapters are based on published papers. Some chapters are mostly based on a published paper with minor modifications of formattings and language or figures. Some other chapters include a part of a published chapter, with adjustments, and finally, some chapters are not based on papers, but may include results taken from publication, poster, or communication. In each chapter, the first section **"Foreword"** provides the necessary information about the sources of the text.

Acknowledgement

I am writing those acknowledgements a few weeks before the defence. I must admit, this is not the easiest section of the thesis to write. How to ensure I do not forget anybody? I even considered creating a graph, since so many people belong to several categories of people I want to thank. So, before going into details, I would like to thank all of those who somehow contributed to this thesis, no matter if their name is specifically written in this section- that I will try to not make too long. If you have a doubt, if you are or not included, just consider that you are included. You can also ask me directly, and I will tell you "Yes, of course you are included".

I would like to use this section to answer people who told me when I started my PhD that a PhD thesis was an individual work. It cannot be more wrong, at least in my case, because research is built on previous knowledge and the PhD path is an opportunity to exchange with many people, get different standpoints and criticism. Therefore, I would like to thank all of those who made this work a shared endeavour, you helped me to improve it.

I would first like to thank those who accepted to evaluate my work for my graduation: my evaluation committee. Thank you Asc. Pr. Adriana Bruggeman, Pr. Alain Mailhot and Pr. Marina Bergen Jensen. Thank you also, Asc. Pr. Thomas Meyn to have accepted to be the administrator for my defence, despite the confusion due to the cotutelle.

At the same time, I would like to thank all the anonymous reviewers who contributed by pointing out issues and weaknesses in submitted articles and gave me the opportunity to improve my work. It is thanks to your comments that I had the opportunity to improve my work when all my co-author and myself were too close to the study to see what should be improved.

I would also like to thank NTNU and INSA Lyon for this opportunity to do my thesis in cotutelle. I often to say that the biggest challenge in my PhD has been administrative. I have to admit it has sometimes been frustrating, but I definitely learnt from the experience.

I would like to thank also all my colleagues both at Deep INSA and in Vassbygget at NTNU, it was a wonderful opportunity to meet so many people, despite challenges linked to covid, short stays, etc. I cannot list everybody without risking forgetting people, so instead I prefer to keep it general. I would like also to thank all my co-authors, and all the people and master students I worked with at any point of the thesis.

I would like now to go more in depth for my acknowledgement. My journey on the PhD started one evening at the end of a lecture when I was looking for a research internship. I went to see you, Jean-Luc and you just asked me where I wanted to go. When I said Nordic countries, you redirected me to Tone, who was going to do a sabbatical year at Deep. Tone and Vladimir, you accepted to take me as an internship student despite not knowing me, and Edvard and Gema you took part in my supervision. At the end of my internship, I told you, Tone, that I wanted to do a PhD, and you gave me this opportunity. Jean-Luc, you accepted to supervise me, and Edvard also. I learnt a lot those last years as your PhD student, and you reminded me that sometimes a simple discussion can change many things.

I wish to thank the people who taught me more about python (especially David, Robert, and Santiago), and also all the people whom I tried to help with python.

I have many people I consider as friends I would like to thank, and listing them would be long. Some know me from middle school, some, from high school, some from prépa, and some from INSA. Among those I would like to mention those with whom I especially discussed research and who decided to take the same path, Loic, Nicolas, Hugo, Donatien, and Pépin (even though you live in an apple).

I would like to thank the TT team of Vassbygget. I strongly believe that our commitment to playing every day contributes to our PhD completion. Again, I can't name everybody who was once part of the team. But I will mention Daniel from the basement, your picture is still under the table, and The Snake who will soon be part of the mythology of the basement.

I would like to thank all my office mates (I had many, despite being mostly in 2-people offices). Thank you Yinghong, Shamsuddin, Elhadi, Noémie and Spyros. And some colleagues with whom I had long discussions about various topics that may have influenced me. Non exhaustively: Thea, Violeta, Damien, Nitesh, Maren, Bulat, and Jo.

I would like to thank the large team of roommates, from the long list of flats where I went to live in the last years. I have not always been very active, often at work, but what I had with most of you were those long discussions about life and our various paths.

I would also like to thank the Vortex, it has become a tradition, apparently. In the same way, I would like to thank the various communities I took part in and especially the long discussions with Slo and Rey. I may have not always been very active (especially in the last months), but you have been part of my daily life during some periods.

I would also like to express a special thanks to Bergstua. It is wonderful that such an organic place exists out of time. Or maybe it does not exist out of time, but right in time, in the present with all the intensity it can carry. In the same line, I would like to thank the people with whom I shared the passion for hiking to cabins and gapahuks.

Finally, I would like to thank the BDLN extended universe (yes, extended universe because we have to admit that our group changed), you were there at the beginning, we are all taking different paths, but from time to time we manage to meet again. I hope we will continue to make the effort to meet despite the distance.

Contents

Abbreviation

AET

Actual EvapoTranspiration.

ANN

Artifical Neural Network.

ANR

Agence Nationale de la Recherche - French national agency for research.

AR

Assessment Report from the IPCC. It is followed by a number (5 or 6 in this thesis) specifying the number of the report.

BMP

Best Management Practice.

CF

Climate Factor.

CMIP

Coupled Model Intercomparison Project.

CORDEX

Coordinated Regional Climate Downscaling Experiment.

CS

continuous simulation.

DEEP

Déchets Eaux Environment Pollution - Waste Water Environment and Pollution, research group.

D-Green roof

Detention-based extensive green roof located in Høvringen.

DIKW

Data Information Knowledge Wisdom hierarchy.

DREAM

DiFferential Evolution Adaptative Metropolis - It is a specific Markov-Chain Monte Carlo algorithm.

E-Green roof

Extensive green roof located in Høvringen.

ESM

Earth-System Model.

ET

EvapoTranspiration.

GCM

It may refer to General Circulation Model or Global Climate Model which is a framework that may include a General Circulation Model. In the thesis unless it is precised, it refers to Global Climate Model.

GHG

Green House Gases.

GI

Green Infrastructure, Low Impact Development (LID), Source Control Measures or Nature-Based Solution refer in this thesis to infrastructure to manage stormwater that are based on infiltration or evapotranspiration.

H2O'Lyon

School of integrated watershed sciences in Lyon France.

HEC-RAS

Fully distributed hydraulic model for river flow.

HIDES

Highly Informative Design Evaluation Strategy.

Hydrus

Software suite for unsaturated flow of water and pollutant in porous media.

IAM

Infrastructure Asset Management.

ibm

Institutt for bygg- og miljøteknikk - Department of civil and environmental engineering.

IDF

Intensity Duration Frequency curve, they are related to Depth Duration Frequency curves (DDF) which are their counterpart with Depth dependency instead of intensity.

INSA Lyon

Institut national des sciences appliquées de Lyon - National Institute of Applied Sciences of Lyon.

iv

Fakultet for ingeniørvitenskap - Faculty of Engineering.

KGE

Kling Gupta Efficiency.

Klima 2050

Research project aiming at reducing the societal risks associated with climate change, increased precipitation and flood water exposure within the build environment.

LES

Local Event Sampling.

LID

Low Impact Development.

MC

Monte Carlo.

MCMC

Markov-Chain Monte Carlo.

MEGA

Mécanique, Énergétique, Génie civil, Acoustique - Doctoral school for Mecanic, Enegetic, Civil Engineering and Acoustic studies.

MET Norway

Meteorologisk institutt - Norwegian Meteorological Institute.

MIT

Minimum Inter-event Time - minimum duration used to split between two events in a rainfall time series.

ML

Machine Learning.

MRC

Multiplicative Random Cascade model for downscaling.

$\mathrm{MRC_S}$

Multiplicative Random Cascade with Scale dependence presented in chapter 4.

$\mathrm{MRC_{S-SEP}}$

Multiplicative Random Cascade with Scale dependence and Stochastic Element Permutation presented in chapter 4.

$\mathrm{MRC_{SI}}$

Multiplicative Random Cascade with Scale and Depth dependences presented in chapter 4.

$\mathrm{MRC_{SI-SEP}}$

Multiplicative Random Cascade with Scale dependence and Stochastic Element Permutation presented in chapter 4.

$\mathrm{MRC_{SIT}}$

Multiplicative Random Cascade with Scale Depth and Temperature dependence presented in chapter 4.

$\mathrm{MRC_{SIT-SEP}}$

Multiplicative Random Cascade with Scale Depth and Temperature dependence and Stochastic Element Permutation presented in chapter 4.

NBS

Nature-Based Solution.

NSE

Nash-Sutcliffe efficiency.

NTNU

Norges Teknisk-Naturvitenskapelige Universitet - Norwegian University of Science and Technology.

NVE

Norges Vassdrags- og Energidirektorat - Norwegian Water Resources and Energy Directorate.

OTHU

Observatoire de Terrain en Hydrologie Urbaine - Field Observatory for Urban Water Management.

PAWN

Density-based global sensitivity analysis method.

PBIAS

Percentage bias.

PET

Potential EvapoTranspiration.

RCM

Regional Climate Model.

RCP

Representative Concentration Pathways.

RDM

Robust Decision Making.

RP

Return period.

RTC

Real Time Control.

SA

Sensitivity Analysis. If not mentioned it refers to a Global Sensitivity analysis (GSA), and not a Local Sensitivity Analysis (LSA).

SCM

Source Control Measures.

SFI

Sentre for forskningsdrevet innovasjon - centre for research-based innovation.

SINTEF

Stiftelsen for industriell og teknisk forskning - Independent research organization.

SMEF

Soil Moisture Evaluation Function.

SSP

Shared Socioeconomic Pathways.

StU

Storage Unit. It consists of a retention basin with a discharge limiter.

SUDS

Sustainable Urban Drainage System.

SWMM

StormWater Management Model. Semi distributed coupled conceptual hydrological nd hydraulic model for stormwater management.

3PA

Stormwater three point approach.

3SA

Stormwater three step approach.

UA

Uncertainty Analysis.

UdL

Université de Lyon - University of Lyon.

URBIS

Software for simulation and decision support in urban hydrology.

va

Vann- og avløpsteknikk - Water and Wastewater Engineering, research group.

VM

Variational method.

General introduction

All we have to decide is what to do with the time that is given us.

Gandalf,
J.R.R. Tolkien,
The Lord of the Rings

Contents

Scientific context

The challenges in stormwater management in the 21^{st} century are numerous and in the context of this thesis can be listed as urbanization, climate change, limited resources, management of existing infrastructures, handling a paradigm shift in the stormwater management philosophy. Indeed, in the last decades a paradigm shift was operated in European cities. The historical system consisted in a long-lasting centralized buried system of infrastructure aiming at evacuation of the water from cities as fast as possible. The more recent approach consists in building a decentralized system in which the water also appears on the surface and which aims to be more resilient. The goal is i) handling the maximum amount of water the closest to the source as possible, ii) managing the remaining fraction with existing grey-infrastructure, and iii) having a risk prioritization approach to handle the most extreme events. While the topic of green infrastructure (GI) becomes trendy for its multiple benefits, it is important to wonder if it can help us to achieve the tasks we want to design it for. The current thesis is interested in developing methods to evaluate the future performance of green infrastructures and to which extent they can be relevant for hydrological purposes.

One of the challenges that stormwater utilities have to cope with is increasing urbanization. Increasing urbanization, do not consist only in a change of land-uses but also their consequences on historical centres, for instance. In many European cities, the dense city centres had an organic urban growth (Choay, 2014). For that reason, urbanization on neighbouring catchments may have influence in those centres where it is complex and costly to install new infrastructures.

Climate change can be interpreted as a shift in weather statistics. From that point of view, adaptation consists in adjusting the service delivered by stormwater infrastructures to that shift. However, that explanation is too simplistic since the current stormwater management design practice is not adequate (Alfieri *et al.*, 2008). A simple shift in design is not sufficient to solve the problem linked to climate change. Moreover, the morphology of cities influences our habits, which on a larger scale can be understood as a feedback loop between human society and the climate or local climate (Næss, 2016). For instance, concrete cover in cities leads to heat island effect and may also influence the weather patterns, especially convective rains (Bornstein and Lin, 2000; Hettiarachchi *et al.*, 2018). It means that, to some extent, there is a two-way relationship between climate or local climate and human society.

The objects of the current thesis are green infrastructures. This terminology has many equivalents in different regions of the world, and its definition evolved with time (Fletcher *et al.*, 2015; Matsler *et al.*, 2021). In this thesis, it refers to multifunctional infrastructures, which in particular have a hydrological function. It consists in: i) managing day-to-day rains locally at the closest to the source of runoff, ii) attenuating major rains to some extent, and iii) contributing to the management of extreme rains. They are inherently a decentralized solution, which aims at mimicking the natural water cycle. In some context they can refer to large infrastructures, but in this thesis they refer to small infrastructures such as green roofs, rain gardens, bioretention cells, infiltration trenches, permeable pavements, etc. In order to restore the natural water cycle, they rely on "natural" processes, even though those processes are engineered in order to satisfy a predefined level of service. Those processes are mainly: i) evapotranspiration that helps to remove permanently a volume of water discharged in the sewer system, ii) vertical infiltration of water directly to the soil and which is also a permanent water removal, and iii) surface and subsurface flow leading to attenuation of precipitation in order to reduce the peak discharge in the downstream sewer system.

In that context, the current thesis explores several aspects to investigate the potential contribution of green infrastructures to the stormwater management philosophy. The first one is related to performance indicators and how to extract the relevant information from model outputs. It also brings the question of "On which indicators should we advise decision-makers to base their decision?". The second dimension in linked to uncertainties. Indeed, adapting stormwater management to climate change involves uncertainties at various levels. It is linked to several levels of deep uncertainty, which can be due to limited knowledge (epistemic uncertainty) or inherent to the processes studied (statistical uncertainty). In the modelling context of stormwater management and climate change adaptation, the climate inputs come together with a cascade of uncertainty. Indeed, global climate models are based on uncertain data, and are yet to be improved. Climate projections are based on socio-economic scenario, which consists in a qualitative level of uncertainty. Global projections are used in regional climate models with their own structural uncertainties. Those results are used with bias correction and statistical downscaling of regional models to bring them to kilometre space scale and daily timescale in order to better represent local climate. Those climate data, resulting from a chained modelling strategy, are the input used for this PhD thesis. In this PhD thesis a subsequent chained modelling strategy is applied which by nature increase further the cascading uncertainty. It brings therefore the question of "In the context of uncertainty related to that thesis, how to convey the information about uncertainty in order to best guide decision-making?". Finally, the question of scales is central in the thesis. Indeed, while the first parts of this thesis are mainly dedicated to site scale green infrastructures, decision-makers have to act on a strategical level at city scale. Therefore, the knowledge at site scale has to be useful and relevant when integrated in a timeline and upscaled to catchment or city scale.

The main research objectives are to provide knowledge and methods to evaluate the potential of green infrastructures for climate change adaptation, in particular:

i. Which climate and hydrologic data are available, and which data should be targeted to assess the future performance of green infrastructure?

ii. How to use available climate data and how to bring them to the necessary resolution for green infrastructure hydrological models?

iii. How to use both climate data and GI models, and how to extract relevant performance indicators?

iv. How to upscale this knowledge from the building to the neighbourhood or small catchment scale?

Outline of the thesis

Figure i presents the scope of the thesis and displays the relationship with climate model and decision-making. The outline of the thesis is divided in 3 work packages B1, B2 and B3. The work package B1 addresses mainly the objectives *i* and *ii*. The work package B2 addresses the objective *iii*. The work package B3 addresses the objective *iv*.

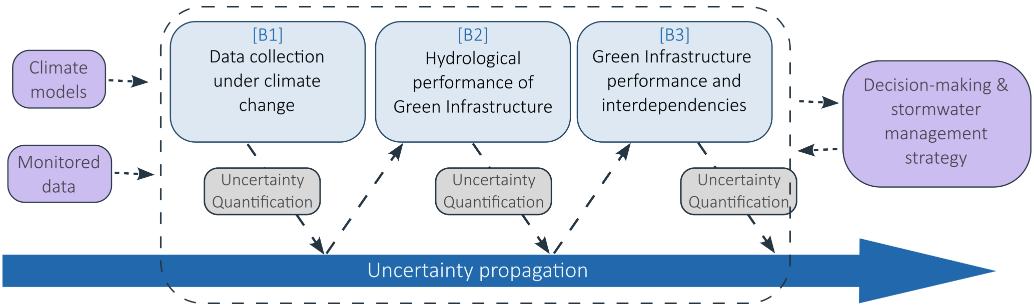

Figure i: Scope of the PhD thesis, in the dotted region, presenting the 3 main work packages.

The thesis is organized as follows. Firstly, the main concepts and notions relevant to that thesis are introduced in Chapter 1. Several notions related to the use of numerical models are introduced. In particular, it includes a section about model calibration and testing and a section about uncertainty management. Then the concept of scale is detailed as it has a central place in the current thesis. A section about climate change adaptation introduces key concepts and a review of climate models and information and how they are used to help with climate change mitigation. Finally, green infrastructures, are described in terms of function, modelling practice and performance.

Chapter 2 focus on the question of relevant data for climate change adaptation. In particular, it consists in using artificial rain to collect data in order to evaluate the future hydrological performance of green roofs. The rainfall simulator allowed to stress the roof under extreme conditions. Those conditions have not been naturally observed of those roofs, but may occur due to climate change. Based on those collected hydrological data, a conceptual model for green roofs is developed. In particular, the model is designed to give an accurate flow estimate for both low and high flow. The model is used in most of the later chapters.

Chapter 3 is dedicated to performance indicators. In particular, it questions the influence of limited data and its influence on performance. It also discusses how to account for natural variability of climate, and how to propagate it to performance indicators. More generally, it addresses the question of which information should be brought to decision-making based on simulation outputs.

Chapter 4 present an approach to produce high-temporal resolution projected time-series of precipitations coupled with green roof models. In particular, it consists in downscaling model development, namely Multiplicative Random Cascade. The hydrological performance of the green roofs based on monitored minutes-resolution precipitation and on the minutes-resolution downscaled data for the current climate are compared. A good agreement between both estimates indicates that the downscaling models produce acceptable inputs. The downscaling models are then used with future climate projections in order to forecast the future performance of green roofs.

Chapter 5 proposes a framework to assess the hydrological performance of green infrastructure for several objectives and accounting for climate change based on the methods developed in the previous chapters. From a stormwater management perspective, the objective of that framework is to realign the practices with the principles of robust decision-making. It aims at quantifying a set of hydrological performances for each GI (the retention performance, the detention performance for common events and the detention performance for extreme events).

The last chapter, Chapter 6, aims at bridging the gap between unit scale GI models and catchment to city scale GI models. More specifically, it aims at using the previously developed framework to assess the influence of GI interdependencies on the global performance at catchment or city scale. It investigates if at an intermediate scale between unit and catchment, the GI spatial combination has an influence on the global performance.

Publications, communications, and posters

This section presents the different publications, communications, and posters produced during the PhD period. For each publication, it is indicated how it is used or not in the chapters of this thesis. Their contribution to the current thesis is detailed in the **"Foreword"** section of each chapter. For the paper directly used in the current thesis, details of the contribution are specified in Appendix F. For transparency reason, details of contribution are specified for papers in which I am not first author.

Publications in peer-reviewed international journals

Paper A

The following paper is used as the basis for Chapter 2. It is a direct contribution to the current PhD thesis. As specified in Appendix F, V. Hamouz and myself had similar contribution to the paper which consisted in conceptualization, methodology, experiments, data analysis, visualization, writing of the original draft, and review process.

Hamouz, V., Pons, V., Sivertsen, E., Raspati, G., Bertrand-Krajewski, J.-L., and Muthanna, T. M. 2020. Detention-based green roofs for stormwater management under extreme precipitation due to climate change. *Blue-Green Systems*, 2(1):250-266. doi: 10.2166/bgs.2020.101.

Paper B

The following paper is not used in the current PhD thesis. My contribution to this paper is in methodology conceptualization (optimization and data analysis), and discussion.

Abdalla, E. M. H., Pons, V., Stovin, V., De-Ville, S., Fassman-Beck, E., Alfredsen, K., and Muthanna, T. M. 2021. Evaluating different machine learning methods to simulate runoff from extensive green roofs. *Hydrology and Earth System Sciences*, 25(11):5917–5935, doi: 10.5194/hess-25-5917-2021

Paper C

The following publication was not used as the basis of any chapter. However, its data and conclusions were used to introduce the Chapter 6. It is an indirect contribution to the current PhD thesis. My contribution in this paper consisted in supervision; contribution to conceptualization, result, and discussion; and review process.

Le Floch, N., Pons, V., Abdalla, E. M. H., Alfredsen, K. 2022. Catchment scale effects of low impact development implementation scenarios at different urbanization densities. *Journal of Hydrology*, 612:128178.
doi: 10.1016/j.jhydrol.2022.128178

Paper D

The preprint of the following paper is used as the basis for Chapter 5. It is a direct contribution in the current PhD thesis. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Muthanna, T. M., Sivertsen, E., and Bertrand-Krajewski, J.-L. 2022. Revising green roof design methods with downscaling model of rainfall time series. *Water Science and Technology*, 85(5): 1363-1371.
doi: 10.2166/wst.2022.023

Paper E

The following paper is used for the basis of Chapter 4. It is a direct contribution to the current PhD thesis. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Benestad, R., Sivertsen, E., Muthanna, T. M., and Bertrand-Krajewski, J.-L. 2022. Forecasting green roof detention performance by temporal downscaling of precipitation time-series projections. *Hydrology and Earth System Sciences*, 26(11):2855-2874. doi: 10.5194/hess-26-2855-2022..

Paper F

The following paper was used as the basis of a section of Chapter 1. It is a direct contribution to the current PhD thesis. My contribution, consisted in conceptualization, methodology,data collection and curation, visualization, writing, and review process.

Pons, V., Abdalla, E. M. H., Tscheikner-Gralt, F., Alfredsen, K., Sivertsen E., Muthanna T. M. 2022. Practice makes the model: a systematic review of green infrastructure modelling practice. *Water Research*, 236:119958. doi: 10.1016/j.watres.2023.119958

Paper G

The following paper is not used in thhe current PhD thesis. Contribution to this paper consisted in supervision of the python code implementation, figure conceptualization, python code cleaning and review of the first draft.

Skrede T. I., Tørustad V., Pons, V., Alfredsen, K., Muthanna T. M. 2022. From flood paths to floodways, an efficient method to map, identify and evaluate suitable floodways: a case study from Trondheim, Norway *[Submitted to Journal of Environmental Management]*

Communications in international and national conferences seminars and workshop

Communication A

The following communication wasn't used directly in this thesis. As based on GI combination it can be considered as related to Chapter 6. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Muthanna, T. M., Sivertsen, E., and Bertrand-Krajewski, J.-L. 2020. A tool to forecast future performance of green infrastructure. *ICUD2020 - young author webinar series*. Melbourne - Online, Australia. https://hal.science/hal-03166619/file/ACT-I 126 Pons et al. 2020 ICUD Melbourne.pdf

Communication B

The following communication correspond to an intermediate state of advancement related to Paper E. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., and Bertrand-Krajewski, J.-L. 2020 Des séries de pluies synthétiques pour évaluer les futures performances hydrologiques de toitures végétalisées sous scénario de changement climatique RCP8.5. *9ème JDHU - Journées Doctorales en Hydrologie Urbaine*. Strasbourg - online, France.
https://hal.science/hal-03386474/document

Communication C

The following communication and the Paper D are similar. The paper is the publication resulting the communication in the Poul Harremoes special session of ICUD 2021. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Muthanna, T. M., Sivertsen, E., and Bertrand-Krajewski, J.-L. 2021. Revising green roof design methods with downscaling model of rainfall time series. *15th ICUD - International Conference on Urban Drainage*. Melbourne - hybrid (physical online), Australia. https://hal.science/hal-03432036/document

Communication D

This study was presented for the application to the EJSW. It stems ideas that led to Chapter 6. It is an indirect contribution to the current PhD thesis. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Muthanna, T. M. 2021. Community-maintained Green Infrastructure by means of water reuse and monitoring. *25th EJSW – European Junior Scien-*

tists Workshop on "Monitoring Urban Drainage Systems and Rivers", St-Maurice-en-Valgaudemar, France.

Communication E

The results of this communication are used indirectly in Chapter 5. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Sivertsen, E., Muthanna, T. M., and Bertrand-Krajewski, J.-L. 2022. How many extreme events to estimate the density of performance of green infrastructures? *NHC2022 - Nordic Hydrological Conference*, Tallinn, Estonia

Communication F

This communication is considered as a draft for Chapter 6. It is an indirect contribution to the current PhD thesis. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Muthanna, T. M., and Bertrand-Krajewski, J.-L. 2022. Can we sum the performance of green infrastructures? The potential of system-based planning. *WWCE - IWA World Water Congress and Exhibition*, Copenhagen, Denmark

Communication G

This communication is based on the results of Chapter 5. The workshop, with contributors from climate sciences (downscalers) and climate change adaptation (using downscaling results), contributed to the structure of the thesis by highlighting the need to bridge further the gap between climate science and climate change adaptation (and especially green infrastructure modelling in the context of this thesis). My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V. 2022. Using climate information for assessing green roofs. ConCord Oslo - Consolidating CORDEX workshop, Olso, Norway

Communication H

This communication contributed to shape the results of Paper C and Paper D and their link to unit and catchment scales. It contributes indirectly to Chapter 3 and Chapter 6. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Muthanna, T. M., and Bertrand-Krajewski, J.-L. 2022. Comment formuler les objectifs de performances hydrologiques de techniques alternatives de gestion des eaux pluviales ? *10ème JDHU - Journées Doctorales en Hydrologie Urbaine*. Lyon, France.

Posters in international and national conferences seminars and workshop

Poster A

This poster is not used in this thesis. Contributions are similar to the one specified for Paper B.

Abdalla, E. M. H., Pons, E., Muthanna, T. M., and Alfredsen, K. 2020. Modelling runoff from green roofs using machine learning. *The 2nd NOAA Workshop on Leveraging AI in Environmental Sciences*. online, USA.

Poster B

This poster helped in the dissemination of advancement in the URBIS software devoted to long term simulation of GI. It also help to enlarge the scope of the PhD to GI beyond solely green roofs that are often used. My contribution consisted in conceptualization, methodology, programming, visualization, and writing.

Pons, V., Sandoval, S., Muthanna, T. M., and Bertrand-Krajewski, J.-L. 2022. Factor prioritization for multi objectives Green Infrastructure design. *UDM 2022-12th Urban Drainage Modelling international conference*. Costa Mesa - hybrid (physical online), USA. https://hal.science/hal-03543953/document

Poster C

This poster helped in the dissemination of advancement in the URBIS software devoted to long term simulation of GI. It also help to enlarge the scope of the PhD to GI beyond solely green roofs that are often used. My contribution consisted in conceptualization, methodology, programming and programming supervision, visualization, and writing.

Pons, V.,Wijesuriya, K., Sandoval, S., Muthanna, T. M., and Bertrand-Krajewski, J.-L. 2022. Modelling stormwater reuse scenarios for green roof irrigation using URBIS. *SIWW 2022 - Singapore International Water Week 2022* Singapore, Singapore. https://hal.science/hal-03646696/document

1

Urban stormwater management, green infrastructures and climate change adaptation

So it begins...

Theoden,
J.R.R. Tolkien,
The Lord of the Rings

Foreword

The topic of the current thesis is multidisciplinary (linked to urban hydrology, climate science, statistics, uncertainty, and decision-making). The main object of the thesis, green infrastructures (GIs), are considered as multipurpose and cover many dimensions and topics (urban comfort, social aspects, environment, risk management, etc.). For that reason, if was decided to introduce a large number of notions briefly in order to set a holistic scope for the later chapter. Progressively along this chapter, the explanations funnel down to the main topic of interest.

The current chapter is divided in 4 sections. First, definitions and concepts necessary to read this thesis are introduced. Then, introductory knowledge linked to climate models is presented because climate data are the main input to the thesis. The main object of the current thesis is then more largely discussed. Finally, the practice of modelling green infrastructure, directly based on some sections of Paper F is presented.

The right grey bar in the margin is used to inform the reader that the work is similar to one of the direct contributions to the thesis. Similar means it was reformatted to fit to the chapter structure. Minor modifications of the text are done in order to fit to the structure of the current PhD thesis. When a major modification is necessary, the section or paragraph is not quoted.

Contents

1.1 Definitions, concepts and terminology

1.1.1 Types of models

In environmental science, a model is a mathematical representation of processes. Given some input data called *predictor*, models generate specific output data called *predictand* aiming to represent the real processes. In the field of urban hydrology and green infrastructures (GIs), the inputs are climate data such as precipitation or temperature time-series, and parameters characterizing the catchment, the soil, or the vegetation. Empirical parameters without a physical interpretation can are also considered as inputs (e.g., in data-driven models). In the current thesis, the difference is made between the following notions. A *model* consists formally of an equation or a set of equations representing a process or a set of processes. A *tool* or *software* is the code in which the model is encoded. In the context of that PhD, models can be classified along three main dimensions:

- the level of *conceptualization*: a model can be a *data-driven* model (black-box), where the parameters have not necessarily a physical meaning. It is the case in particular of machine-learning (ML) models, which consist in general of flexible mathematical structures or methods, independent of the processes to be modelled, that are fitted to observed data. Regression-based methods or more advanced artificial neural networks (ANN) are considered as data-driven models. The opposite of such a model is a *physically-based* model (white box), with meaningful and measurable parameters, often taking the form of differential equations that describe a system's behaviour process by process. Penman-Monteith equation (Monteith, 1965) or Richard equation (Richards, 1931) are typically considered as physically-based models. Between those two approaches lies the *conceptual* model (grey box) which includes models that are none of the two previous types. In particular, it may be possible to give an interpretation of the parameters in conceptual models, but they are not necessarily directly measurable. The above definitions of models are frequently debated and do not make consensus. In this thesis, we will consider the physically-based model as an asymptotic horizon where every process can be modelled with a perfectly meaningful set of parameters for an arbitrary level of detail.

- the level of *determinism*: models can be either *deterministic* or *stochastic*. Stochastic models are typically used when it is not possible to formulate an accurate deterministic formulation. It means that two realizations of a stochastic model with the same inputs can be different.

- the level of *discretization*: the model representation ranges from *lumped* (e.g. reservoir model), to *fully distributed* such as Hydrus or HEC-RAS. In Hydrus a spatial discretization with finite elements to model flow in unsaturated porous media is possible (see Hydrus history Šimůnek *et al.*, 2016). HEC-RAS is dedicated to unsteady flow hydraulic calculation based on finite difference (Brunner, 2002). Between *lumped* and *fully distributed* lies *semi-distributed* models such as StormWater Management Model - SWMM where several lumped models are used together to represent a system (Metcalf *et al.*, 1971).

1.1.2 Calibration and Testing

Due to high level of uncertainty, lack of knowledge and heterogeneity in the systems studied, environmental models often rely on parameter *calibration* (Jakeman *et al.*, 2006). It consists in finding the sets of parameters that allow the best to reproduce the observed data with respect to uncertainty. The previous sentence introduces a simplification in the process. *Reproducing the observed data* should be changed to reproducing the desirable *information* contained in the observed data. In order to evaluate if the desirable information (e.g., the peak flows) is reproduced with an acceptable level of accuracy by the model, an *objective function* is used. An objective function is a mathematical expression that helps to rank models based on their ability to approximate a specific statistic of the observed data. The choice of the objective function directly influences the optimal sets of parameters (Bennett *et al.*, 2013; Kouchi *et al.*, 2017; Krause *et al.*, 2005). For instance, minimizing the sum of squared errors will attribute a higher weight to large errors than minimizing the sum of absolute errors.

Estimating the model's parameters through a calibration procedure and based on a calibration dataset does not mean that the model is reliable. It means that as set of parameters (or distributions of parameters) were found to be optimal in order to match the calibration dataset. In order to evaluate if the model can be used, it is necessary to evaluate if the model can provide reliable results on another dataset. If the model provides reliable estimates, it means that the parameters estimated from the calibration dataset are likely to provide reliable results on other datasets. Such a procedure is necessary for environmental models, it is still necessary to assess if the model can be used for prediction in a specific range. The terminology for this step has been vastly discussed (Beven and Young, 2013). Indeed, the term validation is sometimes considered as misleading, because in practice the models are validated on a restricted range which does not ensure reliable performances in other context. In the current thesis, the terminology *testing* will be used. It means that the calibrated parameter set has been tested to assess if it provides results that are in accordance with the model's objectives for (Crout *et al.*, 2008).

In terms of dataset management, several frameworks can be used for calibration and testing. The most common practice consists in splitting the dataset into 2 sub-datasets, one for calibration and one for testing. A special attention should be given to the splitting of the dataset in order to make sure that the testing dataset allows to accurately evaluate the models according to the predefined objectives. In the field of machine learning, the dataset is generally split in 3 parts. Another practice, k-folded partitioning, consists in splitting the data in k datasets in order to achieve a robust calibration (Bennett *et al.*, 2013).

1.1.3 Uncertainties in modelling

The increasing use of green infrastructure and its implications for urban water management makes it crucial to assess the uncertainty of models, parameters, and performance in order to aid design and decision-making processes (Pappenberger and Beven, 2006). Uncertainty is inherent to the nature of modelling and can be defined with three dimensions (Tscheikner-Gratl *et al.*, 2017; Walker *et al.*, 2003):

i. the *source* of uncertainty. The uncertainty can be located in the model inputs. It consists of model parameters (that can be taken from literature or calibrated) and input data (such as time-series) that are usually monitored, therefore coming uncertainty linked to data collection (Bertrand-Krajewski *et al.*, 2021). Uncertainty linked to calibration comes from both the method used for calibration and the data used. Finally, uncertainty in model structure is linked to the numerical scheme applied for resolution and the choice of equations;

ii. the *type* of uncertainty. While it is often defined as a gradual transition from determinism to ignorance, in the current thesis the opposite paradigm is used (Figure 1.1). It is defined as the transition from ignored uncertainty to the theoretical horizon of determinism. The reason for that paradigm comes from the limited practices of uncertainty analysis in the field of GI (see Section 1.4.1, Figure 1.6). Therefore, the definition should point out that ignoring the concept of uncertainty leads to the highest uncertainties. The horizon of determinism, is, as defined, theoretical since absolute certainty is probably not reachable in this field. On Figure 1.1, deep uncertainty encompass ignored ignorance, recognised ignorance, qualitative uncertainty. On the limit of that domain is placed scenario uncertainty. Deep uncertainty in this context represents a level were uncertainty are difficulty tractable.

iii. the *nature* of uncertainty. Uncertainty can be epistemic, meaning that it can be reduced with additional knowledge by collecting more data or improving the model structure. Uncertainty can also be random/stochastic, which means that it cannot be reduced. It is the case for instance with the uncertainty linked to climate variability.

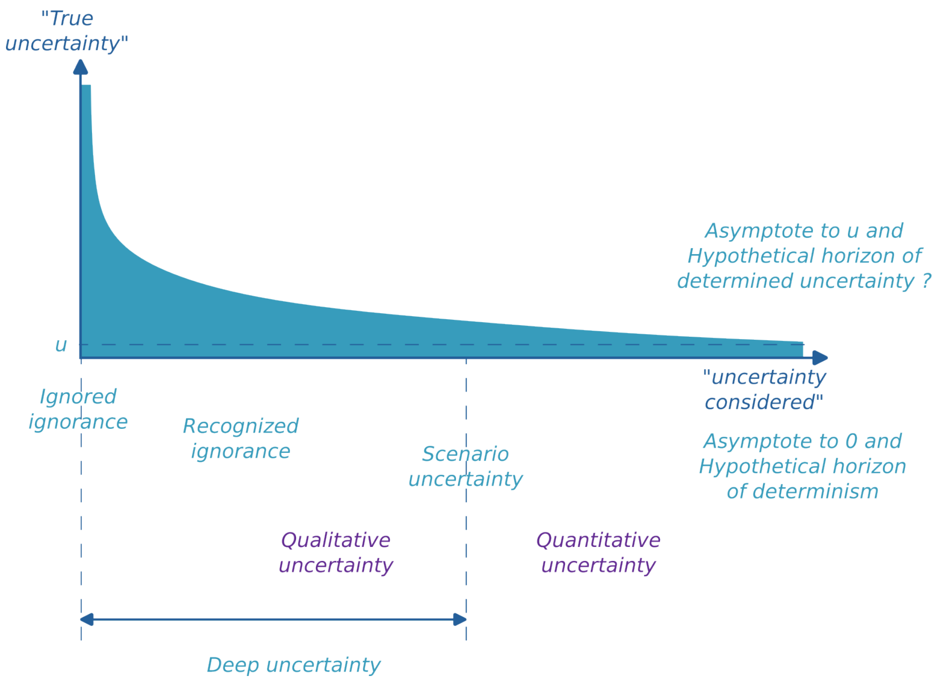

Figure 1.1: Conceptual view of the different types of uncertainties. It starts from ignored uncertainty which represents the maximum of uncertainty and converge asymptotically to the hypothetical horizon of determined uncertainty. The region of deep and qualitative uncertainty is displayed.

Uncertainty stems from inputs, assumptions, and simplifications in the model setup and propagates to the outputs (Deletic *et al.*, 2012). Uncertainty analysis (UA) aims to quantify the level of confidence in a result, including, in a modelling context, three classes of methods:

- *Forward Uncertainty* quantification (propagating uncertainty from inputs to outputs),
- *Inverse Uncertainty* quantification (parameter estimation and model calibration),
- *Sensitivity Analysis* (how the inputs variability and model assumptions contribute to the variability of the output).

1.1.3.1 Forward uncertainty quantification

Most commonly, *Forward Uncertainty* quantification relies on probability theory. It means that probability distributions of uncertain inputs are used to propagate uncertainty to the outputs. Due to limited knowledge, some alternative frameworks based on fuzzy set theory or possibility theory have been used. It should be noted that in the context of deep uncertainty and computationally expensive models, the use of ensemble or scenarios are used to compensate lack of knowledge. The use of degraded methods (i.e., degraded from a formal probability formulation) and limitation to quantify uncertainty lead to the emergence of second order uncertainty. It consists in evaluating the uncertainty related to an uncertainty estimate. For instance, the impact of the choice of a given distribution compared to another.

The method most commonly used to propagate the information of uncertainty of parameters to the output is generally the Monte Carlo simulation (Robert and Casella, 2004). Based on the *Law of Large Number* and the *central limit theorem*, the philosophy is by sampling from a distribution for each factor we can converge through modelling to a propagated distribution. The residual error depends on the number of model evaluations. The more accurate the answer is expected, the more model evaluations have to be performed.

If the model is too expensive to run or the uncertainty too high, another method needs to be used. Ensemble simulation and scenario based approach are two of those by cherry-picking relevant simulations to be run. The concept of ensemble modelling is similar in its way to cope with uncertainty, assuming that a set of simulations capture more uncertainty than a single one. This type of approaches encompasses several challenges (Cloke and Pappenberger, 2009) and limitations in order to adequately exploit an ensemble (Abramowitz *et al.*, 2019). The 6^{th} assessment report of the IPCC recently released, reports the use of multimodel ensembles, single model initiated with different initial conditions and lastly ensemble initialized from observed climate data (Lee *et al.*, 2021).

A scenario based approach is used when the uncertainty is too deep. It consists in a set of hypotheses describing how a system may develop in the future and formalizing it into a modelling approach, such as the one used in the IPCC reports (Lee *et al.*, 2021). It is often impossible to assign a probability other than qualitative to the occurrence of a scenario, in this way such an approach is said to be part of a qualitative uncertainty management (Walker *et al.*, 2003). Other approaches consist in building metamodels, surrogates, or surrogates that cost less in terms of computation (Tscheikner-Gratl *et al.*, 2019).

1.1.3.2 Inverse uncertainty quantification

Inverse Uncertainty quantification is linked to inverse problem. While in forward problem we use inputs in a model to get some outputs, in inverse problem it is the opposite. The goal it to answer that question *Which inputs caused that observed output?*. Inverse uncertainty quantification consists therefore in determining the inputs distributions that caused an output. The Bayesian framework offers an answer to that question (Robert and Casella, 2004). In particular, a formal Bayesian framework, such as Markov-Chain-Monte-Carlo (MCMC) initially proposed by Metropolis *et al.* (1953), consists in constructing a Markov chain to estimate the probability distribution of the output. It consists in determining a posterior distribution of uncertain outputs based on a prior distribution incorporating prior knowledge on the uncertain inputs. This approach is usually more general than determining arbitrary a distribution of inputs to propagate to the output. In hydrology, MCMC algorithms such as DREAM (DiFfeRential Evolution Adaptative Metropolis) are regularly used (Laloy and Vrugt, 2012). Deviating from MCMC, methods such as GLUE can be mentioned as informal Bayesian approaches (Beven and Binley, 1992; Mirzaei *et al.*, 2015). While GLUE (Generalized Likelihood Uncertainty Estimation) is less formal than MCMC, its implementation makes it more user-friendly, even though the choice of relevant thresholds in the algorithm requires some expert knowledge (Blasone *et al.*, 2008). In a similar fashion, constructing an ensemble, or a weighted ensemble (Lee *et al.*, 2021), can be considered as an Inverse uncertainty quantification.

Several alternatives to the MCMC approach can be listed. In particular, variational Bayesian inference recently gained interest in the field of machine learning since it allows to approximate uncertainties (Klotz *et al.*, 2022). While MCMC aims at providing a numerical approximation of the posterior distribution, the variational Bayesian inference, known as Monte Carlo Dropout in the context of ANN, aims at providing an exact analytical solution to an approximation of the posterior. In practice, while such a method has several advantages, it suffers limitations linked to the set of initial solutions and should be further investigated to assess its reliability (Fang *et al.*, 2020). Spectral approaches, aims at producing a surrogate to approximate the likelihood function. Such approaches may be limited in a case where the likelihood function is highly non-linear and high dimensional and therefore complicated to approximate. Transport map approaches proposes to construct a map that is an optimal transport from the prior to the posterior, which consists therefore in solving an optimization problem.

1.1.3.3 Sensitivity analysis

Sensitivity Analysis (SA) is the study of which part of the uncertainty can be allocated to some assumptions and inputs (Saltelli *et al.*, 2007). Therefore, it differs from uncertainty quantification where the magnitude is studied. Sensitivity Analysis, according to Saltelli *et al.* (2007), can be categorized as follows:

- Quantitative or qualitative; Although this aspect is rarely mentioned, there are cases where the influence of a factor on the output is discussed and where simplified strategies can be used for a non-quantitative analysis (i.e., without the use of formal sensitivity index). Later on in this thesis, such methods will be referred to as *informal sensitivity analysis*.

- Local or global whether the effect is studied at a local scale by derivatives or in a predefined subset of the input space. Local sensitivity analysis assumes no uncertainty, since it only explores locally around a nominal value for each factor. Global on its side explore a predefined a subspace of the input space and therefore is directly related to the concept of uncertainty. Only global sensitivity analysis is considered later one in this thesis.

- One at the time (OAT) or All at the time (AAT) whether the variations of model parameters are simultaneous or not. The limitations of OAT are explained by Saltelli and Annoni (2010) in a geometrical proof by invoking the well known *curse of dimensionality*. They consider a unit hypercube and a hypersphere included and tangent to the unit hypercube. They show that the ratio between the volume of the sphere and the volume of the cube tends to zero as the number of dimensions increases. By construction, no matter the initial setting, the points sampled through an OAT method remain internal to the sphere, while obviously, since there is no such constraint in the case of AAT all the space can be explored.

Several ideal and desirable characteristics of SA can be listed (Liu and Homma, 2009). They should be *global* as discussed above. They should be *quantitative*, in a way that they should be computed through a reproducible procedure. They should be *model independent*, which means that no hypothesis on the model is needed. They should be *easy to implement* which means that there is a procedure that allows to compute the sensitivity index. They should be *unconditional* on any input value, which means the sensitivity index. They should also be *easy to interpret*, which mean for instance a variation between 0 and 1 independently of the model output. They should be *stable*, or at least it should be possible to check the robustness of the estimates (though repeated sampling, for instance). Most of the SA methods are considered as variance decomposition methods. This triggers another desirable characteristic for SA: to be *moment independent*, that lead to the development of density based methods (e.g., Pianosi and Wagener, 2015). A last characteristic to be considered, common to most of the UA methods, is to be *computationally accessible*. This last characteristic is in fact model dependent, but worth being mentioned that between two similar indexes the one with the less sampling intensive strategy might be preferred. It should be mentioned that most methods cannot satisfy all of the above characteristics. They SA methods can be grouped depending on their goal (Saltelli *et al.*, 2004):

- Screening, also referred to as factor fixing. The goal can be, for instance, to fix some non-influential parameters in a model. Or more specifically, identifying which factor can be fixed without alteration of the output uncertainty or loss of information. It can therefore be used to simplify models. Mostly Elementary Effect methods (Morris, 1991) and variance based methods (Saltelli *et al.*, 2010) are used.

- Ranking, also referred to as factor prioritization, i.e. quantifying the influence of the inputs considered. It allows to identify which factor needs to be better measured in order to reduce the variance. It also allows to identify which factor needs low effort to be determined. Such methods are often based on variance based indicators (Saltelli *et al.*, 2010)

- Variance cutting, aiming to reduce the variance *to a predefined level* (as a difference with one of the ranking objective) by acting on the smallest amount of factors (Saltelli *et al.*, 2004).

- Mapping, i.e. identifying regions in the inputs space that produce specific outputs. It can be used to cut a set between acceptable and non-acceptable performances. The use of Monte Carlo filtering, which is closely related to GLUE (Ratto *et al.*, 2001), can be mentioned.

Several reviews provide more details on this topic, highlighting the difficulty to implement good practices (Borgonovo and Plischke, 2016; Pianosi *et al.*, 2016; Saltelli *et al.*, 2005) and describe more specifically strategies for computationally expensive models (Iooss and Lemaître, 2015).

Later in that thesis both qualitative and quantitative sensitivity analysis methods will be used.

1.1.4 Upscaling and downscaling

1.1.4.1 Space and time scales

The concept of scale is central in this thesis. Indeed, modelling tasks involve the use of monitored data which often need to be adjusted to a suitable scale for the model. It also means that the data needs of the model can dictate the instruments required to monitor data. The link to decision-making is essential and bidirectional. A requirement, formulated at the decision scale, needs to be translated into monitoring and modelling choices. For instance, a quantitative objective of annual combined sewer overflow per year, involves a monitoring strategy and a suitable modelling approach in order to design a system able to achieve the objectives. Similarly, the outcome of a monitoring campaign and a modelling work needs to be translated into meaningful information at the decision scale. For instance, the time-series of discharge from a combined sewer can be transformed into a distribution of annual overflow. The interdependencies between scales is illustrated in Figure 1.2. Similarly to uncertainty, change in scale can be represented with 2 dimensions. The scale object (e.g., model, observation, decision-making) refer to the part of the environmental decision framework whose scale is considered. The scale transition (e.g., from minutes to daily resolution) refers to that transition from an initial scale to a final scale. The idea of scale and change in scale appear at different steps of the current work and can be (non-exhaustively) listed as follows:

- Downscaling (or upscaling) climate inputs is needed to model green infrastructure. Therefore, downscaling rainfall time-series to minute resolution for both current and future climate is part of this thesis (Subsection 1.2.3, and CHAPTER 4). A connected topic is the study of how to apply downscaled data and how to manage inputs (Chapter 5).

- Extracting meaningful information out of a simulation is the core of this PhD thesis since the goal is to advise for a better model use in order to evaluate the potential of GI in future cities. It means that out of a green roof simulation there is a need to select relevant indicators and evaluate which ones should be avoided since they may lead to wrong decisions.

Table 1.1: Types of spatial scales considered in the PhD thesis.

Scale	**Description**
Site/Unit	scale of a facility / infrastructure (typically a green roof)
Neighbourhoo	scale of a small catchments (typically 20 houses)
Catchment	scale of a urban catchment (typically a set of neighbourhoods)
City	scale of a city or stormwater management system (a set of urban catchments)

- In terms of spatial scale, modelling hydrological processes can involve several scales. Flow in porous medium can be modelled as follows. *i)* At particle scale, with fully distributed 1D or 3D models based on Richards equations to model unsaturated flow (Richards, 1931), it can help to study the contribution of GI to stormwater management at process scale. *ii)* At facility scale using a lumped model relying on, for instance, Green-Ampt equation for infiltration (Heber Green and Ampt, 1911), the objective can be to study stormwater management at facility scale. *iii)* At city scale with implementation of GI on a full scale city or catchment to study how GI integrates in a city and contributes to stormwater management at system scale. In the current thesis the scales of interest are unit scale, neighbourhood scale and city/catchment scale (Table 1.1).

- In terms of timescale, *i)* the type of inputs considered from events to decades-long time-series and *ii)* the horizon of inputs, namely current climate and future climate, can be considered. In terms of outputs, it represents the time-window used to visualize the results and how to represent both climate change and climate variation.

1.1.4.2 Within and to policy scale

When simulating discharge from a GI over a 20-year-long period, communicating the results to decision makers requires synthetic tables or figures summarizing the key messages and information (Figure 1.2b). It should be noted that policy scale itself, in the context of infrastructure asset management (IAM) consists in three scales and time horizon called strategical, tactical and operational (Ugarelli and Sægrov, 2022). The strategy scale sets the goal to reach in, typically a 10-year horizon at city scale. The tactical scale shows the path to follow on a 5-year horizon, placing targets more specifically within the urban area. Finally, the operational scale, usually at a yearly horizon, consists in practical implementation and measures at site scale.

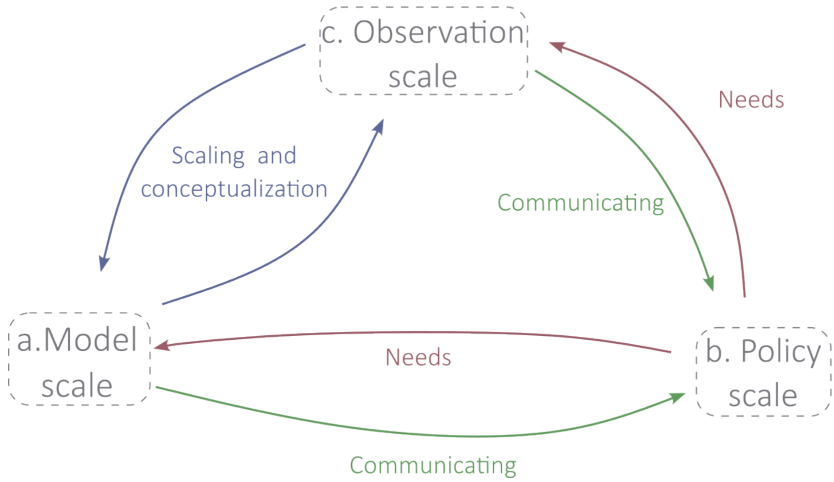

Figure 1.2: Conceptual relationship between observation scale, modelling scale and policy scale.

1.1.4.3 Within and to model scale

Downscaling and upscaling monitored input data for models can consist in changing the resolution (Figure 1.2a). For instance, minute resolution temperature data can be changed to daily mean, min, and max to be used with Hargreaves equation (Hargreaves *et al.*, 1985). When hydraulic conductivity is measured on-site in different points, it can require upscaling the information to derive parameters for a lumped catchment scale rainfall runoff model.

Change from the policy scale to model scale occurs when translating a decision to parameters change in a model. Models such as Darcy equation (Darcy, 1856) can be derived from Navier Stokes equations (Temam, 2001); upscaling consists there in a simplification under specific hypotheses. The parametrization of such derived equations also consists in an upscaling process (Puyguiraud *et al.*, 2019).

1.1.5 Data, Information, and Knowledge

Several concepts are central in this thesis. The concepts of models, uncertainty and scales were described in the previous sections. The current section introduces the concept of information. More formally, it consists in making the difference between data and information. It also brings the discussion forward to the articulation between science and society. And at which point scientific results or engineering methods can be translated into wise decisions for the society.

Ackoff (1989) conceptualized the chain from data to wisdom, also known as the DIKW hierarchy (Data Information Knowledge Wisdom). It describes how those different concepts are related (Rowley, 2007). Specifically, the difference between data and information is of interest in this thesis. Data can be viewed as "without meaning or value" because they are "without context". In practice, they are observations.

They are objective in a sense that they are not interpreted. However, if we consider data collected from a certain perspective, they can lead to subjective interpretation. Data being prone to uncertainty and bias by nature, it may lead to a biased use of the data. As soon as we start to process data, or to analyse them with a specific context or objective, it leads toward information. More precisely, information can be viewed as data processed in order to make them meaningful. From that perspective climate information is defined as climate data with added value. They have to be useful and usable for climate adaptation purpose. And that is specifically where the current thesis aims to bridge a gap: between available climate information and green infrastructures' performance estimation. To make climate information useful and usable for users, dialogue, and interaction between the provider and the user has to define which information should be available and in which form. The provider alone is not necessarily aware of what is useful, and the user alone is not necessarily aware of what is usable. Moreover, what is usable from the provider perspective is not necessarily usable in practice for the user. For instance, the outputs of climate models may be useful for climate adaptation, but they are needed at a fine resolution for local decision-making. That is where climate information services become necessary: bridging the gap of knowledge and information between different groups of researchers that have different backgrounds and practices.

Another articulation between data and information that is later questioned in this study is "Do we use adequately available data?". In an era where we begin to have large enough datasets and enough computational power to substitute existing modelling approaches by machine learning methods, the question of the learning rate out of existing data should be questioned. Arising this question does not mean that machine-learning approaches are not able to efficiently use data, but rather that the interaction between data and machine learning models differs from the interaction between data and conceptual/physically-based models. In particular, Bayesian approaches in modelling consists in, given limited data and prior knowledge, in maximizing the information that can be learnt (especially uncertainty estimation). The machine learning rational is taking a different path, it consists in training a general structure on large datasets without adding prior knowledge in the model structure (i.e., physically based equation). The implication of this paradigm shift in data and knowledge use in order to extract information should be discussed. The GIGO rationale "garbage in garbage out" (Canbek, 2022) is not specific to machine-learning approaches and can also be found in traditional hydrological modelling approaches. In machine-learning approach, the choice of the mathematical structure is guided by the data and prior knowledge (i.e., choosing the correct ML tool, e.g., choice between supervised or unsupervised learning, or specifically between k-Nearest-Neighbours or ANN): the use of knowledge is different. This paradigm shift leads to the question of data versus information. Using models, we input data or information and expect to get new data, from which we can get other information that helps us to build knowledge that we could use to achieve robust decision-making (RDM).

Similarly, recent strategies of monitoring tend to suggest collecting data over (dense) grids of sensors (Lalle *et al.*, 2019). This also constitutes a shift in the monitoring paradigm (Webber *et al.*, 2022). The question of dense sensors grid also arises in connexion with the data versus information dilemma. Indeed, intensive monitoring is costly in terms of direct cost, manpower, skills, and maintenance (Kumar *et al.*, 2015). It can be hypothesized that in a world with limited resources, many urban and rural areas will still face data scarcity and that there will be an unequal access to data monitoring (Cheong *et al.*, 2016). Some cases might in the future be solved by low-cost sensors, but they still require intense monitoring and manpower, so it is likely that such solution is not sufficient.

The data versus information dilemma (should we get more data or should we maximize information from data?) does not have a Manichean answer, and both directions should be explored to some extent. While some fields of research lean toward the question *What information can we get with intense monitoring?*, the current thesis addresses a different path. Accounting for climate change and the context of limited resources, the current thesis explores a different direction *Given the available climate projection data, observed climate and green infrastructure models, which information can we extract about their potential for stormwater management in future cities?*.

1.2 Climate change adaptation

1.2.1 Climate, weather and precipitations

While this thesis is not about meteorology or climatology, it is considered useful to present basic concepts about precipitation, weather, and climate since they drive the main variables affecting green infrastructures. The difference between climate and weather hereafter in this thesis is that the climate can be understood as weather statistics, which leads to an elegant definition of climate change as a shift or alteration in weather statistics. Precipitation can refer to any type of hydrometeors falling (rain, freezing rain, snow, or hail), but the current thesis only considers rainfall. Nevertheless, it is acknowledged that the effect of snow or ice on green infrastructure and particularly the snow melt process is especially relevant in cold climates.

There are mainly three types of precipitation *convective*, *stratiform* and, to a lesser extent, *orographic*. Precipitations are called *convective* when they fall out of an active cumulonimbus cloud (Houze, 2014a, chapter 1). They represent the majority of the storms (Houze, 2014d, chapter 8). *Stratiform* precipitations are falling from nimbostratus (Houze, 2014a, chapter 1). The precipitations generated are sometimes called frontal precipitations. However, complex cloud systems may contain both cumulonimbus and nimbostratus clouds and therefore lead to both *convective* and *stratiform* precipitations. More details about cloud systems can be found in Houze Jr (2014, chapters 9, 10 and 11) and the dynamic between convective cells in stratiform clouds (Houze, 2014c, chapter 6). In chapter 6, Houze Jr (2014) defines the difference between stratiform and convective precipitations kinematically, relatively to air motion and particles fall speed. Precipitations are considered as stratiform if the mean vertical air motion in the cloud is small compared to the typical ice crystal fall velocity. On the opposite, convective precipitations have higher velocity than ice crystals fall.

The cloud circulation can sometimes be affected by the topography triggering precipitation, we refer then to orographic precipitations. An example of such a phenomenon is shadow rain (e.g., Siler *et al.*, 2013). The air raises and adiabatically expands along the windward flank of the mountain and can lead to precipitation. On the lee flank of the mountain, fewer precipitations will occur, and this is referred to as shadow rain. It induces some microclimates. Those effects take place at different scales and different forms depending on the cloud system configuration (Roe, 2005). The term of orographic precipitation is sometimes considered as misleading (Houze, 2014b, chapter 12). It may lead to the presupposition that the terrain causes the precipitation while the precipitations are mainly linked to convective clouds, tropical cyclones or frontal stratiform systems independently of the terrain. What is referred to as orographic precipitation is when one of the above-mentioned clouds or cloud system is triggered by the train and causes precipitation. Consequently, orographic precipitation can be either *convective* or *stratiform*.

A last type of precipitation, similar to orographic precipitation, is precipitation influenced directly by urban area and heat island effects. Already in 1921, Horton (1921) noticed the frequency of thunderstorm formation over large cities. Bornstein and Lin (2000) have shown that New-York City and Atlanta heat island effect affected both the formation and the movement of summer thunderstorms. A review by Shepherd (2005) summarizes the state-of-the-art of evidence of urban influence on precipitation in the early 21^{st} century. The advances in modelling and measurement allow now to forecast the change in convective storms and in precipitation patterns (Steensen *et al.*, 2022). This was one of the reasons to introduce the previous concepts since precipitation patterns are modified globally by human activity, affecting the occurrence of convective storms for instance due to climate change, but also locally due to direct anthropogenic activity. In the context of stormwater management, the objective is to handle precipitation in a robust way to the different precipitation regimes and also to the global and local human induced shifts.

1.2.2 Climate change models and IPCC

In the current section, we refer to the state-of-the-art in the recently published 6^{th} Assessment Report (AR6) of the IPCC that was released after the beginning of the current PhD (IPCC, 2021). Therefore, most of the applications in this thesis are based on the model outcomes of the 5^{th} Assessment Report (AR5) of the IPCC (IPCC, 2014).

The General Circulation Models (GCMs) are used to model climate change at earth scale. The GCM acronym can be used to designate general circulation model or global climate models. It may be ambiguous, since global climate models may refer to a framework that includes a general circulation model. Global climate models are coordinated as part of the Coupled Model Intercomparison Projects (CMIP). The CMIP5 is used in the 5^{th} Assessment Report of the IPCC. The results from the CMIP5 and the CMIP6 are presented in the 6^{th} Assessment Report of the IPCC. The models used in the CMIP6 are referred to as the Earth-System Models (ESMs). Both GCMs and ESMs include equations representing the governing processes in the atmosphere, the ocean, and sea and land surface. They encompass both physical and chemical processes. ESMs include more processes and equations than the GCMs. In particular, they include biogeochemical processes. Another difference between the CIMP5 and the CMIP6 is the scenarios on which they are based (Chen *et al.*, 2021).

In the context of climate modelling, a scenario consists of a description of how the future may develop. It accounts for several key drivers, such as demography, economy, technology, governance, and lifestyle. They result in time series of emission and concentration that can be used to drive the GCM. In the IPCC AR5, the Representative Concentration Pathways (RCPs) are used. These scenarios, namely RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, are labelled based on the radiative forcing they are associated to at horizon 2100.

In the IPCC AR6, the Shared Socioeconomic Pathways (SSPs) are used. They consist of an update of the previously used RCPs. SSPs are based on similar radiative forcing as their predecessors RCPs. In practice, RCP are green house gas (GHG) concentration, aerosol emission and land use patten time series. The pathways were initially based on socioeconomic drivers, but they are no longer considered. In practice, RCPs emissions and concentrations are used in combination with SSPs (Chen *et al.*, 2021).

To be accurate, among SSPs, a distinction needs to be made between the SSPXs and the SSPX-Ys. The first, SSPXs where X stands for the number of the scenario, are based on GDP, population, urbanization, economic collaboration technological development projections. The energy land use and emission are not part of the SSPX. The SSPX-Y is a SSPX where the emission and concentration have also been generated. It therefore enhances the consistency between the socioeconomic part of the scenario (X) and the resulting radiative forcing (Y). It should be noted that it differs from the use of SSPX-RCPY where the socioeconomic part was developed separately from the radiative forcing. In practice, some SSPs were designed based on missing RCPs. While the details of this terminology has no influence later on the thesis, it was decided to keep it in the text to show the complex entanglement between the socioeconomic component and the climate component of the framework.

The outcome of global climate models results in a coarse resolution gridded data (typically a 100 km grid). Such a resolution does not allow to represent well the local conditions and extremes, several other layers in the modelling cascades needs to be added (Doblas-Reyes *et al.*, 2021). Those results are then dynamically downscaled (Subsection 1.2.3) to higher resolution (typically 25 to 12 km grid). Dynamical downscaling is achieved using regional climate models (RCMs). They are coordinated through the CORDEX project (Jacob *et al.*, 2014). It consists in a set of regional grids, typically at continent size, that allow to drive the downscaling of climate variables to a higher resolution. The current results from the RCMs are based on the CMIP5. The downscaling outputs linked to the CMIP6 have yet to be made available.

Those results are still too coarse for urban hydrology applications and need further downscaling process (Schilling, 1991). Additionally, those data have a tendency to be biased and requires therefore bias correction (Benestad *et al.*, 2008). Indeed, the GCM-RCM cascade does not represent always appropriately the orography or convection processes. Therefore, statistical methods such as bias correction or statistical downscaling are often used. In practice, bias correction consists in using a control period for which measurements are available to estimate the bias. The estimated bias is then used to propagate the information to future data. In Norway, for instance, a grid of 1 km data at daily resolution result from this cascade modelling. The resulting data available in Norway consists in a 1 km gridded data at daily resolution (Wong *et al.*, 2016).

The CMIP consists of a multi-model ensemble. It is based on several models, several scenarios, several initial conditions and realizations. Such an approach is made necessary by the cascading uncertainty propagating with the cascading models. Indeed, a realization is based on a scenario, a GCM, a set of initial conditions, a realization, an RCM with a set of boundary conditions and possibly a model for statistical downscaling and one for bias correction. All those modelling steps results in a cascade of uncertainty. Therefore, climate change adaptation should be based on this overall climate information that includes this cascading uncertainty: the use of ensembles is advised for climate change adaptation studies. Ensemble modelling does not go without pitfalls. It is sometimes assumed that multimodel ensemble allow for a better coverage of uncertainty because the models are independents. But to some extent the different research groups share ideas and representations, therefore the independence of models is not complete (Abramowitz *et al.*, 2019).

1.2.3 Downscaling climate information current progress

In the context of climate modelling, downscaling can be classified between dynamical downscaling (also referred to as regional downscaling) and empirical-statistical downscaling (ESD). In terms of application, three categories can be considered. Spatial downscaling aims at increasing the spatial resolution. Temporal downscaling - or disaggregation - aims for the temporal resolution. Bias correction aims to correct model bias and retrieve local information that global models cannot account for.

The dynamical downscaling methods consist, given limited computational resources, of nesting an RCM on a limited area in a GCM in order to improve the resolution. The RCM is linked in time and space to the GCM, with lateral boundary conditions. Those methods are often used with bias correction methods and ensemble modelling in order to improve the estimates (Dickinson *et al.*, 1989; Xu *et al.*, 2019).

The potential of dynamical downscaling and especially regional climate models are more and more discussed. Indeed, they have been very useful when the global climate models unable to reach high spatial resolution. However, nowadays, some global climate models can reach the resolution of GCM with the advantage of not depending on boundary conditions (Tapiador *et al.*, 2020). The RCMs are still meant to be used because they can allow local simulation. Indeed, it is not efficient to run global climate models for any land use change scenario. They have many similarities with GCMs in terms of challenge, and the need for faster and finer resolution model is likely to continue.

On the other hand, there is still the need for more reliable, accurate, and higher resolution estimates. Both GCMs and RCMs, since they are fed with SSPs outputs, have a major caveat. Moreover, many of those model's conceptual limitations are not always acknowledged in climate change adaptation studies. For instance, convection parametrization remains very limited in those models. Recently, models that can overcome those limitations, labelled convection permitting models, allow for better parametrization typically at kilometre scale (Kendon *et al.*, 2017). This is a huge advance because previous models could not account for convection clouds on their grids. In particular, convection permitting climate models have a strong added value in urban or orographic regions (Prein *et al.*, 2015).

Benestad (2016) reports different views of downscaling sceptics. It is interesting to notice that a lot of those critics can be tackled by the notion of data and information. In practice, researchers working on climate change adaptation need information at a scale specific to the processes they are studying. The fact that physically based models are not able to reach that scale-of-interest does not mean that other approaches should not be used. One aim of downscaling is to make an optimal use of available information.

The concepts of data and information allow to get another view of statistical downscaling that is to some extent freed from some previously mentioned drawbacks. Empirical statistical downscaling methods are a set of advanced statistical tools that provide local climate information based on data from climate models data and based on local observation. It should be mentioned that ESD also has caveats that are different from dynamical downscaling. In general, considering a combination of approaches can help to tackle some of those limitations (Benestad, 2016). Concerning ESD, the question of non stationarity should be discussed. ESD models dependencies between multiple variables based on observations (Benestad *et al.*, 2008). While some of those dependencies could remain the same in the future, some others might not. For instance, as mentioned earlier, urbanization can affect the local climate. ESD based on observed data in a period with limited urbanization might not be able to represent the change of condition, especially if this information is not accounted for in GMCs or RCMs. Therefore, the results of downscaling should be considered carefully. They are statistical estimates based on current knowledge and data availability. It is the current state information we can extract, and it can be used to base the development of methodologies for climate change adaptation in the context of stormwater management.

1.2.4 Climate change adaptation in urban hydrology

The current thesis refers to climate change adaptation in urban hydrology. This terminology embeds here the interactions and feedback loops between human society, climate, environment, and hydrology. More precisely, not only the implementation of solutions to cope with climate change is considered in this concept, but also the feedback interaction to society and environment. By proxy, it also includes morphologies change in cities (through urbanization) and society change (e.g., social inclusiveness as defined by Ward *et al.*, 2019).

The topics of climate change adaptation is linked to several concepts that need to be defined. Climate change adaptation is linked to deep uncertainty (Walker *et al.*, 2013). Indeed, planning the long-term future at includes accounting for changes in society, technology, and climate. It involves a lot of uncertain trajectories, which cannot be forecasted with quantified uncertainty. As introduced in Section 1.1.3, ensemble modelling and scenario-based strategies are key families of methods to deal with this type of uncertainties. Later in the thesis, various notions and concepts are studied using scenarios-based methods. Ensemble are also used in the context of downscaling.

Climate change adaptation deals with resistance, robustness, adaptability, and resilience (Liao, 2012; Walker *et al.*, 2013)

- Resistance can be defined as the ability of an infrastructure to face stress without disturbance until a certain level. Above that level, the infrastructure enters into failure mode. By definition, resistance does not describe the failure mode of the infrastructure.

- Resilience is related to the notion of resistance, but also to the behaviour under failure of the system considered. Liao (2012) presents two variations of resilience, namely the engineering and the ecological resilience. Both terms describe resilience in the sense of the duration to reach an equilibrium point after a disturbance of the system. The difference is that engineering resilience aims at reaching the initial equilibrium point, while ecological resilience describes the reachability of another equilibrium point. In terms of urban resilience, ecological resilience may be more meaningful since some infrastructures may be damaged and therefore the system may reach another equilibrium point which has to be considered to have a robust risk management plan.

- Robustness is described by Walker *et al.* (2013) as the ability of a system to face a large range of conditions. In the context of stormwater management, it can describe a system that delivers a similar level of service under climate change. It also encompasses a system that continues to deliver an acceptable level of service under failure.

- Adaptability, the last term discussed in this section, does not directly refer to adaptation to climate change but to a more general property of a system. It describes its ability to be modified easily in order to face new threat. For instance, a solution is said adaptable if after its implementation it is "easy" to upgrade its level of service if it is considered necessary. This property is especially crucial in the context of adaptation to climate change, because of the high level of uncertainty on the future climate conditions. It means that while some municipalities have already started to implement climate adaptation measures, they will need to modify their adaptation plan. Therefore, the solutions implemented should have this adaptability property.

In terms of performance evaluation, studying climate change adaptation requires accounting for a cascade of uncertainty due to a chained modelling strategy. From a conceptual point of view, as shown in Figure 1.3, evaluating future performance consists in evaluating the shift in performance due to the shift in climate variables domains. Evaluating the performance in the current climate is complex, since only a portion of performance under that climate is known and observed. This is why monitored data are used to calibrate hydrological models to upscale the performance to the entire known climate domain. However, when it comes to climate change, it become necessary to use simulated climate data. The chained modelling strategy used for that purpose cascades in terms of uncertainty on the simulated climate domain introducing greater uncertainties to hydrological simulations. Moreover, the reliability of hydrological models under a different climate domains can be questioned. Johannessen *et al.* (2019) showed that the transferability of green roof's hydrological models from one location to another, even within a country with limited climate variation such as Norway, is not a trivial task. The options introduced in this chapter will be further discussed in CHAPTERS 3, 5 AND 6.

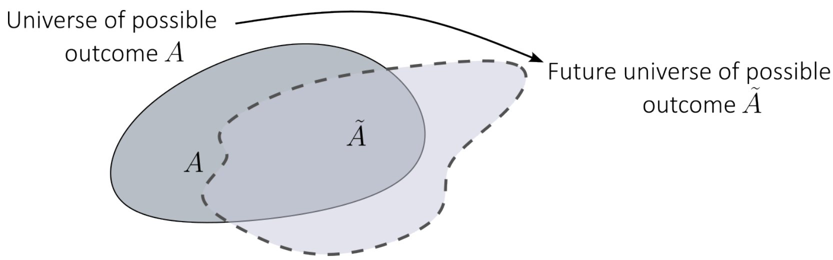

Figure 1.3: Conceptual view of outcome domain shift due to climate change.

1.3 Green infrastructure and stormwater

Despite the term green infrastructure has been succinctly mentioned in Section 1.1.4 and 1.1.3, it has been presented neither holistically nor historically in the current thesis. The three following sections intend to depict i) the main concepts and terminology, ii) the hydrological processes related to GI and iii) a holistic view of GI.

1.3.1 Green infrastructure terminology and concept

The current PhD thesis is dedicated to the study of as green infrastructure for stormwater management. The terminologies (Fletcher *et al.*, 2015) and conceptualizations (Matsler *et al.*, 2021) related to GI differ depending on the region of the world, and vary with time and depending on disciplinary specificities. Indeed, the term green infrastructure is used in several distinct fields, which leads to different communities of scholars. (Matsler *et al.*, 2021) found in their review that studies often fail to clearly define GI. The object of interest is the hydrological dimension of green infrastructures. This term has been extensively debated in the literature (Fletcher *et al.*, 2015) and compared to others such as Low-Impact-Development (LID), Nature-Based-Solution (NBS), Sustainable Urban Drainage System (SUDS), Source Control Measure (SCM), Best Management Practice (BMP), or Sponge City. They acknowledged that the development of terminology both temporarily and geographically plays an important role in the spread of GI and thus should not be refrained. However, it remains important to facilitate the communication between communities. This can be done with a clear definition of the object of interest. To lean toward a definition both holistic and transdisciplinary, several relevant concepts in the context of the current PhD thesis were listed. They emerge from the existing terminologies (Fletcher *et al.*, 2015) and conceptualisations, and are discussed and defined as follow:

- *Decentralization*: As suggested by the terminology of Source Control Measures, the current thesis will consider infrastructures designed to handle locally stormwater "as close as possible to the place where the rain dropped". One goal of SCMs, among others, is to lower the stress on the centralized system. From an urban planning point of view, it also leads to local green areas, ideally connected together to form a green corridor that contributes to biodiversity.

- *Integrated*: It means that GIs do not solely account for technical aspects but also environmental, social and governance matters. It means a paradigm shift from an isolated technical object to a more holistic approach that integrates better multifunctional objects in the cities.

- *Limited development impact*: This notion is here twofold and not equivalent to the term low impact development (Fletcher *et al.*, 2015). The infrastructure of interest should account for the system context to limit its possible negative impact. For instance, in dense city centres, the available space is limited, therefore multifunctional infrastructure can help to optimize space use. Such an infrastructure should also have a low impact on the environment. The impacts linked to its construction (material, vegetation choice) and during its lifetime (maintenance, nutrient supply, etc.) should be accounted for. This aspect is not commonly brought into the field of hydrology, but should be mentioned. Farrell *et al.* (2022) suggests integrating ecological approaches for plant selection in GI. Such an approach could increase the robustness of infrastructures by limiting the need for maintenance. The choice of the vegetation and its "nativeness" can also affect the animal biodiversity (Berthon *et al.*, 2021) and should therefore be accounted for. However, providing a complete analysis of the impact of a green infrastructure, is particularly challenging. In particular, tools based on life cycle thinking still need to be developed to face challenges regarding the complexity of having a holistic approach to GI (Romanovska, 2019). Those topics won't be discussed in detail in the current thesis, since the hydrological performance is the prime matter. However, as mentioned in section 1.2.4, such infrastructure and research should be integrated in a holistic framework accounting for human-climate-environment interactions.

- *Natural process based and restoring the natural water cycle*: It means that hydrological principle governing the infrastructure should involve evaporation, evapotranspiration (ET), vertical and horizontal infiltration, or transport through porous material for stormwater management. The idea of natural-process-based can also be defined by contrast to real time control (RTC). Indeed, Nature-Based Solutions, could be defined as passive systems that do not need real-time control (Webber *et al.*, 2022). As it will be discussed later on in Chapter 6, a system of GI could be considered either passive or active. The terminology of NBS may be debated since in practice the soil and vegetation used are engineered to serve a purpose. It can be interpreted as a rhetoric process of *appeal to nature*. It is mentioned in this chapter since one of the purposes of the current PhD is to investigate the potential of green infrastructure for climate change adaptation. This objective involves avoiding a subjective view of those solutions.

- *Restoring the pre-urbanization stage*: Restoring *the* natural water cycle or restoring the pre-urbanization stage may be used as an objective of GI implementation. This objective of GI is mentioned here for clarification purpose since it may be misleading. While it may be for rhetoric purpose, to make explanation simpler, or as a real objective in a local context (e.g., Feng *et al.*, 2018), restoring the natural water cycle or predevelopment stage may be one of the objectives of GI implementation. GI infrastructure are inherently technical solutions designed to deliver services to the society. Therefore, the term of restoring the natural water cycle or pre-urbanization stage should be understood from that perspective. It means restoring a water cycle that is favourable to human activity. While some of the first large settlements may have been established on marshes (Lawler, 2011), some modern cities that are partly built on marshes that have been vastly engineered in order to make it favourable for human activity (Bertrand-Krajewski, 2021).

1.3.2 Green infrastructure and hydrological processes

As mentioned above, green infrastructures involve the natural water cycle and hydrological process (Figure 1.4). The input flux includes precipitation and inflow. Inflow in this conceptualization may refer to runoff from adjacent surface, irrigation or artificial rain water (cf Chapter 2). The output flux are evapotranspiration, infiltration, and routing. It should be noted that this conceptualization is meant to provide a general overview but is not exhaustive. Other variables representing processes not represented on Figure 1.4 may be conceptualized in advanced models, a different conceptualization of input and output flux may be used depening on the modelling task and the context.

To model evapotranspiration, it is either possible to model both evaporation and transpiration separately or to model both at once. Models for evapotranspiration generally involve 2 steps (see, e.g., Oudin *et al.*, 2005). First the potential evapotranspiration (PET), representing the evapotranspiration in ideal condition for a reference crop, is modelled, which involves external climate data such as air temperature, solar radiation, wind speed and air humidity. Then the actual evapotranspiration (AET) is computed based on the vegetation characteristic and the state variable of the substrate (i.e., the soil moisture). The PET is scaled to the simulated vegetation modelled using a crop factor which can be above 1 if the vegetation evapotranspirates more than the reference crop, or below 1 else, the factor can vary with seasons. The PET is then reduced through what is sometimes called a soil-moisture evaluation function (SMEF) to account for the plant condition (Kumar *et al.*, 2015). Those function use two characteristic moisture levels that depends on the soil and the vegetation characteristics . The field capacity represent the amount of water that can be retained by the soil (i.e, not infiltrated). The wilting point is the moisture level below which the vegetation may die. When the water content reaches field capacity, the water is easily available for the vegetation, therefore the reduction is minimal. When the wilting point is reached in the soil, the vegetation risks strongly drought induced mortality, the evapotranspiration is therefore reduced to zero. Between those two characteristic points lies the hydric stress range, where the vegetation reduces evapotranspiration to keep water to maintain vital functions. The plant should not remain in hydric stress for long periods to not risk drought-induced mortality. It should be noted that this approach of modelling can involve more processes internal to the vegetation (Kumar *et al.*, 2015).

Infiltration theory is based on hydraulic conductivity, which depends or not on soil moisture. Darcy equation (Darcy, 1856) represents infiltration in a saturated porous medium. Richards equation (Richards, 1931) is used for infiltration in unsaturated porous medium. Other equations derived from Darcy for unsaturated flow, such as Green-Ampt (Heber Green and Ampt, 1911) or Horton (Horton, 1939) equations are also used. Horizontal routing through a porous medium is also important, especially for green roofs. For instance, Palla *et al.* (2011) modelled 2-D flows in porous media based on Richards equation.

1.3.3 Green infrastructure holistic approach: engineering, environment, society and integrated stormwater management

It appears necessary to introduce in this thesis GIs holistically, or at least to specify the extent of the limitations in the current thesis. To do so, it is helpful to have a historical view of stormwater management. Having a look at the History of urban projects, Choay (2014) highlights the opposition between "progressivism" and "culturalism". Originally, "progressism" was driven by the idea of progress and seeking for a universal model for the city. "Culturalism" on the other hand, was driven by the idea of culture, a nostalgic view of the pre-industrial organically grown city. While those two utopias have long been opposed, the idea of integrated stormwater management is supposed to

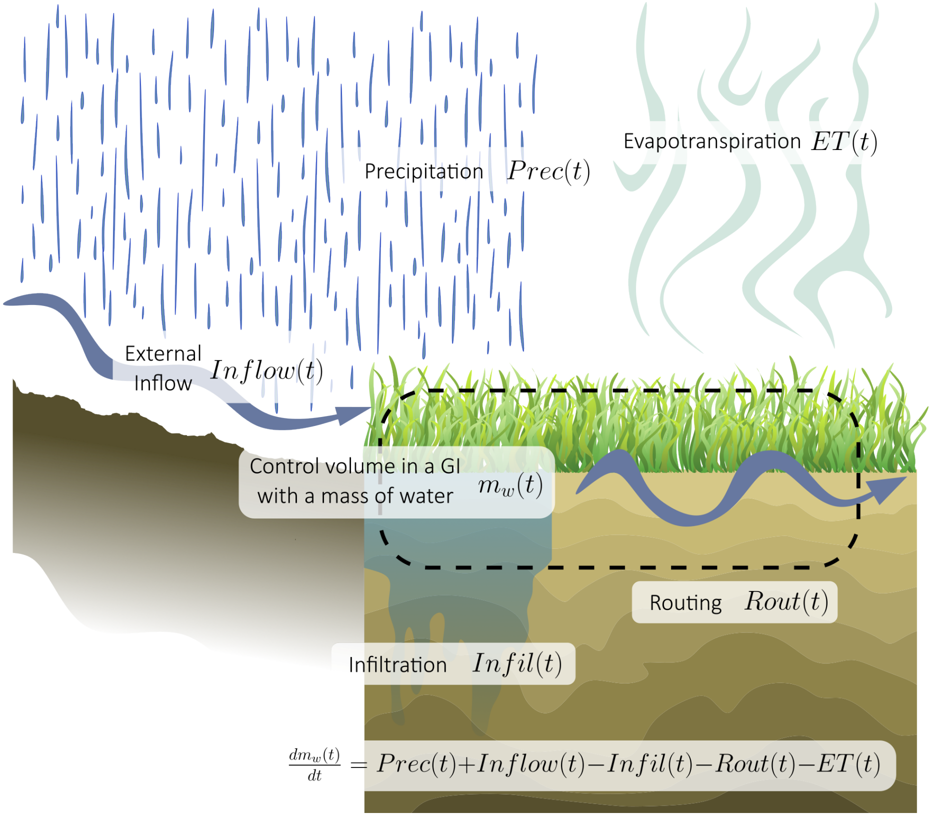

Figure 1.4: Conceptual view of the hydrological processes involved in green infrastructure modelling. The water balance equation is displayed for an arbitrary GI control volume. On this scheme water flux entering the control volume are input flux, and if they leave the control volume they are output flux. It is acknowledged that the context may lead to a different conceptualization. Precipitation refers to natural precipitation(rainfall snow, hail, frozen rain). Inflow refers to external inflows (from adjacent surface, irrigation or artificial rain). In this figure, the routing term refers to both horizontal infiltration runoff and overflow. In GI modelling, the separation between those terms depends on the model conceptualization.

overcome that opposition. Indeed, on the one hand, the local condition (topography, climate, etc.) and local culture have a direct effect on GIs. On the other hand, GIs are inherently technical and engineered solutions. Therefore, despite being a technical approach, integrated stormwater management aims at reconciling technical and social issues.

In order to provide a view of the evolution ot stormwater management, the following paragraphs are mostly based on Bertrand-Krajewski (2021) who provided a review of the history of integrated stormwater management. The development of civilisation is inherently linked to water management. Some of the first large human settlements have been found in marshes (Lawler, 2011). The first traces of a sewer network trace back to 3500 BCE. However, the modern, so-called conventional, sewer system was developed in the first half of the 19th century following the hygienism philosophy. Installing such sewer networks required a significant transformation of cities and a large amount of resources. The concept was based on sanitary consideration to improve the health of the population, but also consisted of a prestigious infrastructure. In that sense, stormwater management was a shift from culturalism to progressism. For decades, the water has been discharged into recipient without treatment. The degradation of the aquatic environment conditions led to the development of wastewater treatment plants.

The main challenge of urban drainage has been defined from an engineering perspective. It was the quantitative problem of sizing the pipes and stations: "How to avoid overflow or flooding?", "At which frequency?". While this section do not discuss the validity of the technical design approach, it is highlighted here that those technical solutions did not follow the yet to be conceptualized ideas of robust decision-making. Indeed, increasing urbanization, and ageing of infrastructures, unveiled the weaknesses of this approach. In a long term, a centralized system with low adaptability and resilience in a system that evolves with increasing urbanization led to the emergence of a new concept: decentralized stormwater management. This approach emerged in the 1960s to rethink urban drainage. Different approaches and terminology were developed in different locations (Fletcher *et al.*, 2015). One of the paradigm shifts is stopping the idea of collecting all water to evacuate it as fast as possible. Instead, it aimed a managing stormwater at the source, by either detaining it or retaining it.

As discussed in Section 1.3.1, the GI evolves with years integrating more objectives, and more functionalities. From a system perspective, this increasing complexity of GI defines the integrated approach to stormwater management. It corresponds to integrating the problem of stormwater to urban design, urban ecology, citizen well-being, etc. In particular, as detailed by Ward *et al.* (2019), while this first paradigm shift toward integrating the question of environment remained a technical approach to stormwater management, integrating social inclusiveness consists in a change of nature of the approach to stormwater from solely technical to sociological.

The change of the approach to stormwater from solely technical and engineered solutions to both technical and social hides another paradigm shift linked directly to climate change adaptation. Indeed, the technical approach to stormwater itself, through the use of a decentralized system, led to a revision of the approach to stormwater quantity management. In Denmark, such an approach is referred to as 3PA (Fratini *et al.*, 2012). This approach stems from the complexity theory detailed in (Geldof, 1995). In Norway, a similar approach is called 3SA (3 steps approach) (Lindholm *et al.*, 2008). This type of approach consists in a differentiated approach to stormwater depending on the type of rainfall. Different strategies are used together to handle different types of events. The most common rain, day-to-day minor rains, can be fully handled on site. The solutions aim therefore at retaining the water through infiltration or evapotranspiration. When a major rain occurs, source control solutions aim at attenuating as much as possible their effect on the stormwater system, since they are not designed to fully retain them. The stormwater system is then used to handle stormwater. The question of defining what is the magnitude of a major rain remains debated and is a local problem for decision-making. The last type of rain is extreme rain. Under this type of rain, the paradigm of robust decision-making is used. It is not realistic to design a system that will not fail, either due to event magnitude or to infrastructure failure. Therefore, it assumes that the main stormwater system (GI, sewer) will fail to contain stormwater, and therefore roadways and habitation may be flooded. It consists in a paradigm shift because it turns stormwater management into a risk-based approach where aiming to resist is not the objective, but rather being prepared for failure "safe to fail" (Liao, 2012). This paradigm shift meets again the shift from technical to technical and social at this last step. Indeed, accepting failure in the city, and accepting the city to be flooded by prioritizing the securing of some areas such as schools is not only a technical problem. It is directly linked to the relationship between citizens and water. It also involves flood memory (Ridolfi *et al.*, 2020) in the sense that having a "flood safe" city though a risk approach implies citizen involvement as they will interact with water in case of flood. The question of acceptable flood frequency is then not only from a technical approach, but also linked to the citizen's flood memory.

In the context of the current thesis, this introduction to integrated stormwater management, with specifically the mention of "culturalism" versus "progressism" aimed at reminding the nature of cities. From a stormwater management point of view, designing a fully new network in a fully new city and adapting centuries of infrastructure to a new paradigm is not the same problem. Integrated stormwater management inherits from the past paradigms and the past designs. In the thesis, though the study of climate change adaptation, the aim is to provide tools to help with performance estimation in order to integrate the failure probability in the current approaches.

1.4 Green infrastructure modelling and hydrological performance

1.4.1 GI modelling practices: A Review

The current section is based on Paper F: "The practice makes the model: a systematic review of green infrastructure modelling practice."

1.4.1.1 Review methodology

Paper Selection

A systematic search for relevant articles was done. First, relevant keywords were generated, as shown in Figure 1.5. Keyword level one indicates the different terminologies often used to describe GI, as summarised by the review of (Fletcher *et al.*, 2015). The second level represents the different hydrological processes within the GI. The last keywords were included to ensure that the paper includes a modelling task. The search was done on the Web of science and Scopus and resulted in more than 900 relevant articles after title screening. The sample consists of papers that were published before April 2020. We excluded studies that focus on modelling GI at catchment scale and only focused on those that developed and/or used a model on single GI units. Hence, we selected 270 papers for the review after reading the titles and screening the abstracts. Figure 1.5 illustrates the steps followed to find the relevant papers for the review.

The number of papers and the period chosen was considered to be sufficient to represent the current practice of communicating GI modelling tasks and how the practice evolved in recent years. Communicating modelling tasks refers here to the details of a modelling task that are shared with other researchers through peer-reviewed publications.

Review bias and limitations

The paper selection was done in a similar fashion to the approach presented in Moher *et al.* (2009). It included keywords search from 2 databases, duplicate removal, title screening, abstract screening, full text screening which led to the selection of the papers for the quantitative review. Based on the quantitative review, examples of good practices were considered as the sample for qualitative review. This review intent to be systematic and therefore to limit bias (Moher *et al.*, 2009). The bias management is here twofold: i) applying a systematic procedure to each paper, and ii) making the reader aware of the existing biases.

Paper selection and bias

The sample selected consists of 270 papers published until April 2020. This constitutes a limitation, since the sample could have been extended until 2022. However, extending the sample by a new sample would have introduced a bias, since the author would not be able to maintain the same bias as for the first sample. Moreover, one of the goals was to reveal the trend of practice in the recent year. The trend itself consists in assessing statistics in yearly subsample. It means that extending the sample would not have changed the results, but only extended them to more recent years.

The total number of papers, 270, was found sufficiently large to get an order of magnitude of the practice in the field. It was not necessary for the conclusion of this paper to have a confidence interval smaller than 10%. This could be confirmed by the use of methods such as confidence intervals or bootstrapping.

The choice of keywords also constitutes a limitation. As it is acknowledged widely (Fletcher *et al.*, 2015; Matsler *et al.*, 2021) the terminology related to green infrastructure is relatively wide and often related to a local context. Other terminologies could have been included in the search and influenced the general trend. However, this does not affect the conclusion linked to the keyword used. And it does not make the recommendation made here necessarily invalid for the other GI keywords.

Paper analysis bias

Each of the papers in the sample were reviewed through a paper analysis methodology which consists in assigning items qualifying the modelling practices to different categories systematically for each paper. The details of the categories and items are detailed in Section 1.4.1.2. For each of the categories, the items were defined iteratively. A first draft was tested on a test dataset. The results and limitations were analysed with all co-authors to update the items.

The review was done category by category and not paper by paper in order to keep consistency in the analysis. It was decided not to do duplicates because it was found more efficient and adequate to select a single author per category based on its expertise. In order to limit the biases, two measures were taken. Automatic word search in the papers was used to draft a prior categorization of the papers. Expert knowledge was then used to analyse each paper and decide on the posterior categorization. When a paper was in a grey-zone between two items, it was brought to discussion between the co-authors to decide.

Reproducibility and ethic

The paper analysis methodology is presented and detailed in Section 1.4.1.2. The list of papers reviewed in the sample is available in the appendix (Table C.1. It was decided not to share the full table of items per paper for several reasons. In terms of ethics, the authors consider that highlighting the good examples consider a better practice than sharing examples with limited practices. Moreover, sharing examples of limited practice would have required the author's consent for good practice. In the analysis process, the bias was limited in order to preserve the general trend and not the individual items. It means that when several papers lie between two items they would not be systematically downgraded or upgraded since it would result in a larger bias in the trend.

1.4.1.2 Review methodology

The articles studied in this paper were assessed according to 10 different categories in 5 different sections based on relevant guidelines of good modelling practice (Crout *et al.*, 2008; Jakeman *et al.*, 2006). They were adapted to the context of GI modelling. They aim at investigating of the alignment between objectives, and methods: i) General study frame (Table 1.2), ii) Model assumptions and selection(Table 1.3), iii) Use of objective functions(Table 1.4), iv) Uncertainty and sensitivity(Table 1.5), v) Parameters selection and model testing(Table 1.6). The assessment criteria consist of evaluating how each of the reviewed studies addressed the nine categories employing categorical or ordinal variables. It should be noted that the steps of the good modelling practice, as mentioned in Tables 1.2, 1.3, 1.4, 1.5, and 1.6, are interconnected and should be assessed in an iterative process (Jakeman *et al.*, 2006). However, the order presented here is not arbitrary. The uncertainty and sensitivity sections were not placed at the end of the list in order to highlight that it is indissociable from a modelling task and not a separate task. The parameters selection and model testing, directly linked to monitored data, were put at the end of the list. This is because monitored data can be considered as the source used to develop models. In addition,

Table 1.2: Paper analysis methodology for the general study frame. [modified from Paper F]

i) General study frame			
a) Are the objectives of the study clear?		**b) Are the modelling task limitations stated?**	
ObjUncl	Some objectives are defined but without clearly stated research questions.	**LimNone**	The limitations of the study and the methodology are not clearly stated
ObjMent	The study presents both a research question and research objectives.	**LimFurt**	Limitations or suggestions for further work are stated (related to objectives)
ObjClear	The study presents a research question, objective for the research and detail how they intend to achieve the objectives.	**LimMeth**	Limitations or suggestions to improve methodology are stated
		LimBoth	Both limitations and suggestions to improve the methodology and for further work

monitored data also needs to be used in a later stage for model testing and uncertainty propagation.

Table 1.3: Paper analysis methodology for model assumptions and selection. [modified from Paper F]

ii) Model assumptions and selection **c) Are the choices of the selected hydrological processes justified?**		**d) Are the choices of the selected/major equations justified?**	
HyNone	The hydrological processes are not mentioned	**EqNone**	None of the equations are mentioned
HyMent	The hydrological processes selected are mentioned	**EqPart**	Some of the selected equations are mentioned
		EqMent	All the selected equations are mentioned
HyJust	The selection of hydrological processes is justified (e.g., from literature or conceptualisation of the system)*	**EqJust**	The choice of the equations is justified (e.g., from literature or equation properties)*
HyNR	It is not relevant to mention the hydrological processes	**EqNR**	It is not relevant to mention the selected equations

Table 1.4: Paper analysis methodology for the use of objective functions. [modified from Paper F]

iii) Use of objective functions **e) How does the objective function choice align with model and study objective?**		**f) How are the objective functions used for model evaluation?**	
OFNone	No objective functions used or mentioned	**OFVNone**	No threshold or no explanation
OFPop	Objective functions used because of their wide use and not because of their properties (i.e. not justified)	**OFVPop**	Threshold selected because of its wide use in the literature (i.e., not justified)
OFRed	Redundant objective functions set used without justification	**OFVLit**	Justified from literature or through author argumentation
OFJust	The selection of objective function is justified*	**OFVObj**	Justified based on the objectives of the study*
OFNR	It is not relevant to select objective functions	**OFVNR**	It is not relevant to use objective functions

Table 1.5: Paper analysis methodology for uncertainty and sensitivity analysis. [modified from Paper F]

iv) Uncertainty and Sensitivity analysis **g h)** How is Uncertainty/Sensitivity analysis included in the study?**	
UncNone/ SenNone	The concept of uncertainty/sensitivity is not mentioned
UncMent/ SenMent	The concept of uncertainty/sensitivity is mentioned in the results
UncUse/ SenUse	A method of uncertainty/sensitivity analysis is used but not specified
UncSpec/ SenSpec	A method of uncertainty/sensitivity analysis is specified but not justified
UncJust/ SenJust	The method (or absence of method) is justified in the context of the study (hypothesis)*
UncDed/ SenDed	The objective of the paper directly involves applying uncertainty/sensitivity analysis

Table 1.6: Paper analysis methodology for parameter selection and model testing. [modified from Paper F]

v) Parameters selection and model testing **i) How are the model parameter selected?**		**j) How is the model tested?**	
ParNone	The parameters selection process is not mentioned or not aligned with the objectives	**TesNone**	The model is not tested, and it is not justified why it is not tested
ParMent	The parameters are selected from literature or measured	**TesLim**	The data for testing are limited (i.e., it is not explained why the dataset is sufficient) and it is not justified
ParLitJust	The parameters are selected from literature or measured; it is explained why their choice is relevant to the study	**TesLJust**	The data for testing are limited, but the limitations are stated, or the dataset is presented
ParMan	A manual calibration is used to select parameters		
ParJust	The parameters are selected through automatic calibration, or their choice is justified by the authors*	**TesSJust**	The dataset is sufficient (i.e., it is justified why the data are sufficient through convergence of performance indicators), and the dataset is presented*
ParNR	Selecting parameters is not relevant in the study	**TesNR**	It is not relevant to test the model.

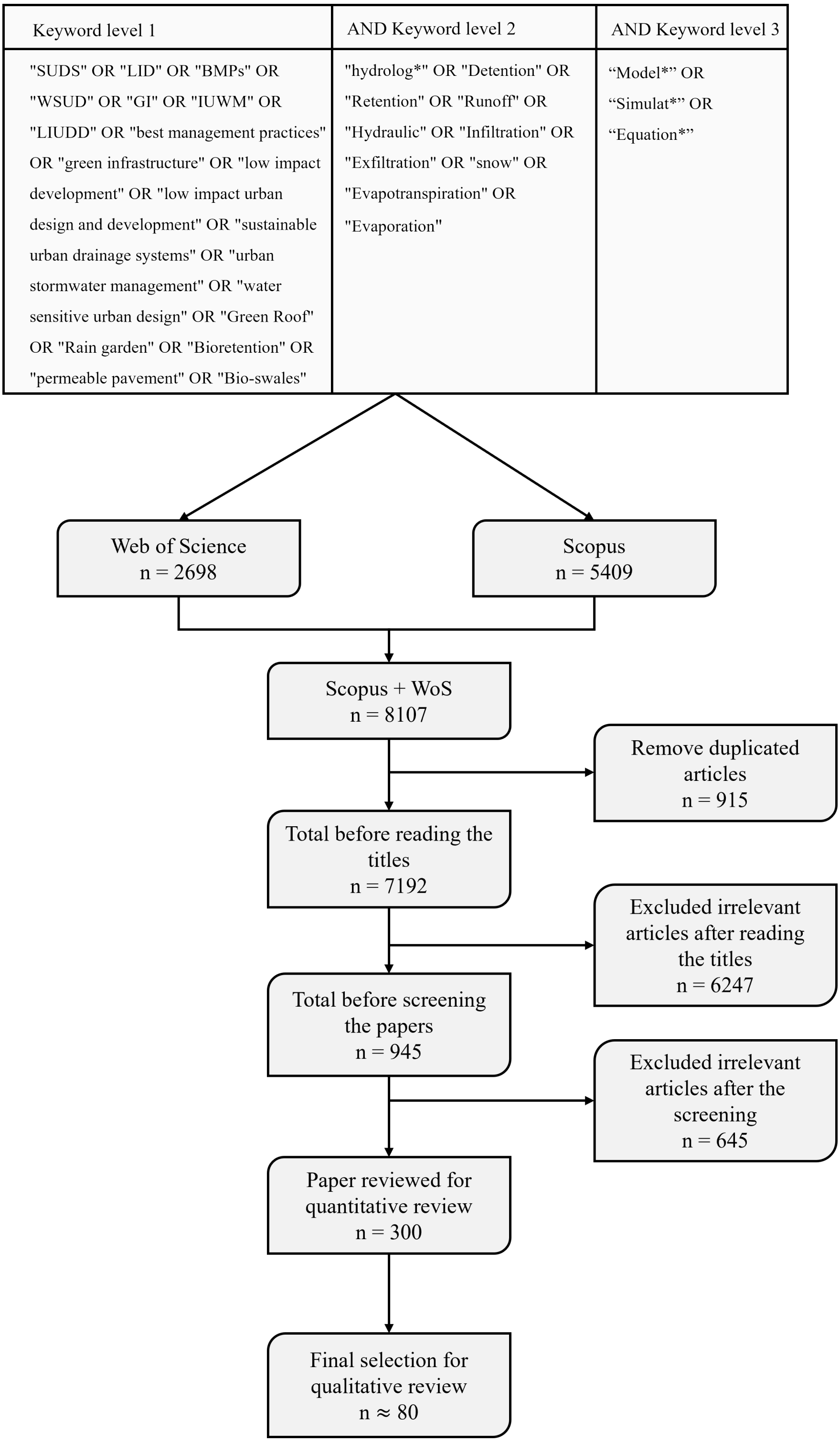

Figure 1.5: Keywords search and systematic methodology for relevant paper selection. [Paper F]

1.4.1.3 The (current) hydrological modelling practices in GI

Clarity of the modelling study and limitations

The practice of communicating objectives is a standard in most published papers. With very rare exceptions, most of the studies stated their objectives and research questions, as shown in Figure 1.6a. However, only 50% seem to detail the objectives clearly, presenting how they intend to answer the research questions. Therefore, the effort put into communicating the objectives should be improved and perhaps standardized. Stovin *et al.* (2013), for instance, presented the aim of the study and then explained the modelling approach before detailing the sections of the thesis. Whist, it could be debated if it is necessary to reach such a level of detail in the introduction section, it serves the purpose of making the information rapidly available. Peng *et al.* (2019) presented the aim of the paper and then the way the aim was achieved through sub-objectives, which communicates effectively the structure of the paper and should be seen as an example of good practice.

The study of limitations showed an opposite trend. The limitations of the study, and more specifically of the modelling approach, are not systematically stated. It might be linked to the limited incentives to publish failure or negative results. Suggestions for further studies, when stated, are often displayed in the conclusion. Some papers, such as Locatelli *et al.* (2015), displayed a limitations section dedicated to the model assumptions before the conclusion. Others, such as Versini *et al.* (2015), included clearly the limitations in the discussion section. This was considered a good practice because it relates the model limitations directly to the context of the study and the results. The good practice in limitations is not necessarily restricted to the model assumptions, but should also include the data and methods section. Stovin *et al.* (2012) acknowledged data limitations and their consequences on the results. Similarly, they acknowledged the limitations of the event definition.

Selection of hydrological processes and model equations

Almost all reviewed papers ($> 95\%$) were found to state all the hydrological processes selected for modelling, as shown in Figure 1.6c. Moreover, around 64% of these studies attempted to justify the selection of the hydrological processes, either by a conceptual description of the GI hydrological cycle (Li and Babcock, 2016; Stovin *et al.*, 2013; Vesuviano *et al.*, 2013), a description of laboratory GI model (Carbone *et al.*, 2014; Jahanfar *et al.*, 2018; Martin III *et al.*, 2020; Yio *et al.*, 2013), or by a sensitivity analysis of the hydrological processes using a numerical model (Hakimdavar *et al.*, 2014). Few studies were found to state the hydrological processes that were excluded from the modelling task, which is considered a good practice. For instance, Hakimdavar *et al.* (2014) justified why ET is considered negligible in their event-based simulations. They assessed the sensitivity of ET during single events using Hydrus and found it to be insignificant. Most of the studies ($> 80\%$) were found to state all selected model equations. However, we identified a gap in the practice, regarding the

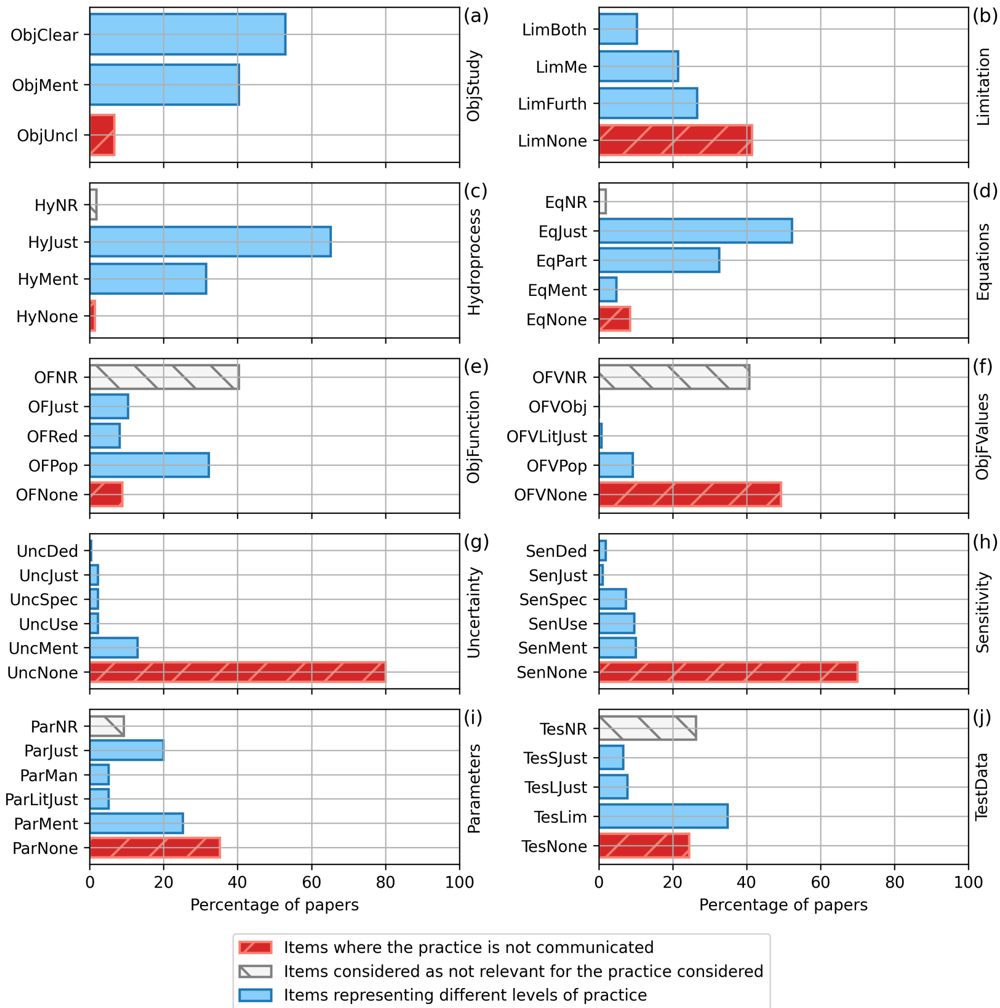

Figure 1.6: Summary of the reviewed categories. [Paper F]

justification of selected model equations, as only around 50% of the studies justified their selection. As mentioned earlier, in "good modelling practice", model equations are selected based on their suitability to the modelling task. A clear justification on why the selected equations fit the modelling purpose should, therefore, be provided. However, the selection of most GI equations seems to be dictated by the availability of the modelling tools, such as SWMM and Hydrus, and not by suitability. For instance, as shown in the supplementary materials (Figure 1.6b), the most selected infiltration equations were Green Ampt (Heber Green and Ampt, 1911) and Richards (Richards, 1931) which reflects the popularity of the SWMM and Hydrus tools, respectively. It could also be due to a hypothetical consensus of equations to be used without need to justify, however no study clearly justifies that consensus.

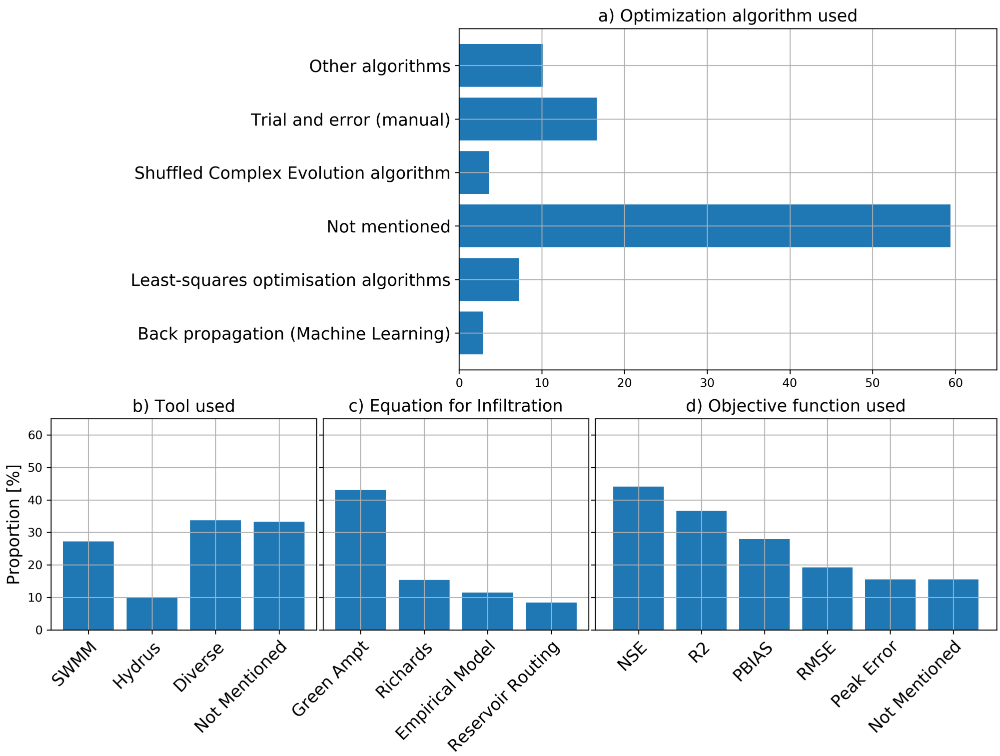

Figure 1.7: Selection of modelling choices collected from the corpus of paper. In particular a) Optimization algorithm used for calibration, b) Tool used for hydrological modelling, c) Equation used to model infiltration, and d) Objective function used for testing and calibration. [Paper F]

Objective functions and interpretation of model results

The Nash Sutcliffe Efficiency (NSE), the percentage bias (PBIAS), and the determination coefficient (R^2), which has clear shortcomings (Kvalseth, 1985), were the most popular objective functions in the reviewed studies, as shown in the supplementary materials (Figure 1.6c). The majority of the studies applied more than one objective function to assess model accuracy. For instance, Haowen *et al.* (2019) applied six objective functions for model calibration and validation. The Kling Gupta Efficiency (KGE), developed by Gupta *et al.* (2009), one of the common objective functions for hydrological modelling of catchments (Knoben *et al.*, 2019), was not used by any of the 270 papers used in the review. Only a few recently published studies in the field were found to use KGE (Iffland *et al.*, 2021; Mohsen Hassan Abdalla *et al.*, 2022). The review indicates that objective functions are often selected based on popularity and not on their suitability to the modelling task. Different objective functions are known to be more suitable for different tasks (low flows, high flows, etc.) (Wöhling *et al.*, 2013). However, there is a lack of clear justification for the selection of objective functions and a lack of discussion on the effects of the selection on model calibration/evaluation in GI modelling studies, which should be further investigated. The values of objective functions are interpreted to evaluate the accuracy of modelling results. Most of the reviewed papers were found to use subjective terms. i.e. "accurate", "good", "poor", "satisfactory", etc. without defining what is an "accurate" or a "satisfactory" result. 28 of the reviewed papers defined threshold values for describing modelling results as "good" or "poor", based on previous literature. For instance, many studies were found to define a threshold of $NSE > 0.5$ to be satisfactory modelling results following the study of Rosa *et al.* (2015), which justified this selection by citing the work of Dongquan *et al.* (2009). The latter authors based this selection on following a modelling protocol, suggested by Engel *et al.* (2007). Another example is the study of N. Moriasi *et al.* (2007), which provided a protocol for hydrological modelling. The paper is commonly cited in GI modelling studies for providing threshold values for describing modelling results as "good" or "unsatisfactory". Nevertheless, N. Moriasi *et al.* (2007) provided these limits based on their experience in catchment modelling, which might not be comparable to the scale of GI measures. Moreover, these limits were discussed by N. Moriasi *et al.* (2007) to be valid only for continuous, long-term simulations and monthly time steps, and they recommended adjusting these values for different cases.

Sensitivity and uncertainty

Uncertainty and sensitivity analysis (UA and SA) are not systematically used in Green infrastructure modelling studies, as shown in Figure 1.8a and b. The practice of mentioning those topics in GI modelling papers appeared in 2008. Even in recent years, more than half of the papers reviewed do not mention uncertainty or sensitivity. UA or SA methods are used and named in less than 25% of the studies. This low percentage can be explained by the computational cost of the methods, their complexity, or the lack of knowledge by the authors despite the efforts made to communicate on those aspects and suggest frameworks to facilitate their spread (Deletic *et al.*, 2012; Dotto *et al.*, 2010; Pappenberger and Beven, 2006; Tscheikner-Gratl *et al.*, 2019). In particular, Figure 2 shows that the application of the best practice in Sensitivity and Uncertainty analysis, as defined in this study by SenJust and UncJust in Table 1.5hi, did not increase in the last years. This is a major issue in the development of the field because a method to propagate the uncertainty to the output is rarely used, which limits the reliability of the published results. UA and SA might have been ignored in green infrastructure modelling because the most used software, such as SWMM and Hydrus, which were used by 27% and 10% of the reviewed papers, respectively, do not include built-in functions for this purpose. Few of the reviewed studies applied a good modelling practice regarding UA and SA analysis. For instance, Brunetti *et al.* (2018) compared different UA methods based on their performance and computational cost. They recommended the use of formal Bayesian methods such as Markov-Chain Monte-Carlo (MCMC) over the generalized likelihood uncertainty estimation (GLUE) method (Beven and Binley, 1992). GLUE was also used by (Feng *et al.*, 2018; Krebs *et al.*, 2016). Fuzzy set theory has recently been used by Lu and Qin (2019) to implement fuzzy parameters in SWMM after sensitivity analysis to allow vagueness. However, the use of the UA framework remains more limited than SA. GI placement studies are slightly out of the scope of the current review, but should be mentioned. Similarly to Lu and Qin (2019), this type of study often deals with a deep type of uncertainty (Walker *et al.*, 2013). It results in the use of a different set of methods, among which can be mentioned ensemble modelling and scenario-based uncertainty. Those methods are often used in climate modelling and climate change adaptation studies (Lee *et al.*, 2021). Ensemble models are used to qualify the range of uncertainty when no formal statistical methods can be applied (e.g., climate model ensembles). Scenarios based approaches are used to split the range of uncertainty in subregions to facilitate its management (e.g., climate scenarios). Among the SA methods, the Elementary effect test, also known as the Morris method (Morris, 1991), has been widely used (Baek *et al.*, 2020; Brunetti *et al.*, 2018; García-Serrana *et al.*, 2018; Li *et al.*, 2020). It should be noted that this method, while cited, is rarely justified or aligned with the objectives. Indeed, this method, being a One-At-the-Time (OAT), suffers limitations and should therefore be used in a restricted context (Saltelli *et al.*, 2007), e.g. for screening purposes. Other methods such as e-FAST, Monte-Carlo filtering, subset simulation, or PAWN can be mentioned (Brunetti *et al.*, 2018; García-Serrana *et al.*, 2018). Nevertheless, in most cases, only a local perturbation (one of the LSA method) is applied to the parameters one-at-the-time (OAT). Such methods can be performed without programming skills, since the number of simulations can be handled manually. However, the information gained from that practice is limited and can be misleading if not analysed carefully (Saltelli *et al.*, 2007).

Parameter estimation and model testing

Almost half of the reviewed papers selected parameters based on literature values or laboratory measurements ($\approx 48\%$) and not on calibration. These include papers in which parameters were obtained through model calibration by the same authors in a previous study. For instance, (Palla and Gnecco, 2020) used a calibrated hydrological model for quantifying the hydrological impact of green roofs. The model was calibrated by the same authors in a formal study (Palla and Gnecco, 2015). The practice of model calibration, however, has gained more popularity in the field of GI modelling in the last years, as shown in Figure 1.8c. We hypothesized that the increased availability of GI measured data in recent years has led to the increased practice of model calibration. Although the practice of calibration is gaining popularity, there is still a lack of clear documentation on the calibration method; 60% of the studies that performed model calibration (82 papers) did not clearly state the algorithm or the tools used for calibration. Moreover, global calibration methods that aim at finding global optimal parameter sets employing automatic algorithms are still lacking for GI models used in GI modelling studies; only 23% (33 papers) that performed model calibration used automatic algorithms. There is no consensus on the calibration algorithm used in GI modelling, as shown in Figure 1.6a. Manual calibration, employing a trial-and-error

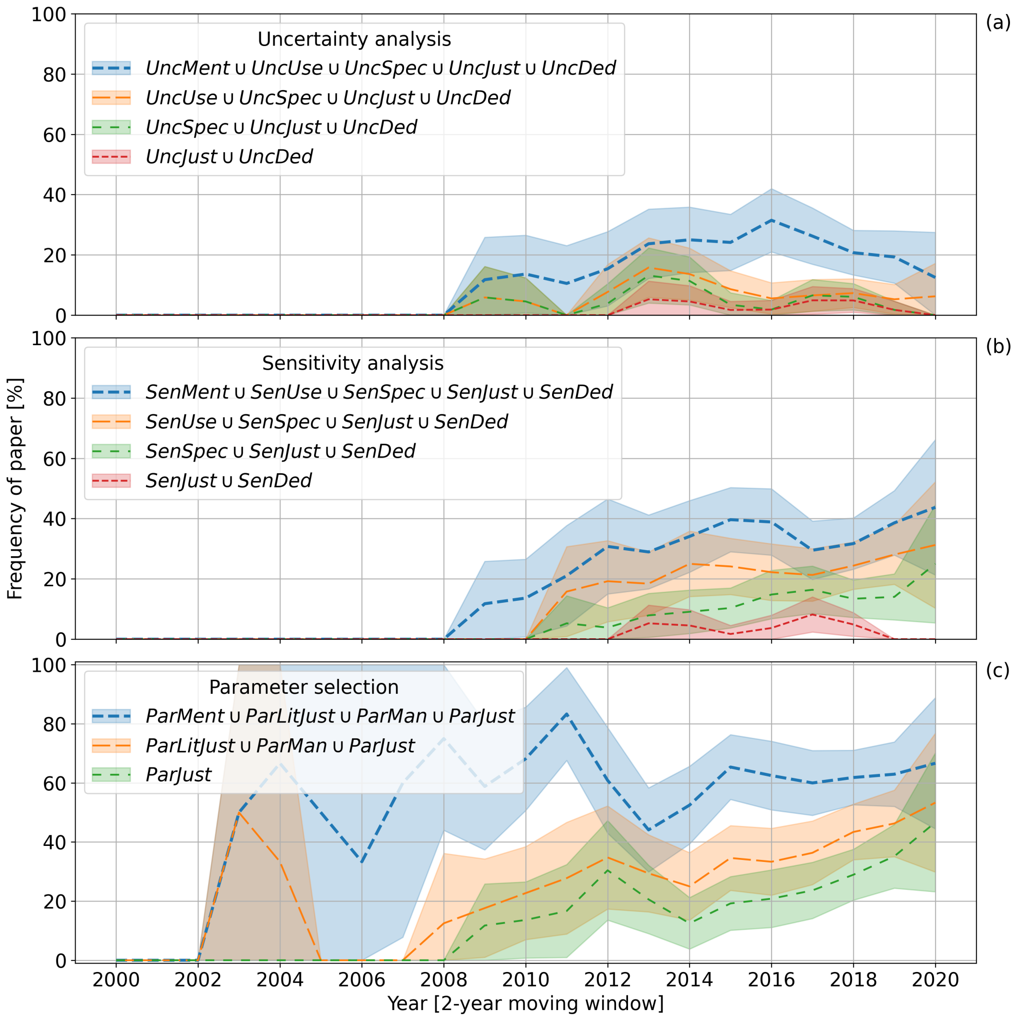

Figure 1.8: Evolution in time of the practices of applying uncertainty and sensitivity analysis and of selecting model parameters. [Paper F]

method, was found to be stated in 23 papers. Recently, a few papers evaluated the transferability of calibrated parameters between similar GI located in different regions (Johannessen *et al.*, 2019; Mohsen Hassan Abdalla *et al.*, 2022). The results of these studies suggested that calibrated parameters could yield poor simulations if used in different climatic conditions from the ones used in model calibration. However, most GI modelling studies applied parameters from published literature or used calibrated models to evaluate the climate change impacts. In both cases, the climatic conditions might differ significantly. In such cases, the use of ensemble modelling (Le Floch *et al.*, 2022), multi-objective calibration (Fowler *et al.*, 2016), and multi-data for model calibration (Mohsen Hassan Abdalla *et al.*, 2022), might offer solutions to account for the uncertainty and can be recommended for future studies. Figure 1.6j shows that the current practices in testing models rely on limited data, as defined in Table 1.6, more than 60% of the studies in the last decades. In a limited number of studies, the data can be sufficient for model testing, as is often the case for multimodel comparison (Zhang and Guo, 2015). In general, the continuous time-series of data monitored from GI are not proven to be long enough to ensure sufficient data to achieve studies objectives. A "Long enough" dataset is defined as a dataset allowing to converge to the quantity of interest. More specifically, there can be a difference between an estimator of the performance of a GI in a specific location based on available data and based on theoretical sufficient data. The difference between the "true" performance and the estimator based on limited data has to be close enough in accordance with the objectives of the study. Aside from proving convergence, good practices of testing under limited data encompass i) the presentation of the characteristics of the testing dataset which include the number and characteristic of rainfall events, e.g. Carson *et al.* (2013) classified events, based on their depth; ii) the consequences and uncertainty linked to the limited dataset, e.g. Maniquiz *et al.* (2010) specified that due to limited data the calibration and validation could not lead to a reliable parameterization of the model. An increase in testing dataset justification should help to improve and increase the confidence in the developed models, and the share of data could help to push back the limitations linked to limited data. Another approach to cope with limited data, especially in the rare occurrence of extreme events, consists in creating the data based on an experimental setup that allows for better control of the calibration or testing dataset e.g., (Hamouz *et al.*, 2020b; Vesuviano *et al.*, 2013).

1.4.1.4 GI models transferability

One of the current limitations in improving the practice in GI model use is linked to transferability of model parameters. Let us consider a green roof monitored in a given location (e.g, climate domain A in Figure 1.9). Based on the data, a model may be calibrated. Depending on the monitored data and the model structure, it may not be possible to transfer the model's parameter to another location (e.g, to climate domain B in Figure 1.9). It could be the case, for instance, if the monitored data are not within the intersection between the two domains. Consequently, the model calibrated would have low reliability in domain B. If it is not possible to use the model in the location B then the model has limited use for decision-making and implementation-scenarios. The difficulty inherent to transferability of model parameters is comparable to the challenge of performance prediction in future climate. Figure 1.9 shows that given two locations the climate domains might overlap, but the universe of possible (or more precisely probable) climate conditions is likely to differ. When it comes to environmental model calibration, it means that the set of ideal parameters set that lead to good model performance in one location might not provide satisfying performance in the other location. This issue is linked to equifinality (Beven, 2006). It occurs when a model has enough degrees of freedom to fit observed data with different sets of parameters. In particular, those sets of parameters, or sets of distribution of parameters, may result from a compensation between the processes modelled. This level of uncertainty is particularly high. If we consider, for instance, a catchment model where we know the rainfall time series at one point and the outflow time series at another point. Based on this data, a parameter set may attribute a part of the losses to evapotranspiration, while another one may attribute it to infiltration. As a result, the model calibrated may not have meaningful parameters sets since too limited information was available for the calibration. It may result in a limited reliability of the model in a transferred location or different climate location (e.g., Johannessen *et al.*, 2019).

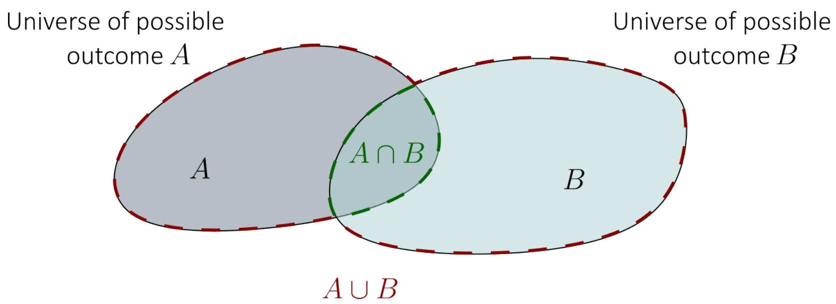

Figure 1.9: Conceptual view of intersection of location-dependent climate domains.

1.4.1.5 Models limitation: Neglected processes, Non-stationarity and Failures

One question that arose from the modelling practice review was the convergence of performance indicators. Indeed, in order to evaluate a performance indicator representing an estimate of the true performance with a predefined level of accuracy, a certain amount of data is necessary. If we consider climate change, it appears that the condition from a decade to another may differ, which makes the convergence evaluation more challenging due to non-stationarity of climate conditions. Another source of non-stationarity lies in the ageing of green infrastructure.

For instance, ageing of substrate may alter the behaviour of green roofs. Despite those processes being studied, it is still complex to find a relationship between performance and age. Therefore, ageing has not been modelled yet. Bioretention cells were found to remain effective in the long term to deal with pollutants, but heavy metal should be more carefully studied (Costello *et al.*, 2020). De-Ville *et al.* (2017, 2018) found the green roof's hydrological performance to increase with age, while Bouzouidja *et al.* (2018) concluded the opposite. It should be added that local conditions, and maintenance, remain diverse. This, combined with the limited data, may explain why it is still complex to account for those limitations.

Vegetation has been proven to vary with both the season and the years (Dunnett *et al.*, 2008; Köhler, 2006). Stovin *et al.* (2015) found vegetation to influence both retention and detention. The process of evapotranspiration depends on the vegetation, its state, and the available water content in the substrate. During a drought, the vegetation enters a state of hydric stress, which prevents from achieving its main function in the green roof: evapotranspiration. If the drought is too severe, it can lead to drought-induced mortality of the vegetation, which in terms of stormwater infrastructure can be interpreted as permanent damage to the infrastructure. It is then necessary to do a maintenance or a rehabilitation. Plants mortality has been studied from a physiological perspective (McDowell *et al.*, 2013; Sapes *et al.*, 2019). Based on a model representing coupled xylem and phloem transport, Mencuccini *et al.* (2015) identified three major drought induced mortality modes: i) carbon starvation, ii) hydraulic failure and iii) phloem transport failure. They acknowledged drought-induced mortality as being challenging to model. Several studies investigated hydric stress in green roofs (Nagase and Dunnett, 2010; Vanuytrecht *et al.*, 2014) or the use of drought resistant species (Szota *et al.*, 2017) and the importance of plant traits for adequate vegetation selection for green roofs (Chu and Farrell, 2022). For example, Du *et al.* (2019) reported a survival rate between 10 and 100% for distinct species at the end of a summer where the soil water content dropped to 5%. Nagase and Dunnett (2010) reported, based on a dry watering regime (once every three weeks), survivability after 11 weeks. Many species had a survivability below 25% while sedum species had mostly high survival rates. Those different evidences shows that the plant selection and plant health might affect significantly the retention performance of green infrastructure. Not taking them into account might result in high estimation errors.

Other infrastructures such as permeable pavements, infiltration trenches or infiltration swales may be subject to clogging. Sañudo-Fontaneda *et al.* (2018) studied the clogging for different vertical-infiltration-based solutions (porous asphalt, permeable pavement, etc.) and suggested taking it into account for design. Brugin *et al.* (2020) found clogging to have a significant effect on the hydraulic properties of the permeable pavement. Therefore, it seems crucial to include clogging in long term modelling studies. It has been modelled assuming a linear increase of the clogging layer thickness to alter the hydraulic conductivity (Bergman *et al.*, 2011). The model was built based on measurement in the 90s, and in 2009, it predicts the decrease of the hydraulic conductivity in the next years. The study showed that hydraulic conductivity decreased significantly. Radfar and Rockaway (2015, 2016) used an artificial neural network (ANN) to predict clogging and the efficiency of the different maintenance procedures. They concluded that ANN was an effective tool to predict clogging, and the choice of the maintenance procedure was not the most significant factor influencing the clogging.

The consequences of those non-stationarities is an unknown shift between the "ideal" modelled performance (i.e., neglecting those aspects) and the "true" performance. This thesis dealing with the use of models for future performance evaluation, accounting for those sources of non-stationarity were not explicitly developed. Some work in the direction of accounting for failure processes has been initiated during the PhD but is not directly presented in the current thesis (e.g., Presentation D and Poster C)because i) of the lack of available models, ii) the lack of available data. The last reason is that accounting for those non-stationarities is not expected to affect the outcome of the thesis which is not quantifying the future performance of GIs but developping methods to do so.

Some hydrological processes such as snow occurrence and cold temperature are mostly ignored in green infrastructure modelling. Yet, snow should perhaps be accounted for more often in the models. Indeed, 13 of the 100 largest cities in the world are classified as cold climate (Kratky *et al.*, 2017). Cold temperature can affect the vegetation state (even causing mortality), and the infiltration rates are modified in frozen soil (Kratky *et al.*, 2017). Lastly, snow itself has several effects on stormwater management. The water out of snow in cities may carry a larger amount of pollutants than regular stormwater (Borris *et al.*, 2021). Snow may also trigger flooding through snowmelt induced flooding. In general, one should also consider rain on snow event, which may accelerate snowmelt and therefore carry both water from rainfall and from snowmelt (Kratky *et al.*, 2017). Snow in GI modelling is only modelled in a very few studies. Hamouz and Muthanna (2019) used SWMM to model event-based runoff from green and grey roofs in Norway during snow and snow-free periods. The SWMM equation for snowmelt is a degraded version of water-energy balance and consists of a simple temperature based equation. A simpler approach was followed by Roehr and Kong (2010) in modelling daily runoff reduction from green roofs. The snowmelt was estimated as the difference between the precipitation and rainfall (rainfall occurs when the air temperature is higher than zero). Such an approximation is only relevant for coarse resolution.

1.4.2 GI model use and performance definition

The hydrological performances of green infrastructure includes retention performance and detention performance. Retention consists of water that is permanently removed from the stormwater management system. It corresponds in general to evapotranspiration and infiltration, depending on the system boundaries. Detention consists in attenuation or dampening of the flow by the infrastructure. The relevance of performance indicators is further discussed in Chapters 3, and 5. Only a brief introduction is presented here.

The performance indicators are usually calculated from continuous simulation/-monitored time series or from event-based simulation/monitored data. The advantage of event-based simulation lies in storylines that are sometimes used. Extreme events can be sometimes very informative for communication purpose, for instance the 2011 Copenhagen cloudburst had a strong impact on stormwater management policies (Rosenzweig *et al.*, 2019). The main caveats of event base simulation lies in initial condition control and events definition. The events are often defined with a minimum inter event time (MIT) which consists in the threshold used to split time-series in several rainfall events (see Chapter 3). In particular, the 6-hour definition of event is often used but rarely justified (Stovin *et al.*, 2012). The use of continuous time-series is sometimes preferred event for event-based analysis because the initial conditions at the beginning of an event are directly accounted for through continuous simulation. However, those simulations are more time-consuming and do not always include representative extreme events.

The type of indicators can be classified between singletons and density based indicators. The first one represents a single number while the second one, based on a probability distribution, incorporates information about a probability of occurrence. The advantage of singletons is that they are commonly considered as easier to understand, but they are not representative, which makes them misleading. This "advantage" of being easily explained by comparison to probability density distribution is perhaps not fully relevant. Pappenberger and Beven (2006) presented in their opinion paper several reasons why uncertainty analysis might be avoided and discussed whether the arguments are valid or not. The 4^th argument is "Uncertainty (probability) distribution cannot be understood by policymakers and the public". In particular, taking the example of the confusion between flood frequency and probability of exceedance, they suggest that poor communication may be the main problem rather than a real lack of understanding. To support that, they also show that the concept of uncertainty and risk can be understood by the public. A probability-density distribution can be used to convey a better information if communicated efficiently. The singletons indicators are often event-based. Stovin *et al.* (2017) showed that even event-based singletons can be used in a relevant way by considering a representative set of events in order to build a probability density distribution. A performance indicator, similarly to sensitivity indices, should be informative, not misleading, easy to interpret, and easy to compute. For instance, the peak delay, which represents the delay between the peak of rainfall and the peak of runoff, is ambiguous because it is not always obvious which peak should be considered. Moreover, it is often understood as easy to interpret since its meaning is simple to understand, it represents the delay between the maximum of a storm event and the maximum of runoff. The centroid delay, which represents the delay between the mass centre of the rainfall event and the runoff, is less intuitive in that matter since it is less visual.

A performance indicator such as peak flow reduction alone is misleading. It consists of a normalized indicator, which can lead to misuse. For instance, let us consider two solutions monitored on different periods and with different sensors. It may not be possible to compare the peak flow redution. The first reason is the sensitivity to noise. Considering two comparable events, if one of the sensor is an optical rain gauge and the other tipping bucket, the resultling performance indicator may not be comparable if the data are not processed. The second reason is the comparability between events. If one were to compare the performance on two sets of events that are not comparable then the conclusion of the comparison may be biased. While those weaknesses can also affect other performance indicators, flow peak reduction is particularly sensitive to those. For instance peak runoff since it is not normalized contains a different information. In practice, even though the previous examples look simplistic, such invalid comparisons are likely to be done with different sets of events for two solutions and used to conclude which one performs better. The indicator seems very easy to interpret since it provides a percentage of reduction on an event, but it is easily misused though invalid comparison.

The current PhD involved conceptualization of performance indicators to convey uncertainty while keeping the simplicity of interpretation (Chapters 3, and 5). The question of performance indicator is directly linked to the transfer from data to information and upscaling simulation results to the decision scale (Chapter 6).

1.4.3 GI models and scales

The relation between GI models and scale is complex due to the multifunctional nature of GI. In the context of this thesis, it is important to account for that relationship in order to provide useful knowledge for decision-making. In particular, while Chapters 2, 3, 4, 5 mostly consider GIs at site scale, Chapter 6 aims at upscaling this knowledge at a different spatial scale. Therefore, the current section aims at providing prior motivation for such a structure in the thesis, even though the interaction between GI and scale will be further discussed in Chapter 6.

In terms of hydrological modelling arise the questions of the necessary level of details at city scale to account for GIs hydrological impact on the system. But the scale problem is extended by the connection to other fields. In terms of governance scale, it is necessary to wonder, apart from the direct implication of social inclusiveness and equity (Ward *et al.*, 2019), what it can imply from a hydrological point of view. In terms of biodiversity and ecology, apart from the direct bioecological benefits, it is necessary to model partly how biodiversity influences the urban water circle, especially in a context where processes such as evapotranspiration are considered. In terms of climate, urban comfort, and rainfall pattern, studying the loops and interaction between the hydrological sphere and meteorological sphere become important since, for instance, large surface of concrete can lead to heat island effect, and can influence the precipitation pattern which may directly influence the service needed from green infrastructure. In simpler terms, while social inclusiveness, bioecology and urban microclimates are involved in GIs function, their processes may also affect indirectly the hydrological function of GIs.

The theory of urban resilience is directly linked to the concept of scales (Ward *et al.*, 2019). It consists in studying how a system is able to respond recover and adapt to a stress (chronic or event-based), across scales. Those scales may be site, catchment, city or regional scale from a spatial scale perspective, or household, community, or organisation for a governance scale perspective. Indeed, the decentralized characteristic constitutes a challenge in terms of governance since the ownership of the system is distributed among individuals, communities, and organisations.

From a bioecological point of view, modelling the hydrological behaviour of GI together with its bioecological benefits involve scale issues (Zhang and Chui, 2019). If the hydrological processes are considered as an input to the bioecological behaviour, the main goal is to keep track of the moisture level in the soils, and the water flows. Bioecological benefits quantification requires implementation on large areas that involve green corridors. In other words, while stormwater management often only involves city scale, bioecological benefits involve also larger surrounding natural areas. Zhang and Chui (2019) highlighted the dependency between both fields and how processes and scales have to be chosen in accordance.

Closer to the concern of the current PhD and in accordance with previous parts, Ruangpan *et al.* (2020) found many studies investigating green infrastructure configuration though multi-objective optimization. While SWMM has been frequently used, it should be questioned whether such a tool is relevant for this type of optimization, i.e., if the hydrological equations to represent green infrastructure are accurate enough. It should also be questioned if the methodologies applied, often relying on event-based simulation, are adequate to investigate the performance of GI at city scale. Torres *et al.* (2021), for instance, used a surrogate approach in order to reduce the computation time of the optimum finding of GI implementation plan. However, even under such a scheme, only a single 10-yr return period event was used for simulation. This constitutes a limitation since different rainfall events lead to different detention performance, therefore a single event may not represent appropriately the detention behaviour of a system. Moreover, event-based simulation cannot represent the retention performance of GIs which require continuous simulation. Palla and Gnecco (2015) studied hydrological modelling of GI at catchment scale and was also based on synthetic events. The practice of using only a few rainfall events remains common since it is not affordable to realize long simulations but is not aligned with the objective of most green infrastructure, which is to reduce the volume of runoff in the sewer network. However, Ferrans *et al.* (2022) showed that the proportion of continuous simulation used in studies is increasing.

The multi-objective optimization used often relies on evolutionary algorithms, for they are adequate to find global optimum in complex systems (Ruangpan *et al.*, 2020). Additionally, such optimization being multi-objective, some studies rely on a multi-objective-optimization algorithm providing a Pareto front (set of Pareto optimal solutions). Lastly, and in accordance with the question of ownership mentioned at the beginning of the current section, it should be asked if it is relevant to pinpoint optimal locations when scaling questions are yet to be answered: Can we maintain the performance in the current governance paradigm? Is optimal GI implementation spatially sensitive, or more exactly to which extent the optimal implementation plans are robust and adaptable? Considering an optimal implementation plan for GI in a municipality, if, after feasibility study, several locations are found to be unavailable, the consequences should be investigated. It should be investigated if the modifications are likely to affect the objectives, and if a new implementation plan should be optimized with new constraints. It should be studied if the solutions planned can be shifted to nearby locations without impacting the system performance. Therefore, while it is recognized in this thesis that those approaches will be of interest in future studies, it is yet to be investigated to which extent they can be considered as robust climate adaptation plans.

To conclude, while some progress is being done in allocating green infrastructure at city scale, it still lacks proper performance evaluation methods and quantification of cascading uncertainty and sensitivity. One of the objectives of the current thesis is therefore to improve quantification of GI performance and to upscale it at a scale between unit and catchment that allows for interdependency modelling with large climate input datasets.

1.4.4 GI and design perspectives

Green infrastructure and in general stormwater infrastructures are often designed based on event-based design (Bertrand-Krajewski, 2021). The philosophy behind that practice is that an infrastructure is said to be designed if it can pass some simulation test showing its capability to withstand a predefined level of service. In urban hydrology, the predefined level of service corresponds to the return period of extreme events. For instance, in Trondheim, Norway, designing against a 20-year return period rainfall event (Trondheim Kommune, 2015) aims to ensure that there is a chance of $\frac{1}{20}$ each year that the infrastructure do not withstand an event. In practice, it is complicated to prove that. Especially, the common practice consists in testing against a synthetic design event. It can be therefore discussed if the calculation can stand for a hypothesis test that the GI can resist to the predefined threshold. In particular, as conceptualized in Figure 1.10, if a model is calibrated based on observed data which does not include extreme events, the model is likely to have a limited reliability when predicting behaviour under extreme events. The design practices consist is sizing the roof in order to withstand a synthetic extreme event with that model. It results in a conceptual issue in the use of models for design purposes: the models may neither be conceptualized nor calibrated to be used under extreme events. Several limitations can be listed: i) such approaches often do not account for initial conditions, ii) the models used are extrapolated to unobserved data without necessarily proofing the reliability of the model outside the observed space (Figure 1.10), iii) the synthetic event is not representative of the climate variability. To summarize, infrastructures are designed to withstand rare events, which make it challenging to confirm if they are properly designed. It should be noted that due to those limitations, infrastructures might be undersized in which case it results in an increased risk, or oversized, in which case it results in waste of resources. Oversizing an infrastructure to prevent the effect of climate change can be defended, but such an approach has to be documented and not based on arbitrary factors.

Another major limitation of those methods is that green infrastructures such as green roofs are generally more efficient for retention than detention performance. Therefore, a practice solely based on extreme events does not indicate if the infrastructure is able to reach its main objective: retaining water.

Several design practices can be mentioned, such as evaluating if a given infrastructure retains, e.g., 90% of the inflow volume, or ensuring that the infrastructure handles on-site the first 15 mm of a rainfall event (Greater Lyon council, 2020).

1.5 Conclusive remarks

The current chapter, after introducing key concepts for the thesis, several important aspects are presented and discussed. The chained modelling strategy inherent to

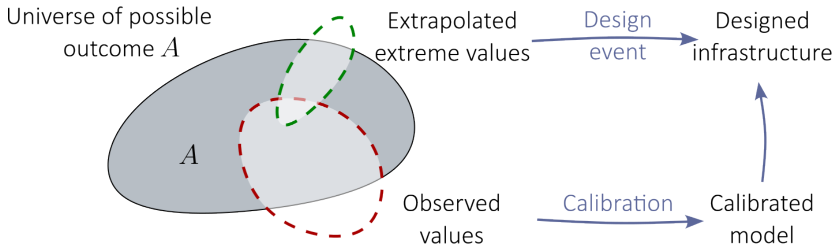

Figure 1.10: Conceptual view of current design practice limitation.

climate change models results in uncertainty cascading into the input data used for climate change adaptation. In addition to climate change, several sources of deep uncertainty are affecting the planning of future cities in terms of stormwater management (e.g., environmental aspects, social aspects, urbanization). It also showed that, outside the scope of the current thesis, the complexity of stormwater management system, especially including green infrastructure, is very high due to numerous connections with other fields. It was decided to present in the current chapter the interdependencies between the different fields linked to GI, even though the current thesis does not pretend to address all those aspects. This work aims to increment the knowledge in evaluating hydrological performance of GI embedded within a large and complex system. Ignoring the complexity of the system would affect the reliability of the performance evaluation.

The current thesis is mostly a modelling-based approach. It was showed that the practice in using green infrastructure models remains insufficient, especially in terms of uncertainty management and alignment between objectives and methods and transparency. It is therefore one of the current objectives to realign the methods and practices in terms of climate change adaptation for stormwater. It was also showed that several processes are not modelled or cannot yet be modelled. The current work does not aim to improve the models themselves, but rather improving their use, especially in accounting for uncertainty and climate variability in performance estimation. When more advanced models, including the processes ignored in the current models, will be available, it will be possible to exchange them with the one used in the current study.

The knowledge developed at site scale may not be applicable at city scale. In particular, due to computational power limitations, the study at city or catchment scale often rely on coarse scale simple simulations to account for hydrological performance. It is therefore one of the last objectives of the current thesis to investigate the scalability of GI performance from unit scale to catchment scale.

2

Artificial rains to evaluate green roofs performance under extreme precipitations

It is perilous to study too deeply the arts of the Enemy, for good or for ill. But such falls and betrayals, alas, have happened before.

Elrond,
J.R.R. Tolkien,
The Lord of the Rings

Foreword

The current chapter is mainly based on Paper A but is not limited to it. In particular, the model development presented in Paper E, is introduced to a large extent in the current chapter since: i) it is based on the experimental data collected in Paper A, and ii) the model is used as the basis for the modelling approaches in the later chapters.

The chapter consists of, first, the content based on Paper A (including introduction methods results and discussion), and then model introduction (presented in a second part of results and discussion).

The right grey bar in the margin is used to inform the reader that the work is similar to one of the direct contributions to the thesis. Similar is defined as reformatted to fit to the chapter structure. Minor modifications of the text are done in order to fit to the structure of the current PhD thesis. When a major modification is necessary, the section or paragraph is not quoted.

Abstract

Rooftops cover a large percentage of land area in urban areas, which can potentially be used for stormwater purposes. Seeking adaptation strategies, there is an increasing interest in utilising green roofs for stormwater management. However, the impact of extreme rainfall on the hydrological performance of green roofs and their design implications remain challenging to quantify. In this study, a method was developed to assess the detention performance of a detention-based green roof (underlaid with 100 mm of expanded clay) for current and future climate conditions under extreme precipitation using an artificial rainfall generator. The green roof runoff was found to be more sensitive to the initial water content than the hyetograph shape. The green roof outperformed the black roof for performance indicators (time of concentration, centroid delay, T50 or peak attenuation). While the time of concentration for the reference black roof was within 5 minutes independently of rainfall intensity, for the green roof was extrapolated between 30 and 90 minutes with intensity from 0.8 to 2.5 mm/min. Adding a layer of expanded clay under the green roof substrate provided a significant improvement to the detention performance under extreme precipitation in current and future climate conditions.

The data collected allowed to study the behaviour of the detention-based green roof under extreme events, however it did not allow quantifying its performance in terms of probability. To allow for this performance quantification later on in the thesis, the data based on extreme tests were then used to calibrate a conceptual model with a "data-frugal" calibration strategy. The model was developed with the objective of giving a reliable representation of two green roofs with distinct hydrological behaviours. The performance of the calibrated model is tested and found adequate for the model's purpose.

Contents

2.1 Introduction

Climate change is increasing the exposure and vulnerability of urban environments to local flooding (Few, 2003; Hettiarachchi *et al.*, 2018; Miller and Hutchins, 2017, among others). The increasing frequency of extreme precipitation and growing urbanization have amplified the need for sustainable design and management of stormwater measures in urban areas (Arnbjerg-Nielsen *et al.*, 2013; Mentens *et al.*, 2006; Zhou, 2014). Consequently, green roofs have become a common and popular green infrastructure (GI) solution around the world (Fassman-Beck *et al.*, 2013; Stovin, 2010; Voyde *et al.*, 2010). The use of green roofs as a stormwater solution is rapidly growing across the Nordic countries, and several municipalities have set targets for their implementation (e.g., following the cloudburst in Copenhagen in 2011, cf. (Rosenzweig *et al.*, 2019)).

Norway has adopted a three-step approach 3SA to stormwater management, where step 1 aims to infiltrate all small events onsite (a well-established and effective solution to reduce peak runoff from impervious surfaces), step 2 aims to safely detain all medium-size events, while step 3 aims to ensure safe floodways for all extreme events (Lindholm *et al.*, 2008). Green roofs target events covering both step 1 and step 2. Although there is no infiltration into the ground from green roofs, the small events typically do not generate runoff from the roofs as the water is retained in the substrate and later released through evapotranspiration. Small to medium events are both partly retained in the roof and partly detained and released as delayed runoff. Recently, new research dealing with a lightweight expanded clay-based roof (also called grey roof) has demonstrated the potential to attenuate intense rainfall (Hamouz *et al.*, 2018). However, little research has been conducted on the performance of green and grey roofs during extreme events. Extreme events, by their nature, occur neither regularly nor frequently, and they are therefore difficult to capture. Additionally, due to climate change, extreme events are expected to increase in intensity and frequency (Hanssen-Bauer *et al.*, 2017; Hoegh-Guldberg *et al.*, 2018; IPCC, 2014). A great amount of uncertainty is linked to the change in extreme events as the trajectory of climate change itself remains uncertain. This is why several scenarios depending on impact of human activities on climate have been developed to evaluate and predict this change (Hanssen-Bauer *et al.*, 2017).

Green roofs offer stormwater solutions that can conceivably contribute to the management of extreme events as they allow the opportunity to deal with stormwater directly at the source. The critical performance provided by green roofs is their retention and detention capacity. Detention performance is principally related to runoff delay, attenuation, and peak flow reduction (Hamouz *et al.*, 2018; Stovin *et al.*, 2017) which are crucial to dealing with extreme events since retention capacities are limited during extreme precipitation (Johannessen *et al.*, 2018; Speak *et al.*, 2013; VanWoert *et al.*, 2005; Villarreal and Bengtsson, 2005). The use of a combined solution comprised of both green and expanded clay-based (grey) elements is expected to provide a way to design a structure able to achieve long-term retention and event-based detention performance capable of dealing with both conventional and extreme events. There is a consensus in the literature that the performance of green roofs is subject to local weather patterns (Berndtsson, 2010; Li and Babcock, 2013; Stovin *et al.*, 2017). Common practices to study the performance of green roofs under various locations rely on: field studies limited by available data and location, and modelling studies limited by available data and the transferability of the model (Johannessen *et al.*, 2019). The assessment of detention performance can be challenging due to the irregularity of natural precipitation patterns and the variable storage capacity available at the time of a given precipitation event (Stovin *et al.*, 2017). Due to the difficulties involved with identifying detention metrics that describe the performance of green roofs for natural precipitation and lack of data on extreme rainfall events, the use of a rainfall simulator was found to be an effective method for testing the roof under extreme 'input-controlled' (e.g. hyetograph and initial water content) variables and evaluating the roof performance. Artificial rain has already been used to simulate various hyetographs to deal with lack of data associated with intense rain (Bengtsson, 2005; Villarreal and Bengtsson, 2005). Spatial uniformity of the simulated rainfall has been investigated in a certain number of studies (Naves *et al.*, 2019, 2017). However, no research was found to apply the rainfall simulator to test different hyetographs on a full-scale green roof under changing initial climate conditions.

As a green roof's performance is dependent on water content, the use of a rainfall simulator might be a solution for controlling storm characteristics and initial conditions, including initial water content for a full-scale roof. Due to the rare occurrence of extreme events, utilising artificial rain is a way to fill the knowledge gap. Therefore, the purpose of this research is to assess a procedure for using artificial rain to study the hydrological performance of a detention-based green roof (D-Green roof) under extreme events. More precisely, this study focuses on 20-year return period (RP) rain events for three Norwegian cities (Bergen, Oslo, Trondheim), taking into account climate change.

The main objectives of this research were as follows:

i. Develop a method to test extreme precipitation on a full-scale, detention-based green roof using a rainfall simulator.

ii. Assess the hydrological performance of a detention-based green roof under extreme precipitation, exceeding a 20-year return period in current and future conditions and including a 1.4 climate factor.

iii. Develop an explanatory conceptual model that ensure reliable performance on a large range of events.

2.2 Material and methods

2.2.1 The study area

A full-scale field setup was built on top of a roof located approximately 10 meters above ground and 50 meters above sea level. The setup was built to study the hydrological performance of different roof configurations at Høvringen in Trondheim, Norway ($63°26'47.5''$ N $10°20'11.0''$ E). In this paper, a green (underlaid with $100mm$ of expanded clay – material characteristics in appendix, Table A.1) (FLL, 2008) and a black roof, which both had a total area of $88m^2$ and a longitudinal slope of 2%, were considered (Figure 2.1). More information about the field setup may be found in previous studies (Hamouz *et al.*, 2018; Hamouz and Muthanna, 2019). The detention-based green roof, referred hereafter as the green roof, was tested in this study. The black roof was used as a reference for comparison.

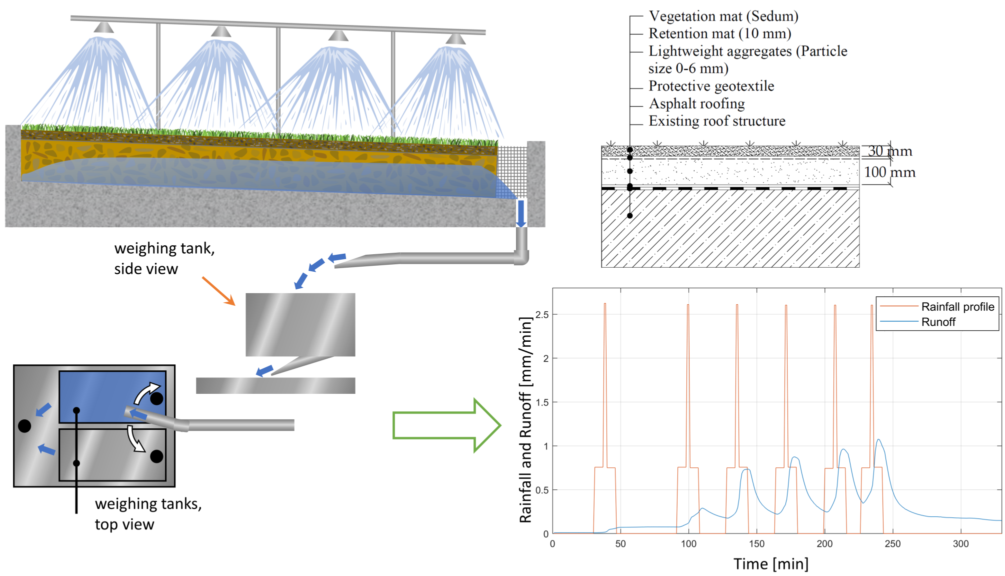

Figure 2.1: Conceptual view ot the experimental pilot for artificial rains. [Paper A - (Hamouz *et al.*, 2020b)]

2.2.2 Field data collection

The meteorological and experimental data were collected during a period lasting from May 2019 to October 2019. Natural precipitation was measured by a heated tipping bucket rain gauge (Lambrecht meteo GmbH 1518 H3, Lambrecht meteo GmbH, Göttingen, Germany) with a resolution of $0.1mm$ at $1 - min$ intervals and with an uncertainty of $\pm 2\%$. Runoff was measured using a weight-based system (accuracy class C3 according to OIML R60) with two tanks located downstream of the drainage outlet (a $110mmpipe$). All data were recorded at 1-min intervals using a CR 1000 data logger (Campbell Scientific, Inc.). More information related to the instrumentation may be found in other studies (Hamouz *et al.*, 2018; Hamouz and Muthanna, 2019). Additionally, eight plexiglass tubes were buried vertically along the longitudinal edge of the roof for visual observation and estimation of spatial water distribution within the roof at the beginning and the end of each individual event during the tests.

2.2.3 Rainfall simulator and future climate scenarios

The field site was equipped with a setup using a grid of non-regulated nozzles (4 nozzles per line, 4 lines) connected to a water supply pipe that was used to generate the precipitation input. The artificial precipitation is considered as an inflow such as defined in Section 1.3.2. The nozzles were placed $1.5m$ above the roof to ensure the maximal spreading effect of water. The enlarged uncertainty (BIPM *et al.*, 2009) with respect to the water spatial distribution was $\pm 3\%$. The enlarged uncertainty of inflow was estimated to be $\pm 0.06 mm \cdot min^{-1}$ and caused by variations in inflow (i.e. a pressure drop in the water supply).

The inflow rates were measured by an electromagnetic flowmeter (Siemens Sitrans FM MAG 5000; uncertainty $\pm 0.4\%$ of the flow rate) and regulated using two valves to allow changes of inflow duration and intensity. The decision was made to run rainfalls with different durations, intensities, and inter-event periods (ranging from $5min$ to more than $74min$) to enable different initial water contents (IWC) in the roof and differently shaped hyetographs. The range of intensities (from 0.8 to $2.5 mm \cdot min^{-1}$) was limited by the minimal flow due to nozzle spread and maximum flow by the capacity of the flow measuring tanks.

Climate change was considered in this study through an increase in precipitation using a climate factor. The Norwegian Climate Centre published recommendations for future short-term precipitation until 2100 (Dyrrdal and Førland, 2019; Hanssen-Bauer *et al.*, 2017). Based on this recommendation, a 1.4 climatic factor (CF) is advised in Norway. Firstly, precipitation depths for the 20-year return period (RP) were derived from Depth-Duration-Frequency (DDF) curves for three different cities: Bergen (BER), Oslo (OSL), and Trondheim (TRO) (Table 2.1). The locations were chosen because of their different climatic conditions. Secondly, these DDF curves were multiplied by a climate factor of 1.4 to estimate expected rainfall in the period between 2071 and 2100, including a worst-case scenario with Representative Concentration Pathway (RCP) 8.5 for shortterm events. The use of this factor was also suggested in other studies (Kristvik *et al.*, 2019, 2018).

2.2.4 Experimental design

To study the behaviour and performance of the roof under extreme rainfall, four primary variables were identified: (1) IWC (based on water balance), (2) rainfall duration, (3) mean intensity of the rainfall, and (4) shape of the hyetograph (impact of varying intensity). Additionally, secondary variables (depending on primary variables) were considered: (5) depth of the rainfall, depending on its duration and mean intensity and (6) location and climate change scenario, linking duration and mean intensity using Intensity-Duration-Frequency (IDF) or Depth-Duration-Frequency (DDF) curves. The main objective was to identify the most significant variables governing the behaviour of the roof. The experimental design has been driven by the Bayesian principle to minimise the number of experiments. This means that the method has been updated by considering the results obtained in the previous steps. The experiments' three main steps were as follows:

i. The first step was conducted to include a primary analysis of the behaviour of the roof. The influence of rainfall intensity was measured by performing the time of concentration (TC) test. The TC was defined as the time for the roof's runoff to equal inflow under constant intensity rainfall. Subsequently, the water drainage was assessed.

ii. Based on the results of the first step, the second experiment was conducted to compare the influence on runoff of a change in hyetograph to a change in IWC .

iii. Finally, the third step, based on the results of the first two steps, was conducted to study the influence of the duration and intensity while considering the impact of water content (WC).

Step 1: assessing hydrological behaviour of the roof

To fulfil the first step, the green roof TC was estimated for different inflow intensities (0.8, 1.0, 1.2, 1.4, 1.7, 2.0, and $2.5 mm \cdot min^{-1}$) and compared with the black roof TC. The duration of each event was monitored to ensure that both inflow ($\pm 2\%$) and outflow ($\pm 2\%$) lay within the boundaries for measurement uncertainty which was set as a threshold for ending the individual tests.

The roof drainage was studied as part of the first step by recording the outflow after the end of the inflow (precipitation) stopped at the conclusion of the TC test. The drainage curves were later updated with the data from steps 2 and 3 to refine the results.

As the performance of the roof depends to a large degree on WC, and given the fact that short, intense rainfalls typically pose the biggest challenge to urban drainage systems, the choice was made to focus on short-duration events by running the rainfalls successively during step 2 and 3. Each hyetograph presented below in step 2 and 3 was applied in a sequence separated by dry periods (from 5 to $74 min$). Each hyetograph was repeated 3–9 times (see example Figure 2.1). The inter-event duration was adapted with real-time control of runoff to increase IWC: (1) the peak of runoff had to be reached, (2) IWC had to increase, (3) the set of IWC had to be evenly distributed.

Table 2.1: Summary of the tested rainfall events derived from DDF curves for three locations: Trondheim, Oslo, and Bergen. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

ID -	Intensity [mm/min]	Depth [mm]	Duration [mm:ss]	Number of blocks [-]	Notes -
TRO 1	1.7	12	07:00	9	-
TRO 2	1.0	16	16:00	8	16 min with 1 mm/min intensity
TRO 2a	1.0	16	16:00	7	2 min with 2.6 mm/min followed by 14 min with 0.8 mm/min
TRO 2b	1.0	16	16:00	8	14 min with 0.8 mm/min followed by 2 min with 2.6 mm/min
TRO 2c	1.0	16	16:00	6	7 min with 0.8 mm/min followed by 2 min with 2.6 mm/min and 7 min with 0.8 mm/min
TRO 2d	1.0	16	16:00	6	2 min with 2.6 mm/min three times
TRO 3	2.6	9	03:30	9	-
TRO 4	0.8	20	26:00	6	-
OSL 1	1.7	28	16:00	5	-
OSL 2	1.0	45	44:00	3	-
BER 1	1.7	16	09:00	6	-
BER 2	1.0	23	23:00	5	-

Step 2: influence of the hyetograph

In the second step, the choice was made to run events with different hyetographs in order to identify to what hyetograph the roof runoff is the most sensitive as well as to assess the significance of the WC in contrast with the hyetograph. In this step, all simulated hyetographs corresponded to the same overall rainfall depth (16 mm) and duration (16 minutes), although with different distributions named TRO 2, 2a, 2b, 2c, and 2d (see Table 2.1). The duration and intensity were based on the 20-year return period curve of Trondheim with the 1.4 climatic factor.

Step 3: influence of duration and intensity

The third step was split in two sub-steps. Firstly, four events were selected on the 20-year return period curve of Trondheim with the 1.4 climate factor (TRO 1, TRO 2, TRO 3, and TRO 4, see Table 2.1). Secondly, based on the results of the first sub-step, the list of events was expanded through selecting events from the DDF curves of Bergen and Oslo (Figure 2.2). The intensities of TRO2 and TRO3 were chosen to select the events and study the influence of the rain duration: two events for Oslo (OSL 1 and OSL 2) and two events for Bergen (BER 1 and BER 2) (Table 2.1 and appendix, Table A.3 and Table A.4). An overview of the individual events was plotted for the different locations – both with and without the climatic factor as shown in Figure 2.2.

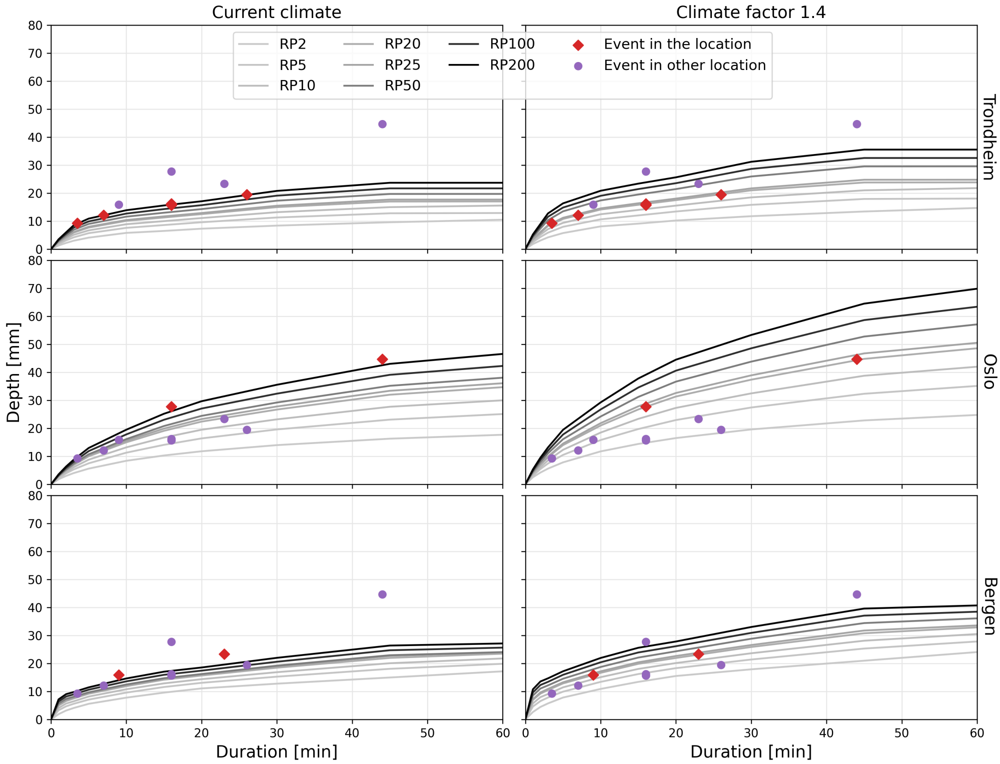

Figure 2.2: DDF curves for different return periods, locations, both with (on the right) and without (on the left) the CF of 1.4. The same events, represented by dots are displayed on all subplots. The purple circles represent the events from other locations from the one in the subplot. The red diamonds represent events corresponding to the location corresponding to the subplot and under a 20-year RP with climate factor. [modified from Paper A - (Hamouz *et al.*, 2020b)]

2.2.5 Performance indicators and condition indicators

For all simulated rainfall events, a set of performance indicators was estimated:

- $Peak\ Runoff$ [mm/min]: maximum runoff at 1 min intervals;
- $Peak\ Attenuation$ [-] $= \frac{Peak\ Rainfall - Peak\ Runoff}{Peak\ Rainfall}$ where $Peak\ Rainfall$ is the maximum rainfall intensity at 1 min interval in mm/min;
- $Peak\ Delay$ [min]: the time between the peak rainfall (the maximum and the last peak when observing multiple peaks) and peak runoff;
- $Centroid\ Delay$ [min]: delay between the mass centre of the rainfall and mass centre of the associated runoff;
- $T_{50-delay}$ [min]: a delay between 50% of the volume of the rain supplied on the roof and 50% of the volume released out of the roof. $T_{50-delay}$ was only

computable when more than 50% of the rain depth was drained from the roof, whereas Centroid Delay and Peak Delay rely only on runoff (they do not consider retained water).

Condition indicators:

- $Initial\ Relative\ Water\ Content$ [mm]: IWC for each event was based on water balance;
- $Peak\ Relative\ Water\ Content$ [mm]: $PRWC$ highest value of WC observed before peak runoff (especially, for constant intensity rainfall it corresponds to the WC at the end of the test).

2.2.6 Data processing

The water balance equation was applied to compute WC within a $1-min$ time resolution. It was not possible to know the IWC; hence, the WC was computed using the stable tail of the outflow (see section 'Drainage of the roof') as a reference: $WC_t = WC_{t+1} + R_t - P_t$ if $t < t_{ref}$ and $WC_t = WC_{t-1} + R_{t-1} + P_{t-1}$ else with t_{ref} the daily reference time on the stable tail of the outflow, R the runoff, P the rainfall depth and t the time. The unit was kept as mm to facilitate comparison with rainfall depth. The enlarged uncertainty of WC due to water balance was estimated to be ± 0.7 mm based on the Monte Carlo Method. The raw data were analysed using custom `Matlab` scripts.

Due to the short inter-event period between artificial rains, it was not possible to use raw data to compute centroid delay and $T_{50-delay}$ for each rain. Thus, with respect to the first step results, the falling limb between two events was best-fitted using the data from the observed drainage curve. Linear interpolation between successive time intervals was used to minimize the error between the falling limb during dry periods and the roof measured drainage curve. The fitting with the falling limb was evaluated using Nash-Sutcliffe efficiency (NSE). The data from each event was completed to ensure that the outflow volume is equal to the inflow volume and that most of the indicators were computable. Natural precipitation recorded during the experimentation was included in the analysis. However, since the intensity of natural rainfalls was very low compared to the artificial rainfall, the impact of the natural rainfall could be disregarded.

2.3 Results and Discussion: Data analysis

2.3.1 Hydrological analysis of the roof

2.3.1.1 Time of concentration

To study the behaviour of the roof, the time of concentration (TC), was first assessed. Figure 2.3 shows the TC curves for different intensities for both the black and the green roofs. TC of the green roof was found inversely proportional to the intensity, i.e. decreasing from $90min$ to $30min$ for increasing intensity from $0.8mm \cdot min^{-1}$ to $2.5mm \cdot min^{-1}$. In contrast, TC of the black roof was found around 5 minutes independently of the intensity. The events defined by their TC and corresponding mean intensity were found to be close or greater than a 200-year return period (RP) event in Trondheim, Bergen and Oslo, having a 1.4 climate factor. The exact TC was challenging to estimate due to its sensitivity to IWC and its slow asymptotic convergence. Moreover, in the $0.8mm \cdot min^{-1}$ and 1.0 mm/min tests, TC was based on concatenation of the runoff, which might have altered the result. Data from concatenation were monitored under different conditions, inner porosity was saturated (inner porosity was hypothesized to distinguish water standing between the aggregates and water stored in the aggregates), which could have led to underestimating TC. The beginning of an event is subject to a transient state (explained later in 'Sensitivity to hyetograph') leading to overestimating TC, even though the transient state was excluded as much as possible. Due to the characteristics of the tested extreme rainfall events, ponding was observed. It was visually inspected that this was linked to the detention properties of the expanded clay and that the outlet was not submerged. Figure 2.1 shows water distribution in the longitudinal cross section in the middle of the roof.

2.3.1.2 Dynamic spatial distribution of water within the roof

During all the tests, the spatial distribution of water through the roof longitudinal cross-section was assessed by manual measurement, i.e. the depth of water standing in the roof measured in the 8 plexiglass tubes. This measurement showed the head loss along the flow path toward the outlet. It was found that different distributions of water within the roof for different rainfall events could lead to the same average WC. In addition, it was also observed that, for high WC (more than 35–$45mm$ of WC), the same average WC could lead to minor differences in outflows (the uncertainty increases with the WC), which is likely linked to different spatial distributions of water within the roof. This phenomenon was understood as the dynamic effect linked to both the dual-porosity properties of the detention layer (expanded clay) and the size of the roof as the water cannot be instantly transferred to the outlet. Figure 2.4 shows that the water distribution within the roof at the end of an artificial rainfall was not linear. It was found, especially in OSL 1, BER 1, and BER 2, that the water distribution was

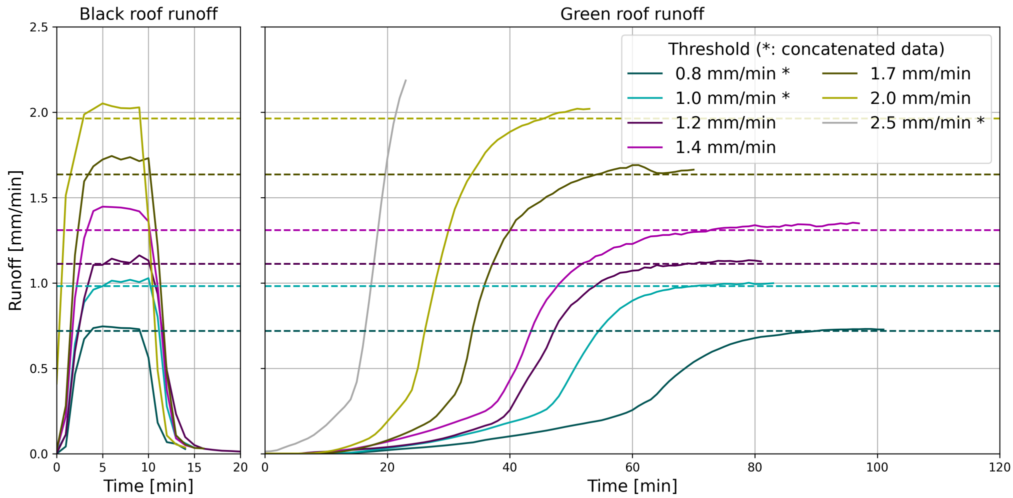

Figure 2.3: The TC for different rainfall intensities and rooftop solutions. The TC test for 0.8, 1.0 and $2.5 mm \cdot min^{-1}$ intensity started on a partially saturated roof and the curves were completed using concatenation. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

dependent on the rainfall intensity and duration acting as a feedback loop: higher intensity led to higher runoff and greater dynamic effect, leading in turn to higher runoff. In the upper part of the roof (left side of Figure 2.4), the water level followed a parabolic distribution. During the inter-event period, the water distribution tended to maintain a steady state influenced by gravity and detention properties (the distribution became more linear). Variation of water distribution was explained by capillarity and gravity effect in the detention medium. It was also influenced by both the imperfection of the rainfall simulator (the rainfall spread was not perfectly homogeneous with $\pm 3\%$), and the upper side of the roof having a boundary effect (i.e. close to the top of the roof, no flow was coming from upstream). In addition, a different distribution near the outlet would have been expected if the measurement longitudinal cross section aligned with the outlet due to a different boundary condition. It was also hypothesized that inner conductivity (i.e. the aggregates hydraulic conductivity) was lower than the medium hydraulic conductivity. After saturating the medium, the inner porosity was not yet completely saturated. For this reason, it was not found relevant to simplify the behaviour of the roof as initial losses until field capacity was reached and followed by runoff, as these two processes are interconnected.

2.3.1.3 Drainage of the roof

For all events, a smooth falling limb, decreasing exponentially, was observed from a nearly saturated roof after various rainfall events (Figure 2.5). The drainage curves were plotted and processed together with the same starting value. Figure 2.5 presents the median-observed runoff curve estimated from 14 different events, including the

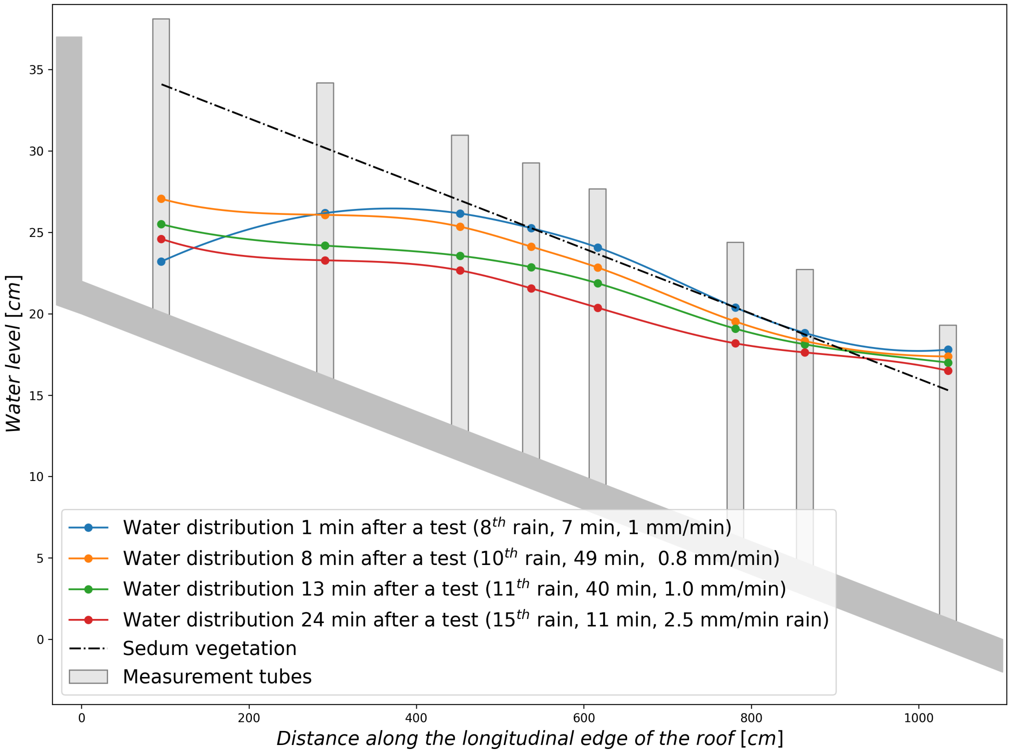

Figure 2.4: Cross-section of water distribution in the roof with $50mm$ of WC. Data measured during 10.7.2019 along one of the longitudinal edges of the roof. The shaded area (grey) represents the existing concrete structure. [modified from Paper A - (Hamouz *et al.*, 2020b)]

5^{th} and 95^{th} percentiles. Falling limbs strongly affected by natural rains were excluded from the sample. Additionally, the corresponding relative WC was computed. Even with a minor variation of observed drainage curve, the difference from the 5^{th} percentile to the 95^{th} percentile led to significant variations when computing WC. The WC used with performance indicators was computed based on raw data; hence, while any instability of WC computing should not affect the results presented here, it does highlight the sensitivity of the water balance during long-term events. The WC curve suggests that the detention time is long: starting with $60mm$ of WC, it took 3 hours to drain 50% of the water and $6hours$ to drain 66% of the water. The analysis of the dynamic distribution of water within the roof and the hypothesis of a dual porosity of the roof material suggests a relevant explanation to interpret the roof drainage curve. The standing water was drained during the first hour, inducing a quick change of outflow. During the second phase, the outflow had smaller variations as the runoff was driven by its exchange with inner WC (i.e. water in the aggregate). The roof has a long saturation and inner porosity drainage time. Therefore, the previous day rainfall and the corresponding detained water can have a significant influence on the roof performance. Based on this it was chosen to run short events several times per day to experience a range of WC during the experiments second and third steps.

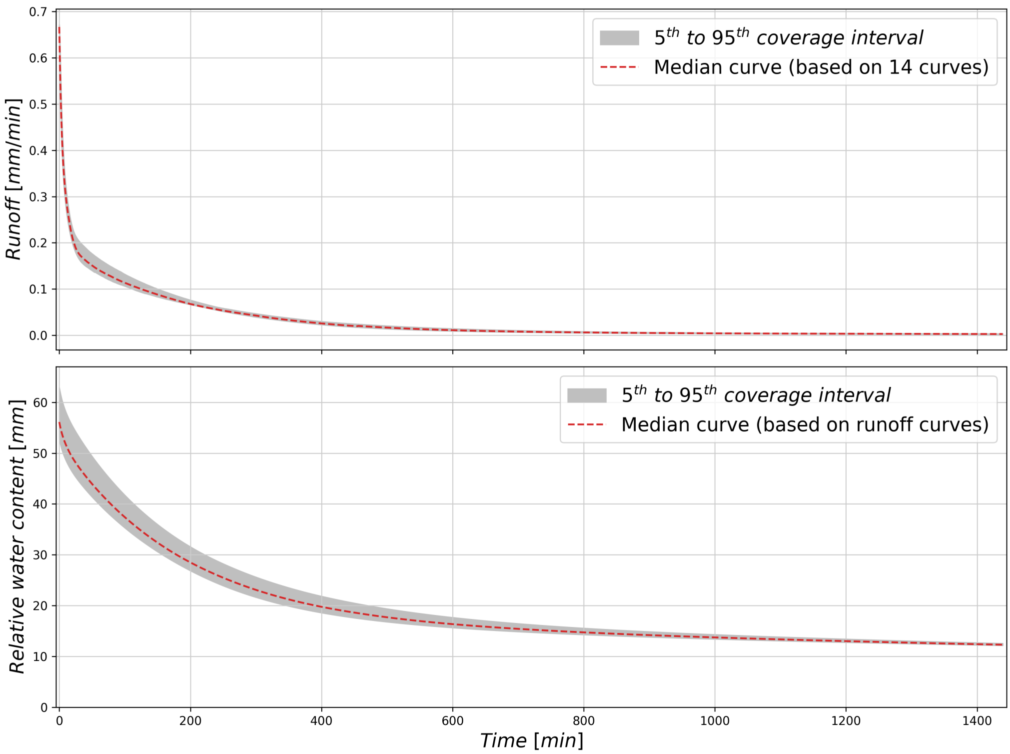

Figure 2.5: Median-observed drainage curve for the green roof with 5th and 95th percentile. [modified from Paper A - (Hamouz *et al.*, 2020b)]

2.3.2 Sensitivity to hyetograph

The hydrological performance of the roof as a source control may be explained and understood using a variety of indicators, as can be seen in the Appendix, Table A.2, A.3 and A.4. When the IWC was low (e.g. lower than field capacity), a plateau of runoff occurred (Figure 2.6). Consequently, it was not possible to close the event's mass balance, which might slightly alter some indicators. The five artificial events (Table 2.1 and A.2) chosen to study the influence of the hyetograph shape on the runoff hydrograph were plotted and compared (Figure 2.6). Tables A.2, A.3 and A.4 show the roof initial condition, which is represented by starting outflow and starting relative water content (soil moisture), both of which were found to be important for the performance of the roof. As the peak runoff rose, the roof performance deteriorated with respect to the peak attenuation, $T_{50-delay}$, centroid delay, and peak delay. The performance of each artificial rain cannot be compared directly without considering these initial conditions.

The green roof was tested using different hyetographs (Figure 2.6). Absolute values of runoff increased in proportion with increasing IWC. Similarly, a dependency between the initial runoff and peak runoff was found. Running different hyetographs enabled the identification of the sensitivity of the roof. As shown in Figure 2.6, the position of the peak at the end (TRO 2b) of the rainfall had a large impact on the green roof performance. Following TRO 2b, the green roof generated higher and steeper peak outflows than following TRO2 a, c, d or e. Regarding event flow duration, one can easily read the duration of runoff above a threshold and compare this with the hyetograph. For example, only hyetographs peaking in the middle (TRO 2c) and at the end (TRO 2b) generated runoff from the roof that was greater than $1mm \cdot min^{-1}$. There are four observable parts in each runoff hyetograph (illustrated with shaded area on Figure 2.6):

- the start, a transient state influenced by rainfall (a sudden change of the runoff's gradient);
- the increase, a steady state of the gradient influenced by rainfall;
- the end, a transient state after rainfall stopped that is linked to the dynamic water distribution in both the roof and peak delay (a drop of the gradient);
- the drainage, a steady state of the gradient not influenced by rainfall.

The gradient of the runoff changed smoothly under constant rainfall or without rainfall. Between two stable stages, the gradient changed abruptly: it is the transient stage. The duration of the transition was influenced by the size of the roof and the IWC.

The three indicators selected to assess the effect of the hyetographs are shown in Figure 2.7. Similarly to previous research (Li and Babcock, 2013; Locatelli *et al.*, 2014; Villarreal and Bengtsson, 2005), there was a relationship between IWC and peak runoff. Given the same IWC , having the peak at the end (TRO 2b) or in the middle of the rainfall (TRO 2c) event caused higher peak runoff. However, the relationship between the peak runoff and peak relative WC was not notably influenced by the hyetograph. The same conclusion may be drawn by analysing centroid delay in comparison with the IWC. Centroid delay, representing the delay between the centres of mass of rainfall and runoff, was not sensitive to the shape of the hyetographs.

2.3.3 Sensitivity to the rainfall duration and intensity

It was concluded from the second step that the IWC had a stronger influence on performance than the shape of short-term rainfall. Therefore, in order to investigate the roof sensitivity to the rainfall intensity and duration, constant intensity events were studied. Events were chosen based on the 20-year RP IDF curves to ensure realistic values and facilitate a comparison between rainfall events. It should be noted

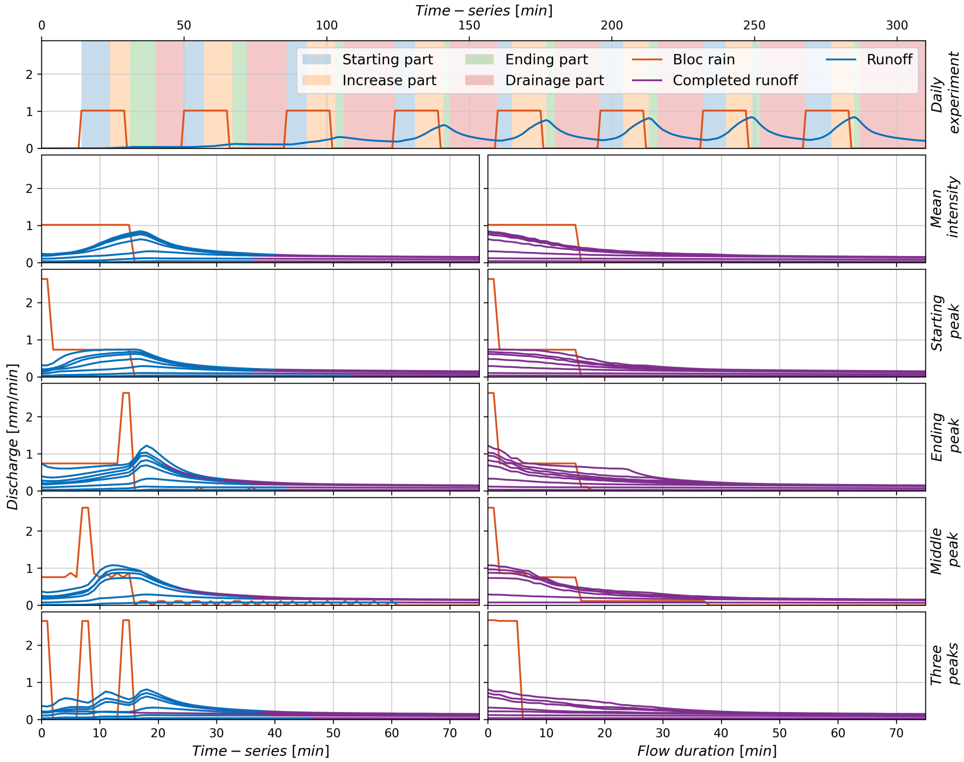

Figure 2.6: Comparison of event flow duration for several artificial rainfalls and runoffs for the green roof after $16min$ blocks with $1.0mm \cdot min^{-1}$ intensity. Mean rainfall $depth = 15.9mm$ and $std = 0.5mm$ for all 35 runs. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

that both future 20-year RP events for Oslo were larger or equal to 200-year RP events under current conditions in Trondheim and Bergen. The roof provided a peak attenuation higher than 93% with the exception of OSL 2. It strengthened the roof's resilience and the capacity to handle a short duration 20-year return period rain in a future climate.

The events corresponding to the Oslo curve generally generated higher runoffs with respect to IWC than events from Bergen and Trondheim (Figure 2.8). High IWC caused the peak runoff to be close to the peak rainfall. However, when specifically considering the low IWC, the roof was more sensitive to longer rainfalls with lower intensity (e.g. worse performance under OSL 2 than under OSL 1 with IWC lower than field capacity). The roof with a high starting IWC was more vulnerable to shorter events with higher intensity (e.g. worse performance under OSL 1 than under OSL 2 with IWC higher than $30mm$). Although the same analysis could have been done with OSL 2 and BER 1, or BER 1 and BER 2, the shift appeared with a higher WC ($50mm$). Consequently, the roof is sensitive to different short-duration rainfalls depending on its initial condition. Thus, in addition to the DDF curves, the design should be location specific, and based on different events depending on a range of

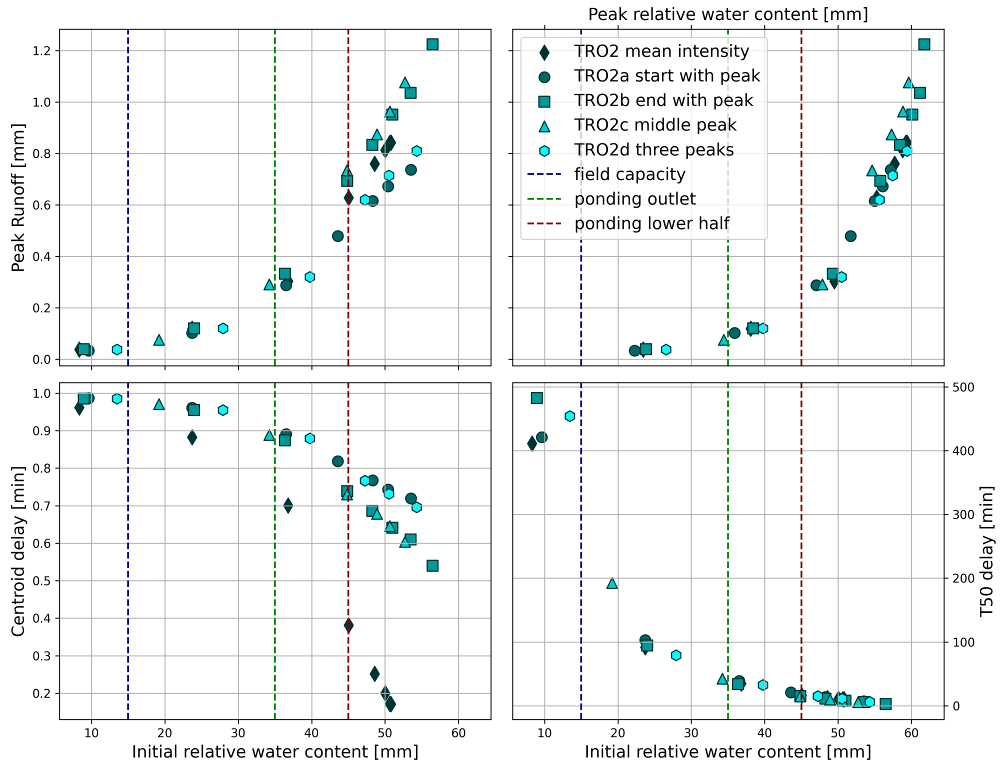

Figure 2.7: Observed peak runoff versus IWC and peak relative WC, and centroid delay versus IWC for different hyetographs. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

IWC.

Comparing the last artificial rains for TRO 1 and TRO 2 with $50mm$ WC, it is noticeable that the peak runoffs were very similar (Tables A.3 and A.4, Figure 2.8). However, the peak attenuation remained very different, showing 50% for TRO 1 and 17% for TRO 2. Moreover, similar observations could be done for TRO 2 and TRO 2 a b c d (Table A.2). For TRO 2 and TRO 2 a b c d that had the same rainfall depth, but different hyetographs; comparable peak runoffs were found, but the attenuation remained different. Thus, even though peak reduction is a popular performance indicator, it should be presented carefully.

Peak runoff against peak relative WC followed an exponential tendency independent of the type of artificial rain. However, a scattering of peak runoffs was observed with a high peak of relative WC (over 45 mm, with ponding in the middle of the roof), which could be explained by the dynamic spatial distribution of water within the roof. This scattering effect is governed by the mean intensity of previous intervals (i.e. considering previous artificial rain and dry periods). If the roof had not been saturated, a high mean intensity prior to an artificial rain led to a more curved distribution of water within the roof, i.e. to a higher peak runoff than the other events having the same peak relative WC. OSL 2 was the event with the most significant rainfall depth, and thus, it also had the longest inter-event period. This led to smaller dynamic effect, resulting in a steady water distribution across the roof. On the contrary, OSL 1 and BER 2, due to shorter inter-event durations (and to a pipe disconnection during one of the BER 2 tests), underwent more intense antecedent rainfall, which explains why the scatter effect is more noticeable.

The centroid delay in contrast to initial relative WC may be separated into two domains. Having an IWC lower than field capacity, the centroid delay was over $200min$. The centroid delays having IWC at field capacity were independent of the rainfall intensity and duration. When the IWC ascended from field capacity (of approximately $15mm$) to $55mm$, the centroid delay decreased by an exponential decay from 200 min to between 5 and $10min$, which showed that even a nearly saturated roof outperformed the black roof. Comparable results were found using the $T_{50-delay}$, which means that the hyetograph, intensity, and duration do not influence centroid delay or $T_{50-delay}$ delay, i.e. the performance only depends on the IWC.

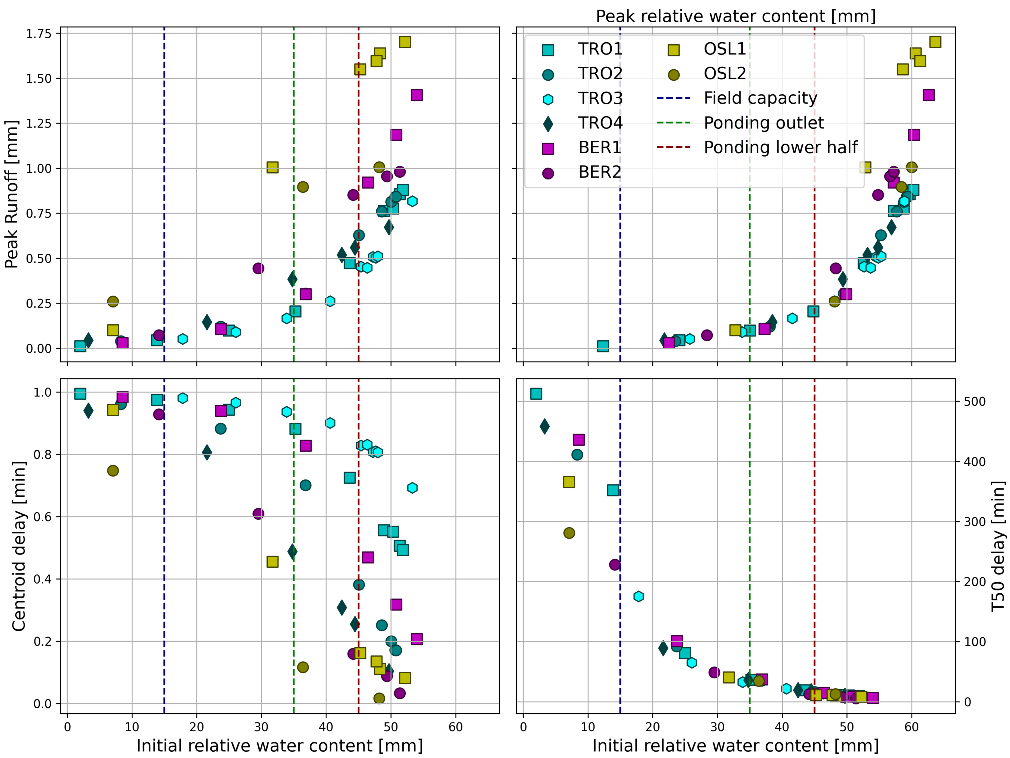

Figure 2.8: Comparison between peak runoff, peak attenuation and centroid delay for different locations, including the 1.4 CF. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

2.3.4 Performance depending on location

Events linked to Oslo lead to worst performance as their characteristics are more intense than Trondheim or Bergen events. Nevertheless, the performance of the roof depends to a large extent on the IWC. To assess the performance of the roof under a given location those aspects shall be considered. The IWC depends on the climate, i.e. the number and succession of events and the temperature are supposed to greatly influence those parameters. There are more warm days in Oslo than in Trondheim or Bergen. Consequently, a higher Potential Evapotranspiration (PET) is expected in Oslo, even though limited in Nordic climates evapotranspiration is expected to influence the IWC. Moreover, the PET is likely to rise with temperature increase (Hanssen-Bauer *et al.*, 2017). The number of rainy days per year and annual precipitation were found for each location: Bergen ($205 \pm 18d$, $2715 \pm 450mm$), Oslo ($122 \pm 15d$, $861 \pm 146mm$) and Trondheim ($174 \pm 14d$, $1191 \pm 184mm$) according to the Norwegian Meteorological Institute. This shows that initial conditions are likely to change according to each location. This also means that it is necessary to know the IWC conditions to assess future roof performance.

The worst performance of a short-term artificial rainfall (with, $45min$ for all the rainfalls) linked to the DDF curves of Oslo does not mean that a higher peak is likely to occur in Oslo than in Bergen. According to the number of days with rainfall, the IWC is expected to be higher in Bergen and Trondheim than in Oslo. However, defining a rainfall with a 6-hour antecedent dry weather period, the initial relative WC could not be higher than $25mm$ due to the roof's characteristics (Figure 2.4). A more realistic initial condition would be to consider one that is less than $20mm$. When initial conditions are between field capacity and $20mm$ of WC, the roof's performance would be slightly worse in Oslo than in Bergen for short-term rainfalls. It appeared that OSL 2 ($0.25mm \cdot min^{-1}$ peak runoff), with initial conditions lower than field capacity, led to worse performance than TRO 1, 2, 3, and 4 with $20mm$ of IWC (less than $0.15mm \cdot min^{-1}$ peak runoff). Nonetheless, it did not perform significantly worse than BER 1 and 2 with $20mm$ of IWC. In this case, the peak runoff would depend more on the characteristics of the hyetograph than on the location. The centroid delay does not depend on the hyetograph and is likely to be higher in Oslo (more than 200 min) with lower initial conditions than in Bergen (between 200 and $100min$). Nevertheless, these expectations only consider short-term rainfalls up to 45 min. Understandably, 20-year return period events are likely to be more intense in Bergen than in Oslo, having a duration over $140min$. This study does not reach a conclusion about long duration rainfalls, which occur more often in Bergen and Trondheim than in Oslo. The hyetograph was not significant in comparison to the IWC with shortterm rain. Nevertheless, it would affect a long duration rain.

2.4 Results and Discussion: Model development

2.4.1 Motivation - a data-frugal approach to models

In the context of the current PhD, one of the aims is to evaluate the future hydrological performances of GI. Those performances include retention performance, detention performance, and behaviour under failure (extreme events). The previous sections of the current chapter were dedicated to collecting data to assess the behaviour of the D-Green roof under future extreme events. However, testing more extensively the roof under other climates would require significantly more experimentation. In the context of the paradigm chosen in that PhD (cf. Section 1.1.5), which consists of limiting the data-hunger of approaches, it was aimed to develop what could be called a "data-frugal" calibration for green roof models. Indeed, in a context where ML methods are becoming more common, the hunger for data increases (Chia *et al.*, 2022). It seems necessary, in a resources-limited context, to explore an alternative that uses the best out of available data to offer a better ratio data/information.

Indeed, to some extent, green roofs offer the opportunity to have a semi-controlled environment. Therefore, it was possible to collect data corresponding to the behaviour of the roofs under extreme rains. Therefore, instead of training a model on long time-series, it was aimed to use efficiently available data to maximize the information extracted.

In terms of model need, the current PhD requires a model with conceptual parameters and low computational time in order to allow for the use of Monte-Carlo (MC) like methods. The models should be accurate enough for the estimation of retention (water balance), detention (both high and low flow) and behaviour under extreme events. It is also required to have several models that show a variety of behaviour in order to compare GI and study their interactions.

Based on the data collected during extreme tests on both the detention-based extensive green roof (D-Green roof) and extensive green roof (E-Green roof) (see Hamouz and Muthanna, 2019) it was decided to conceptualize, develop and calibrate two simple non-linear reservoir models with high reliability. The choice of the E-Green roof and D-Green roof is to provide a model for 2 infrastructures that don't have the same behaviour. The D-Green roof is not sensitive to the same hyetographs as the E-Green roof which is, due to limited storage, sensitive to short duration intense rainfall. It is acknowledged as a limitation that both of those roofs are not infiltration-based solution, but such a limitation was not considered impacting the main objective of this PhD which is to develop a framework in order to better understand which place to give to green infrastructure in future cities. It will be possible in further work to extend such a methodology to other GIs. The use of extreme-tests based data ensures that model is to provide a model calibrated with a low amount of data.

2.4.2 Model data

The E and D-Green roofs located in Trondheim were modelled. They were selected due to data availability and the contrast of their behaviours: *i)* A typical extensive green roof (E-Green roof) with sedum vegetation, $30\ mm$ of substrate, and $25\ mm$

of "eggbox" drainage layer (Hamouz and Muthanna, 2019), and *ii)* a detention-based extensive green roof (D-Green roof) with sedum vegetation, $30\ mm$ of substrate, and $100mm$ of lightweight clay aggregates (Hamouz *et al.*, 2020b). It should be noted that the D-Green roof is a green roof solution installed after and inplace of the E-Green roof. Except for the layer charasteristics they share the same geometry. When considering natural precipitation, an area of $100\ m^2$ is considered while during extreme test the edges of the roof (impervious, $12\ m^2$) are excluded since they are not irrigated. Since the model later developed is lumped, intensity is adjusted (mass conservation) to account for this change in the geometry considered during experiment and natural precipitation. This assumption can be verified during the testing phase of the model development.

2.4.3 Model equation

Based on the data gathered for both roofs and the behaviour observed on Figure 2.8 it was concluded that using a linear reservoir model, no matter the calibration and objective function chosen, it would not be possible to have both reliable high and low flow estimates (e.g., below and above $0.25\ mm/min$) with a single parameter set. Moreover, a linear reservoir for green roof models leads to a segmented linear function. It leads to a sudden transition from no-flow to flow. It has been seen on the results of the experiments, that in practice there is a gradual transition from no-flow to flow.

Therefore, the models' conceptualization, based on observed information, should have the following properties:

- Given a threshold of water content, the roof's discharge starts gradually to increase.
- The substrate type and the size of the roof and other geometrical parameters has an influence on the abruptness of that transition.
- Once field capacity and homogeneous spatial water distribution is reached in a specific layer, the dependency between the water content and the discharge becomes linear.

In terms of conceptualization, it was decided to use a function that allows for a soft transition between the different pieces of the segmented linear function. A piecewise continuous function based on a logistic function and a linear function was chosen for that purpose.

The model (Eq. 2.1) is a simple reservoir model with smoothed linear function. Equation 2.1c is the piecewise continuous function describing the relationship between the water content and the outflow. Oudin's model for Potential Evapotranspiration was used (PET, Eq. 2.1b). With a numerical approximation of the water balance, Soil Moisture Evaluation Function was used to estimate Actual Evapotranspiration (AET) (Johannessen *et al.*, 2017). The PET is computed at daily resolution and discretized uniformly. This assumption was bone by comparing the the characteristic time of the evapotranspiration and of the runoff (Schilling, 1991).

$$WC_i = WC_{i-1} + P_{i-1} - Q_{i-1} - WC_{i-1} \times PET_i \times C \tag{2.1a}$$

$$PET_i = \begin{cases} 0, & \text{if } T_i <= 5°\text{C} \\ \frac{Ra}{\lambda\rho} 0.01(T_{mean} + 5), & \text{if } T_i > 5°\text{C} \end{cases} \tag{2.1b}$$

$$Q_i = \begin{cases} \frac{S_K}{1+\exp(-\frac{4\times K}{S_K}\times(WC_i - WC_K - \frac{S_K - 1}{2\times K}))}, & \text{if } WC_i > WC_K + \frac{S_K-1}{2\times K} \\ K \times (WC_i - WC_K) + \frac{1}{2}, & \text{else} \end{cases} \tag{2.1c}$$

(2.1d)

WC_i is the water content (mm) at time t_i. P_i is the precipitation ($mm \cdot min^{-1}$). The discharge Q_i ($mm \cdot min^{-1}$) is based on Equation. 2.1c. The temperature T_{mean} is in Celsius degree, the extra-terrestrial radiation Ra is derived from the latitude and the Julian day. The constant $\frac{1}{\lambda\rho} \approx 0.408$ depends on latent heat and volumetric mass of water. The factor C is a calibrated factor depending on the maximum storage and the crop factor.

The smoothed linear function (Eq. 2.1c) has three parameters: K the conductivity slope, S_K the smoothing factor and WC_K the starting delay. The starting delay is related to the water content at which the function becomes linear. The model for the E-Green roof include a single layer. The model for the D-Green roof includes two layers, a pseudo code in appendix show with the example of the D-Green roof the application of the model to multilayered roofs (Algorithm A.1). The model was developed based on data from extreme tests with artificial precipitation presented in Sections 2.2 and 2.3 (Hamouz *et al.*, 2020b, *[= Paper A]*) by establishing a relationship between water content and runoff. The data used for the D-Green roof are the one presented in the current chapter. The one used to calibrate the E-Green roof result from unpublished experiments following the same procedure as the concentration time experiments (Figure 2.3). The intensity used for testing the E-Green roof in a concentration time test was $1.7\ mm/min$. In practice the data of a single day of experiment (1440 points on minute resolution) offering a large range of discharge was used in order to satisfy the "data-frugal" strategy. The outflow depending on water content was used as input for calibration of the parameters of the discharge function using Bayesian calibration with DREAM setup (Laloy and Vrugt, 2012). The error model chosen was heteroscedastic. In particular, it was a linear error model with 2 parameters. Including the error model, 5 parameters were used to calibrate the detention model of the E-Green roof (7 for the D-Green roof which has two layers). It should be noted that the model remains limited, as it lumps processes and neglects dynamical effects described in the previous sections of the current chapter. In particular, the wetting of the aggregates and substrate and the spatial distribution of water content within the roof are not accounted for (Hamouz *et al.*, 2020b).

2.4.4 Green infrastructure model evaluation

The D-Green roof's model was tested against measured discharge with, as input, a rainfall series of two and half months from July 2018 to the 25^{th} of September, and a one-month series from the 5^{th} of September 2019 to the 5^{th} of October. The E-Green roof's model was tested against measured discharge, with a rainfall series from April 2017 to September 2017 as input. Snow periods were excluded for the evaluation.

The performance was evaluated both on the time series and individual events extracted from the time series all at 1-minute resolution. The criteria were: i) NSE indicator on time series for both discharge and water content, ii) NSE for rainfall events defined with a minimum inter-events time of $6h$ to analyse further the behaviour of the model, and iii) the volumetric error on the time series to account for model retention evaluation. The water content was estimated directly from discharge measurement using the empirical curve. The performance was as follows:

- $NSE > 0.8$ for both discharge and water content for the extensive green roof. For the three largest events, the NSE ranged from 0.98 to 0.61 (details in Table A.6). Those three largest events had each a duration of more than a day. The water balance error was found to be 2.1%.

- $NSE > 0.94$ for both discharge and water content for the detention-based extensive roof. For the three largest events, the NSE ranged from 0.97 to 0.85 (details in Table A.5). Those three largest event had each a duration of more than a day. The water balance error was found to be 5%.

The conceptual limitation of the model can be seen in Figure 2.9 at the beginning of the events of the testing period. It suggests that short events with low intensity are not reproduced well by the model, as it cannot represent the delay induced by the wetting of the different layers of the roofs. Since the objectives of this study involve the use of a simple model to reproduce the behaviour of two roofs, the model was not further improved.

2.5 Conclusion

In this chapter, a method to test extreme precipitation on a full-scale detention-based green roof consisting of sedum mats underlaid with expanded clay was developed using an artificial rainfall simulator. Rainfall events with 20-year return periods, including a climatic factor of 1.4, were derived from DDF curves for three different cities: Bergen, Oslo, and Trondheim, and tested at the field station in Trondheim. This multistep method that compares different variables depending on the previous steps was found relevant to analyse the global performance of the roof.

The assessment of the hydrological performance showed that retrofitting the black roof as a green roof increased the performance significantly. Furthermore, the roof was found to be sensitive to water content strengthened by long drainage and time of concentration. The study also strengthened the understanding of dynamic phenomena

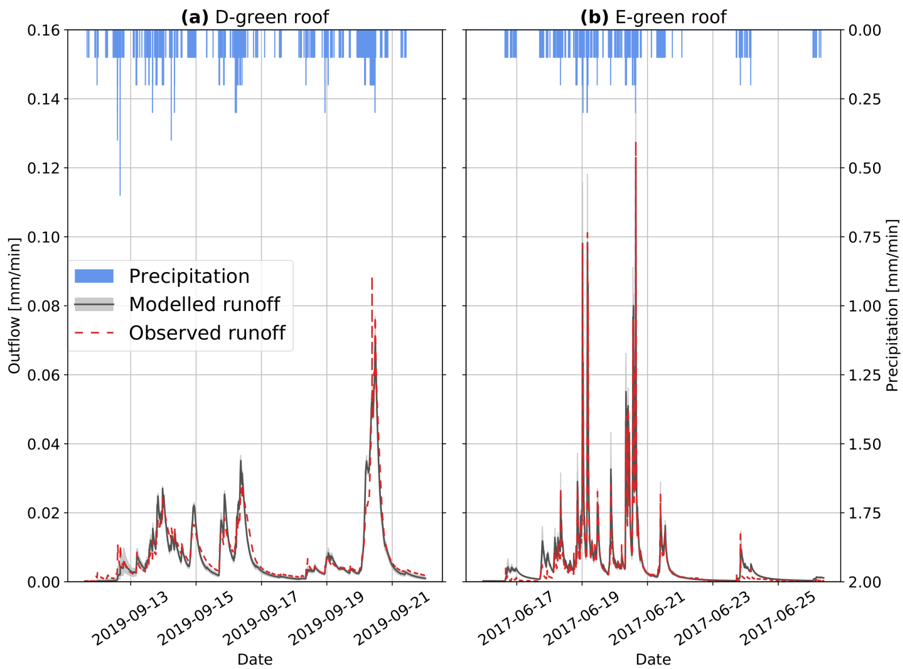

Figure 2.9: Testing of the green roof's reservoir model. Observed and modelled runoff of the detention-based extensive green roof (D) model on ten days period (left) and extensive green roof (E) for a period of eight days (right) in Trondheim. [Paper E - (Pons *et al.*, 2022a)]

governing the flow within the roof and the limitations that are linked to the use of artificial rainfalls. The use of various short-term hyetographs led to different roof performance. It was found that the hyetographs with a peak at the end caused the worst performance, and that the initial water content had a greater influence on the performance than the shape of the hyetograph. Considering water content as a main variable, an indicator such as centroid delay that depends on the initial relative water content is suitable for characterizing the roof without depending on the hyetograph. Indeed, the lower the initial water content was, the longer the detention was observed.

With respect to the general performance of the roof and considering initial conditions according to the location, it was possible to assess that the same roof would perform better in Trondheim than in Oslo. It was also found that rainfall in Bergen (BER 1 and 2, with a higher initial water content) and Oslo (OSL 1 and 2, with lower initial water content) is likely to lead to similar peak runoff. Consequently, initial conditions need to be taken into account for design purposes as a more favourable hyetograph may be counterbalanced by a high initial water content. This study has highlighted the relevance of using performance indicators as a function of input parameters instead of using a single-value performance indicator and discussing commonly used indicators. Based on these results, further study is needed to provide statistics to extend the results to longer lasting rainfalls and make generalizations about locations using modelling.

The development of a conceptual green roof model with meaningful parameters lead to satisfying results. It showed the relevance of wisely targeting the data to collect in order to optimize the ratio information/data. The development of green infrastructure models is not the objective of the current PhD, therefore the potential of such a model is not explored further. However, it gives a first direction toward wiser data collection for adaptation to climate change. Green infrastructure can be tested under extreme events in order to increase the model reliability under both extreme and low events. According to the current results, such a task may be achieved with a low-data-intensive strategy. Such a statement has to be considered carefully and further investigated. In particular, the effect of maintenance strategies and ageing of green infrastructure is still poorly understood and require monitoring strategies. However, monitoring infrastructure for maintenance purposes does not necessarily require the same information as the one required for hydrological modelling.

3

Green roof's performance estimation and uncertainty: the effect of limited inputs

For even the very wise cannot see all ends.

Gandalf,
J.R.R. Tolkien,
The Lord of the Rings

Foreword

This chapter is not based on a paper published during the PhD. It influenced the understanding of green roof's performance and therefore the work published after this study. It presents the influence of limited climate data on green infrastructure performance estimation. It also presents how to account for climate variability using existing performance indicators.

Abstract

The concept of robust decision-making is an approach to decisions under deep uncertainty. It can be used to cope with climate change and the impact of anthropogenic activities. In the context of stormwater management and the three-point approach, it requires an appropriate evaluation of the performance of green infrastructure. The current chapter studies the influence of limited inputs and resolution on performance indicators. Based on an informal sensitivity analysis, it evaluates the amount of data needed to achieve reliable estimation. It finds the needed amount of data to vary with the characteristics of the green roof considered and of the performance target. The chapter concludes that the output data from green infrastructure hydrological simulation has to be treated to extract the relevant information. This information, in alignment with the principle of robust decision-making, should represent stochastic uncertainty to account for the natural variation in climate data. The epistemic uncertainty should be addressed carefully to not lead to misuse of natural variation performance interval.

Contents

3.1 Introduction

Design methods for stormwater measures often rely on a resistance paradigm. A common design method relies on the use of a design rain derived from Intensity Duration Frequency (IDF) curves in order to prove that the solution is likely to meet the requirements of a given municipality. It could be based on the rational formula or the rain envelop method (Trondheim Kommune, 2015, among others). Especially, in the context of the three point approach in Denmark (3PA) (Fratini *et al.*, 2012), or the 3SA in Norway, local stormwater measures such as green roofs are supposed to ensure a level of service under steps 1 and 2. It means handling day-to-day rains and major rains. The definition of major rain can be discussed. Here it refers to the design return period. In general, green roofs are neither conceptualized nor designed for extreme rains. Hence, their design return period may vary from 5 to 20-year. It could be argued that since their primary function is to reduce the volume through evapotranspiration, their design requirement should be based on retention. In Lyon, the green infrastructures (GIs) must permanently retain the first $15\ mm$ of the rain (Greater Lyon council, 2020). The 3PA/3SA paradigm requires a shift in design and performance evaluation practice in order to adapt to climate change. In Norway, the use of climate factor is recommended to take future climate into account when using IDF-curves (Hanssen-Bauer *et al.*, 2017).

In order to adapt to climate change and plan stormwater management, uncertainty needs to be taken into account in modelling tasks (Deletic *et al.*, 2012; Tscheikner-Gratl *et al.*, 2019). Uncertainty needs to be defined by type, nature, and location (Walker *et al.*, 2003). Uncertainty and sensitivity are more often addressed in model parametrization or measurement (Deletic *et al.*, 2012; Pianosi *et al.*, 2016) than on input data characteristics. Indeed, in Section 1.4.1 practice of uncertainty analysis was found to be limited. The idea of limited data was rarely mentioned, and its impact on the uncertainty and performance estimation was not found to be quantified.

Input data are of prime importance as they condition the results of a modelling study, they are one of the *source* of uncertainty. As detailed in Chapter 1, uncertainty can be defined in terms of nature type and source. They include uncertainty with different *nature* which make it challenging for sensitivity analysis: i) epistemic uncertainty, reducible with more data or higher quality data; and ii) stochastic uncertainty not reducible and due to the nature of the process involved (e.g. weather). The *type* of uncertainty remains a challenge for decision-making. Depending on the type, uncertainty can be quantified using uncertainty analysis, studied using scenario-based methods or ensemble approaches, or finally deep uncertainty that cannot be quantified. This last type is of special interest for decision-makers as it affects future climate, future urbanization and anthropogenic activities. To cope with it, Walker *et al.* (2013) advocated for the use of robust decision-making (RDM). This paradigm contrasts with the resistance paradigm. The key principles are static and dynamic robustness. Static robustness consists in exploring the largest range of possibilities. Dynamic robustness, also referred to as adaptability, refers to the adaptability of a plan and to which extent it can be easily modified if necessary. It consists in keeping the flexibility of short term decisions in order to achieve long-term objectives.

To improve the practices in evaluating detention performance, Stovin *et al.* (2017) advocated for a more rigorous use of performance indicators and the use of distribution-based indicators. In the continuation of those recommendations and with respect to the principle of static and dynamic robustness, this study aims to study the uncertainty in input rainfall time series for modelling of green roofs:

- Explore further the distribution-based indicator for detention performance.
- Study the sensitivity of the different performance indicators to input quantity and resolution.
- Discuss the influence of limited input consideration on a decision-making process.

3.2 Methodology

3.2.1 Study case

The model presented in Chapter 2 was used in the current chapter. It was found relevant in terms of performance, since the two green roofs (E-Green roof and D-Green roof) have a different behaviour. Their performance was accurate enough to study the impact of data limitation and resolution limitation on hydrological performance estimation.

3.2.2 Performance indicators

The different indicators were calculated based on an existing 29-year long time series of rainfall and temperature in Trondheim. The data were split in sub-time series to simulate limited input: 29 series of one year, 26 series of 3 years, 24 series of 5 years and 19 series of 10 years. The 29-year long time series was used as the overall reference.

Splitting the 29-year long time series had two goals. The first, as mentioned above, is to account for limited inputs by comparing the estimates with limited time series to the estimates with long time series. The second objective is to show the variability of performance and show evidence of the information lost when not accounting for the natural variability in performance estimation. Two types of indicator were derived: time series-based indicators and event-based indicators. The time series-based indicators were:

- The retention performance, defined as the percentage of volume of rainfalls retained along the time series. The performance depending on the series shows both the natural variability and the influence of limited input.

- The detention performance, defined as the survival distribution of discharge. The input precipitation time series includes both dry weather and rainfall events. The rainfall events can be day-to-day events, which means that they are expected to be retained by the green roofs according to the 1^{st} step of the 3SA. The time series may also include more extreme events corresponding either to step-2 or step-3 of the 3SA. The roof is then expected to attenuate the rainfall.

The event-based indicators were derived from the events identified in each time series. The events were defined with a minimum inter-event time (MIT) of 6 hours. This definition of event is acknowledged as a limitation (Joo *et al.*, 2014) even though the 6-hours criterium is common in the field (e.g., Hamouz *et al.*, 2018; Stovin *et al.*, 2013). To evaluate if the indicators were sensitive to the MIT choice, the indicators were also studied with a MIT of 4 and 8 hours. Only the events greater than $1\ mm$ were included in the study. The event-based indicators were:

- The centroid-delay, defined as the delay between the mass centre of the rain and the mass centre of the runoff.

- The peak runoff (with 1 min resolution).

Other event-based indicators were not accounted for. In particular, the peak-delay is sensitive to the rainfall resolution and the peak chosen (see Chapter 2). The peak attenuation can be misleading and was therefore excluded. It was concluded in Chapter 2 that this indicator alone without information on the value of peak runoff or on the magnitude of the event has a limited meaning. It is a normalized indicator, sensitive to input rainfall resolution. The T_{50} delay was not included because the centroid-delay was considered sufficient for the current analysis.

3.2.3 Informal sensitivity analysis

The two factors of the modelling task are considered for the sensitivity analysis are the amount of data (length of the time series considered), and the resolution of the data (in minutes). In order to map the influence of the two factors on the survival distribution of discharge, a metric was defined. The metric measures, for several probability levels, the error in estimating the discharge. It is defined as follows:

$$Agg_{error}(p, length, res) = |F^{-1}_{29,1}(p) - F^{-1}_{29,res}(p)| + |Range_{length,1}(p) - Range_{length,res}(p)| \quad (3.1)$$

The formula is divided into 2 terms. One accounting for the effect of the resolution solely. And the second one for the range of possible estimate due to the amount of data used for estimation and the resolution. $length$ is the amount of data used as input (1 year, 3 years, 5 years, and 10 years). The resolution is represented by res (from 2 minutes to 120 minutes). p is the probability level considered (10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5}). It is a probability of exceedance. $F^{-1}_{29,1}(p)$ is the discharge estimated, for a probability of exceedance p with the 29-year long time series at 1 minute resolution. $F^{-1}_{29,res}$ is the discharge estimated when changing the probability. This term measures only the influence of the resolution. $Range_{length,1}(p)$ represents, given a probability of exceedance level p, and a time series length $length$, the maximum range of discharge. $Range_{length,res}(p)$ is similar for variable resolution. When $length$ tends to 29, the full amount of data available, $Range_{length,1}(p)$ and $Range_{length,res}(p)$ tend to zero. When res tends to 1, both terms tend to zero.

The choice of an informal sensitivity analysis was mainly motivated by the fact that only two factors are considered. Therefore, it is possible to visualize the influence of the choice. Moreover, this analysis is meant to be qualitative in order to evaluate if those two factors influence the performance estimation.

3.3 Result and Discussion

3.3.1 Performance indicators and sensitivity

3.3.1.1 Context of discussion

Three different performance indicators were studied. The survival function of the discharge was chosen to assess the performance under different levels of probability (i.e. from daily rainfall to extreme events). The annual retention fraction was estimated in percentage. Finally, the centroid delay and peak runoff were measured as a distribution, splitting the data into events.

Figure 3.1 shows the survival distributions of discharge from both roofs and rainfall. In particular, it shows the variation depending on years. The red shaded area in Figure 3.1 shows that there is precipitation in Trondheim during 20% of the time. The performance of the E and D green roofs are evaluated during their functioning time. The functioning time, is defined here as the time of activation of their hydrological function. This fraction of the data includes both the daily and negligible rains and more extreme events. The performances during day-to-day rains are important to evaluate, as they represent the majority of the service period of the roof. Retaining and attenuating day-to-day rainfall events, is the main hydrological function of green roofs. The tail of the distribution represents the performance under extreme events. Attenuating extreme rain is a secondary function of green roofs. However, the green roofs are designed using (extreme) design rains. Design hyetographs may not allow for an accurate estimation of the hydrological performance of the roof. Indeed, the design hyetograph does not represent a probable hyetograph (Alfieri *et al.*, 2008) and the initial moisture conditions are often neglected (see CHAPTER 5). It has been shown, for the detention-based green roof, that the initial water content, and the shape of the hyetograph can have a significant impact on performance under extreme events (Chapter 2). It may lead to an inaccurate estimation of performance. Such estimation may induce a poorly decision-making, resulting in an oversized roof or undersized roof. For that reason, the following analysis is presented in the context of continuous simulation to estimate the influence of limited data and resolution on the primary hydrological functions of green roofs.

3.3.1.2 Detention performance - survival distribution of discharge

In the city of Trondheim, the city put a regulation on the water released to the network, depending on the reduced area (construction area) of the project and on the nature of the sewer (combined or separated). The condition of $2.4\ L/s$ for $300\ m^2$ with a combined sewer is equivalent to $0.48\ mm/min$ and $0.3\ mm/min$ for a reduced area of $500\ m^2$ and a separated system (vertical black lines on Figures 3.1 and 3.3). On Figure 3.1, according to the simulation with the 29-year time series, the detention-based green roof would meet the target while the E-Green roof would not meet the target of $0.3\ mm/min$ during 3 hours.

The maximum discharge shows that the solution with detention-based solution outperforms the E-Green roof with a maximum flow of less than $0.08\ mm/min$. The light shade of blue represents the simulations using less than 1 year of data. It shows a possible mistake from 0.04 to $0.08 mm/min$. The same analysis on the E-Green roof shows a possible error of estimation from $0.1\ mm/min$ to more than $0.8\ mm/min$ (not displayed on the figure). The range of variation ($0.7\ mm/min$) is larger than the target ($0.3\ mm/min$). It means that using limited data can affect the performance estimation. It also means that performance indicators should convey the information about the range of variation. Indeed, the D-Green roof outperforms the E-Green roof not only in terms of probability to meet the target, but also in terms of robustness to climate variability. The results of this simulation show two different aspects:

- **i.** The lack of input data result in poor estimation of performance. In particular, due to the nature of extreme events, the shorter the input time-series is, the less likely it is to have a representative extreme event of a given level. Therefore, performance under extreme events is more sensitive to limited data.
- **ii.** Point estimation is not appropriate to measure the performance of the green roofs. The information about the range of variability should be conveyed.
- **iii.** Using a long time-series does not ensure an appropriate communication of the information relative to climate variability. The data needs to be transformed (e.g., from a single distribution to a range on Figure 3.3)in order to be appropriate for robust decision-making.

3.3.1.3 Sensitivity analysis - Impact of data on discharge estimation

To account for the sensitivity due to input data resolution and amount, an aggregated error on different probability was estimated. The results on Figure 3.2 have to be assessed together with Figure 3.1. Therefore, the results for the detention-based green roof have to be compared to the maximum runoff of 0.08 mm/min, and 0.9 mm/min for the E-Green roof. Formal sensitivity indices, such as Sobol indices (Saltelli *et al.*, 2007) are dimensionless. In the context of the current analysis, the choice of

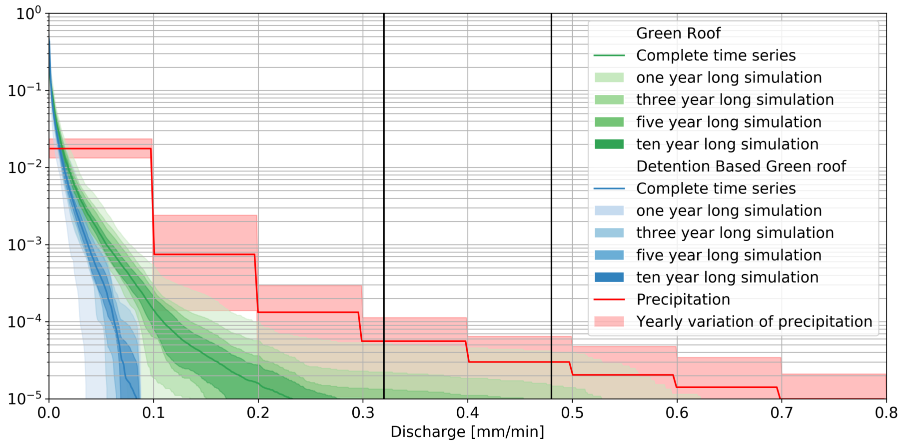

Figure 3.1: Survival distribution of the modelled discharge depending on the amount of input data. The vertical lines represent the criteria in Trondheim municipality for $500\ m^2$ and separated sewer, and $300\ m^2$ and combined sewer.

an informal sensitivity analysis here is also motivated by the need to keep a reference to the discharge. In particular, it has to be considered with respect to the roof's characteristic, to the threshold of interest and the probability level of interest. On Figure 3.2, for a probability of 10^{-5} or 10^{-4}, even a resolution of 5 min leads to an error in estimation of the annual range of discharge while the error remains negligible for 10^{-2}. The reason those parameters (roof's characteristic, threshold of interest and probability of exceedance) have to be considered carefully is that two *natures* of uncertainty are included. The natural variation of weather cannot be reduced, while the uncertainty due to temporal resolution can be reduced using more accurate data. Therefore, in the case of low error, a careful assessment has to be done. A low error may be due to compensation between both uncertainty, or may indicate a low sensitivity for the choice of data amount and resolution. Mapping the sensitivity helps with analysing in such a case.

3.3.1.4 Detention performance - Peak runoff distributions

Comparably to the survival distribution of discharge, the survival distribution of peak runoff provides information on rainfall attenuation performance. This event-based indicator is here analysed to evaluate the relevance of the current design practice. There is a mean number of events of 114 per year according to the definition of events used. The probability that the peak runoff of the E-green roof exceeds the threshold of $0.3\ mm/min$ is $2.5 \cdot 10^{-3}$. Given the time-series length, it is similar to a return period of runoff between 3 and 4 years. The event generating the highest runoff ($0.9\ mm/min$) on the E-Green roof had a depth of 27.4 mm and a duration of 500 min. This event had a return period of less than 5 years in Trondheim. As a comparison, a 5-year constant intensity rainfall using the variational method and

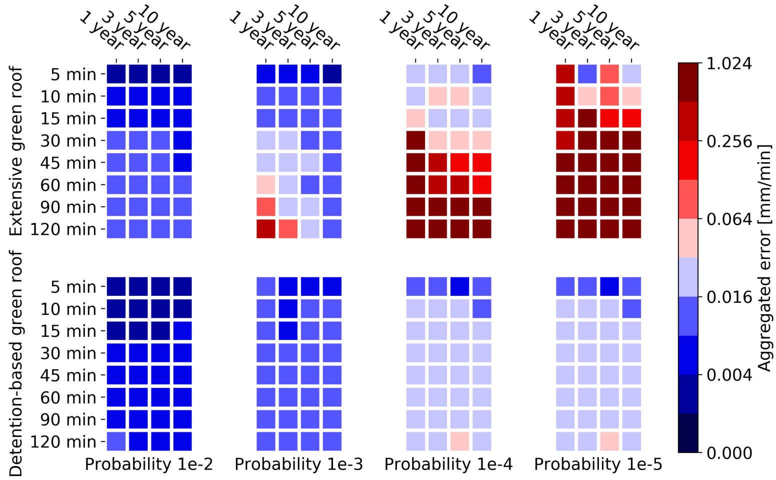

Figure 3.2: Aggregated error of the survival discharge for different log-probability level depending on resolution (y-axis) and amount of input data (x-axis).

an initial water content equal to the mean water content in the 30-year time series leads to 0.15 mm/min. The simulated probability of exceedance and the maximum peak runoff highlight both the limitation of the definition of events and the practice of using design rain. A high peak runoff can result of a combination of conditions, such as initial water content and shape of the hyetograph. Therefore, this suggests revising the assumption that the return-period of a rainfall event is equivalent to the return period of a level of performance. Moreover, as the distribution of peak flow targets events, and in particular rare events, it is more sensitive to limited amount of data.

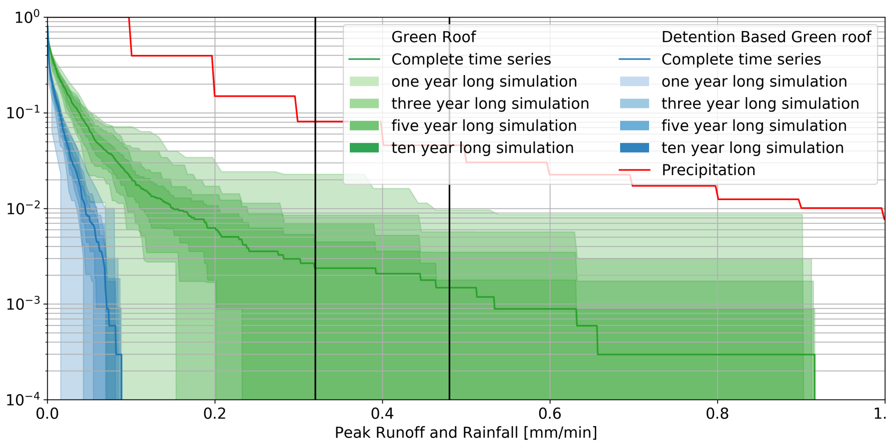

Figure 3.3: Survival distribution of peak runoff compared to peak rainfall. The vertical lines represent the criteria in Trondheim municipality for $500\ m^2$ and separated sewer, and $300\ m^2$ and combined sewer.

3.3.1.5 Detention performance - Delay performance

An important performance to measure is the ability of the roof to delay the rainfall. Indeed, if two solutions do not attenuate the rainfall to a required level but contribute with peak at different times in a sewer network, the requirement may be reached at system level. Conversely, green infrastructures contributing with their peak runoff at the same time leads to higher peak discharge. To measure the delay, the peak delay is often used, but it is unstable depending on the resolution and due to multiple possible peaks. The centroid delay is a solution to avoid those biases. Comparably to previous results, the simulation demonstrated a large annual variation of performance (Figure 3.4). The Figure 3.4 shows a large variability of the results. 50% of the events are delayed between 200 min and 400 min on the E-Green roof and between 350 min and 550 min for the D-Green roof. The D-Green roof shows better performance than the E-Green roof for most of the events $(p > 0.03)$. However, they perform similarly for the remaining 3% of the events. In order to take more informed decisions, the distribution may not be sufficient. It is necessary to analyse the performance depending on the type of events. If two solutions are sensitive to different types of hyetographs, their coupled implementation might lead to better performance from a system perspective. Comparably to the results on Figure 3.3 the definition of rain event is found to be a limitation. Since the extreme performance depends so much on the events, the same time series with the same sets of events should be used to compare different solutions.

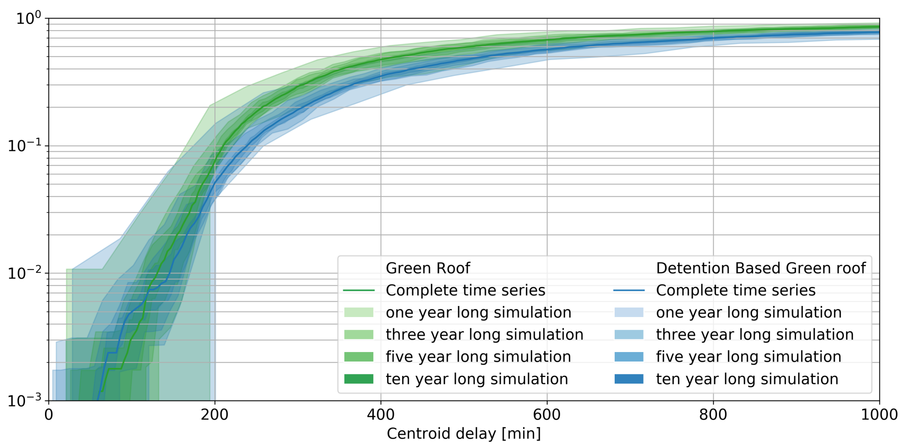

Figure 3.4: Cumulative distribution of centroid delay for event higher than $1\ mm$ of rainfall, depending on the amount of input data.

3.3.1.6 Retention performance

Figure 3.5 shows the retention performance estimation depending on the amount of data available. The shade of colour on Figure 3.5 shows the range of uncertainty in estimation due to lack of data. In particular, this should be taken into account when comparing two solutions evaluated on two different periods. If the period is short (e.g., a year) it is likely not to converge to the true value of the performance under the climate considered. During monitoring, the measured performance of the E-Green roof showed better retention performance than the D-Green roof. However, those two solutions had not been evaluated in the same period of time. After a model development and continuous simulation, the current results suggest that the difference in performance could be due to natural variability. Testing the model more extensively in terms of retention would improve the confidence in the results. Similarly, showing the performance using a long time series without considering the annual variation can lead to a misunderstanding of the roof behaviour. The two roofs have similar performances over the 29-year time series (15%). The annual retention varies from 10% to 30%. When deciding which roof to install, the information of the annual retention variability should be accounted for.

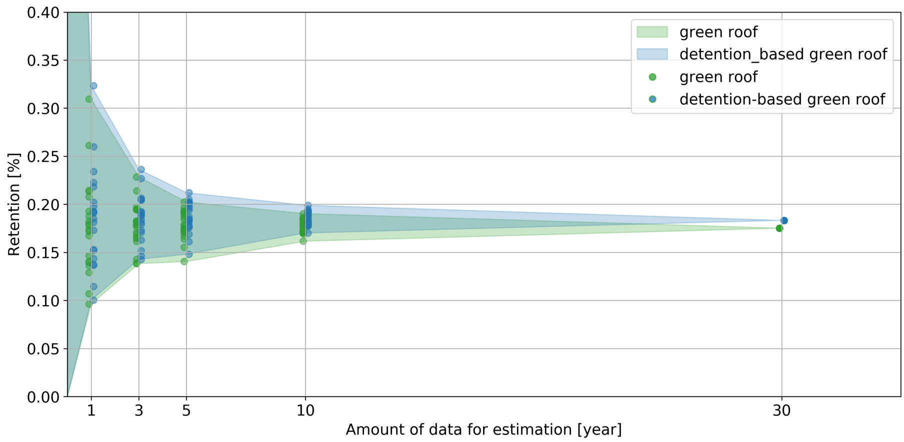

Figure 3.5: Retention performance of the different solutions depending on the amount of data for estimation.

3.3.2 Recommendation for Robust Decision Making

A comparison of the performance of the E and the D green roofs shows that the D-Green roof has better detention capacity than the E-Green roof, even accounting for yearly variation. However, the retention performance indicators are similar for the two roof solutions, although the yearly variation is large. It shows that using a large amount of data without considering the natural variation might lower the robustness of the performance estimates.

The definition of events and indicators is considered as a limitation. However, if used, the definition should stay consistent in order to achieve meaningful comparison. The time series used should be similar, especially when only a limited amount of data is available. Since the current definition of events is limiting, time series based simulation are more suitable to evaluate the performance of green infrastructure as they can account for initial water content that is not realistically taken into account in event-based design. It is however possible to couple continuous simulation to sample initial conditions for extreme event-based simulations.

Instead of aggregating the performance of both solutions only to rank them, the decision-making process could evaluate the ability of the different solutions to perform as a system. If two solutions are not sensitive to the same events and might not contribute at the same time, their combination might lead to a more robust design at system scale. The other characteristics of the two solutions will also influence the decision.

For instance, the E-Green roof may be less expensive than the detention-based one. They can however have different structural constraints due to the weight. The area required by the detention-based green roof to achieve similar performance might counterbalance this aspect. The decision-making process does not only rely on the hydrological performance, therefore the information conveyed about their hydrological performance must be efficient and meaningful in terms of variation due to climate.

3.4 Conclusion

A 29-year long time series was used to evaluate the influence of the amount of data on the hydrological performance evaluation of the D and E green roofs. Three different performance indicators were evaluated:

- The retention performance was found to annually vary from 10% to 30% for both solutions. It shows both stochastic uncertainty due to natural variation and epistemic uncertainty due to limited inputs in terms of amount of data should be accounted for.

- The discharge distribution show as well similar results in terms of managing uncertainty with different nature. Moreover, it shows that evaluating performance under extreme events requires long time series. The length of the time series depends both on the desired level of accuracy and the property of the solution. Indeed, the D-Green roof is less sensitive to the amount of input than the E-Green roof.

- The evaluation of centroid delay shows the issue of defining a performance indicator and defining an event: comparing the performance curve without accounting for initial condition is not relevant. The negligible events are not relevant in terms of centroid delay.

The study shows the limitation of performance evaluation based on point-estimate and on return period of rainfall. Rather than that, the return period of the events should be considered with the hyetographs and combination of events for which the roof is found sensitive.

Later on in the current thesis, density-based indicators will be favoured because they convey better the information on climate variability. It is possible to convert density-based indicators to informative point indicators. For instance, instead of using the retention performance over an 29-year time-series, it is possible to estimate a distribution of yearly performance and set a threshold (e.g., the annual retention fraction 90% of the years). A similar definition of probability of exceedance of a discharge threshold can be defined. A distribution of annual duration of exceedance could be used, and a threshold could be defined (e.g., less than $60\ min$ in 90% of the years). The information of such an indicator includes the climate variability in its formulation. Pappenberger and Beven (2006) suggested that uncertainties and probability distributions can, if properly formulated, be efficiently communicated for decision-making.

4

Forecasting green roof detention performance by temporal downscaling of precipitation time-series projections

The world is changed. I feel it in the water. I feel it in the earth. I smell it in the air.

Galadriel,
J.R.R. Tolkien,
The Lord of the Rings

Foreword

The current chapter is based on Paper E in praticular the section related to model develpment has been removed since the model is introduced in Chapter 2. First, the state of the art of statistical temporal downscaling is presented, then methods used to develop models of Multiplicative random cascades are established. Finally the models are tested against green roofs models to evaluate their suitability as inputs for performance estimation.

The right grey bar in the margin is used to inform the reader that the work is similar to one of the direct contribution to the thesis. Similar is defined as reformatted to fit to the chpter structure. Minor modifications of the text are done in order to fit to the structure of the current PhD thesis. When a major modification was necessary, the section or paragraph is not quoted.

Abstract

A strategy to evaluate the suitability of different multiplicative random cascades to produce rainfall time series, taking into account climate change, inputs for green infrastructures models. The multiplicative random cascades reproduce a (multi)fractal distribution of precipitation through an iterative and multiplicative random process. In the current study, the initial model, a flexible cascade that deviates from multifractal scale invariance, was improved with (i) a temperature dependency and (ii) an additional function to reproduce the temporal structure of rainfall. The structure of the models with depth and temperature dependency was found to be applicable in eight locations studied across Norway and France. The resulting time series from both reference period and projection based on RCP 8.5 were applied to two green roofs with different properties. The different models led to a slight change in the performance of green roofs, but this was not significant compared to the range of outcomes due to ensemble uncertainty in climate modelling and the stochastic uncertainty due to the nature of the process. The hydrological dampening effect of the green infrastructure was found to decrease in most of the Norwegian cities due to an increase in precipitation, especially Bergen (Norway), while slightly increasing in Marseille (France) due to decrease in rainfall event frequency.

Contents

4.1 Introduction

Hydrologic performance of stormwater green infrastructure (green infrastructure (GI)) is usually divided between retention and detention. Retention refers to water stored, infiltrated, or evapotranspirated. Actual evapotranspiration can be estimated from a water balance including potential evapotranspiration, accumulated precipitation, a soil moisture evaluation function, and a crop factor (Johannessen *et al.*, 2017; Oudin *et al.*, 2005). The temporal resolution for modelled evapotranspiration process for green infrastructure (GI) is typically daily (Stovin *et al.*, 2013) or hourly (Kristvik *et al.*, 2019). Detention refers to water temporarily stored in the GI before being discharged into a downstream stormwater network. The process temporal resolution is typically minutes. Consequently, modelling GI detention performance requires higher-resolution data to estimate its outflow (Schilling, 1991). Therefore, both highresolution climate data and projections at subdaily and subhourly scales are needed in order to model GI and to estimate their potential as a climate change adaptation measure.

In Norway and most of the European countries, precipitation has been measured with tipping buckets in numerous cities from years to decades. Moreover, climate projections at daily resolution for future precipitation and temperature from the EURO-CORDEX project are available at 1x1 km spatial resolution in Norway (Dyrrdal *et al.*, 2018) and 12x12 km resolution in France (Jacob *et al.*, 2014). Consequently, the use of such data by urban hydrologists to assess the resilience of GI solutions to face climate change is conditioned by the possibility to downscale them to a subhourly resolution.

Downscaling includes two families of methods: dynamical downscaling and statistical downscaling (Benestad, 2016). Dynamical downscaling methods use physically based equations and are usually computationally expensive specially to generate high-resolution data. Statistical downscaling consists in improving the resolution of data based on statistical properties observed from a lower-resolution dataset. The computational cost is lower; therefore, statistical methods might still be used to fill the gap in the next decades until the computational power is sufficient for routine dynamical downscaling. In addition, the use of a stochastic approach is necessary due to the current limitation in parametrization of small-scale processes (below the truncation scale) and the lack of coupling between resolved and parameterized scales (Sanchez *et al.*, 2016).

Statistical downscaling has already been extensively used to temporally downscale data for various temporal resolutions, usually hourly or daily data. Three popular methods can be mentioned: (i) the method of fragment, (ii) the method based on point process theory, and (iii) the method of multiplicative random cascades. The method of fragment (Li *et al.*, 2018; Lu *et al.*, 2015) is a resampling method based on k-nearest neighbours (Kalra and Ahmad, 2011), which has been applied to derive hourly data from daily data. It can be accurate and effective due to its resampling nature, but it requires a large dataset, and by its design it cannot ensure extrapolation from observed data. Therefore, it might not be suitable to downscale climate projections. Methods based on point process theory have been used (Glasbey *et al.*, 1995; Onof *et al.*, 2000). The main principle is to generate storm occurrences and then describe them based on rain cells and statistical distribution based on Poisson point process. Multiplicative Random Cascades (MRCs) consist of using successively random cascades to split data in N data of finer resolution ($N = 2$ in most of the cases). It is a very popular method that deserves further investigation (Gaur and Lacasse, 2018; Rupp *et al.*, 2012; Thober *et al.*, 2014). They were originally based on the hypothesis of multifractal scale invariance (Schertzer and Lovejoy, 1987) and were further developed by Gupta and Waymire (1993) and Olsson (1998). While multifractal scale invariance continues to be studied (Gires *et al.*, 2020), several studies noted a deviation from that behaviour which led to the use of more flexible models (Koutsoyiannis and Langousis, 2011; Veneziano *et al.*, 2006). Multiplicative random cascades can be divided between canonical and micro-canonical types. The canonical one ensures conservation on average, while the micro-canonical one ensures exact conservation. The parameters of the canonical Multiplicative Random Cascade (MRC) are often calibrated by fitting between observed and simulated noncentred moments of depths or intensity through the timescale (Paschalis *et al.*, 2012). The principle of micro-canonical MRC is usually based on reverse cascades: studying how the data are split and then reproducing the properties of the weights distribution depending on different quantities. The influences of timescale, rainfall intensity (Paschalis *et al.*, 2012; Rupp *et al.*, 2009) or season (McIntyre *et al.*, 2016) have been extensively studied. (Lombardo *et al.*, 2012) suggested that the commonly used MRC suffers from conceptual weaknesses due to the non-stationary process of autocorrelation and proposed a method to improve the model. More recently, Bürger *et al.* (2014, 2019) suggested to include a temperature dependency in MRC models to make them more robust. This also enables them to be used with projections.

Green infrastructures, due to their retention and detention capacities, are seen as a promising solution to manage storm water and cope with climate change, especially in cities where urbanization increases. Among green infrastructures, green roofs are especially suitable for dense urban centres. They are designed to retain day-to-day rain by evapotranspiration and attenuate major rainfall events (Stovin, 2010). Depending on their characteristics they can also help to detain extreme rainfall (Hamouz *et al.*, 2020b). Due to the timescale of their detention process, and their sensitivity to initial water content at the beginning of a rainfall event, they are suitable for evaluating downscaled time series. Moreover, it is especially relevant to evaluate their detention performance by the end of the century under a scenario such as RCP 8.5 (Thorndahl and Andersen, 2021). The results could be used to evaluate, at strategic level, their potential in mitigating storm water in order to make robust decision (Walker *et al.*, 2013).

While downscaling models have been used to model the performance of green infrastructure under current climate (Stovin *et al.*, 2017) or applied to intensity–duration–frequency (IDF) curves to do an event-based simulation of local stormwater measures (Kristvik *et al.*, 2019), none has been developed to produce future high-resolution time series as input for green infrastructure models. The aim of this research is to evaluate different MRC downscaling models and their potential to produce input time series to predict the performance of stormwater green infrastructure, for the case of green roofs. In order to achieve this aim, different parts are detailed in the paper: (i) the development of a general structure of MRC, (ii) the improvement of the MRC structure by adding a temperature dependency, (iii) the addition of an ordering function to improve the temporal structure of the produced rainfall time series, (iv) the evaluation of the capability to reproduce the performance of GI based on observed data, and finally (v) the analysis of a possible shift in performance of GI at the end of the century.

4.2 Methods

4.2.1 Meteorological data

Time series of precipitation and temperature from six locations in Norway and two in France, representing four different climates (Table 4.1) according to the Köppen–Geiger classification (Peel *et al.*, 2007), were used to apply the downscaling method. In Norway, the precipitation was measured by $0.2\ mm$ plumatic tipping rain gauge manufactured by Kongsberg Våpenfabrikk. The rain gauges were not heated and thus did not operate in cold temperature. They were successively replaced by Lambrecht 1518H3 (measuring tip of $0.1\ mm$) in the 1990s and 2000s. The stations were operated by the Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Meteorological Institute (MET Norway). The data were quality checked by the Norwegian Meteorological institute (MET) (Lutz *et al.*, 2020). In Lyon and Marseille, precipitation was measured by $0.2\ mm$ Précis-Mécanique tipping bucket rain gauges. Ten climate projections (temperature and precipitation) on daily resolution with the RCP 8.5 for the period from 2071 to 2099 for Norwegian cities were available online Norsk Klima Service senter (Dyrrdal *et al.*, 2018, last access: 26 may 2022;). For Lyon and Marseille (France), 12 climate projections at daily resolution were available for the same period and RCP (2071 to 2099, RCP 8.5) from DRIAS-climat (last access: 25 May 2022). The RCP 8.5, a scenario with a high gas-emission baseline leading to a radiative forcing of $8.5\ W \cdot m^{-2}$ in 2100, and the end of the century were chosen to test the methods since it was the scenario and period that deviate the most from the current climate among the available data in both countries. In practice, it is relevant to evaluate GI performance at the end of the century, but their design could be based on a different period depending on their lifetime.

Table 4.1: Locations and input data for current and future climate; The climate column gives the Köppen Geiger classification for climate, Observed days is the number of observed days with data. [modified from Paper E - (Pons *et al.*, 2022a)]

Location	Observed Days	Climate	Latitude
Bergen – Sandsli, MET 50480, NVE no. 56.1.	6150	Cfb	60.4
Bodø – Skivika, MET 82310, NVE no. 165.11.	7204	Dfc	67.3
Lyon (France), 6-min time-step	7671	Cfb	45.7
Hamar – Hamar II (Disen), MET 12290	4011	Dfb	60.8
Kristiansand – Sømskleiva, MET 39150, NVE no. 21.49.	5219	Cfb	58.1
Kristiansund – Karihola, MET 64300, NVE no. 110.1.	8664	Cfb	63.1
Marseille (France), 6-min time-step	7305	Csa	43.3
Trondheim – Risvollan, MET 68230, NVE 123.38.	10722	Dfc	63.4

Table 4.2: Characteristics of the climate in current and future conditions. YearPr is the annual precipitation in mm, YearWt the annual number of wet days ($> 1mm$). YearTe is the mean annual temperature; for these three indicators the 5^{th}, 50^{th} and 95^{th} percentiles are displayed. [modified from Paper E - (Pons *et al.*, 2022a)]

Location	Period	YearPr	YearWt	YearTe
Bergen	**Obs:**	$1505, 2081, 2504$	$153, 189, 218$	$-2.1, 8.0, 17.8$
	Proj.:	$2240, 3012, 4009$	$169, 201, 238$	$2.2, 10.3, 19.3$
Bodø	**Obs:**	$643, 991, 1858$	$114, 152, 266$	$-3.9, 5.4, 15.4$
	RCP 8.5:	$1150, 1600, 2139$	$147, 178, 214$	$-0.3, 8.1, 18.2$
Lyon	**Obs:**	$706, 865, 1161$	$80, 97, 114$	$0.5, 12.8, 24.3$
	RCP 8.5:	$550, 830, 1187$	$77, 105, 135$	$3.9, 15.9, 29.9$
Hamar	**Obs:**	$406, 546, 659$	$70, 92, 105$	$-9.8, 5.7, 18.6$
	RCP 8.5:	$508, 689, 861$	$88, 110, 134$	$-5.3, 8.1, 21.0$
Kristiansand	**Obs:**	$1155, 1512, 1868$	$120, 137, 161$	$-0.9, 9.7, 18.6$
	RCP 8.5:	$1258, 1662, 2099$	$115, 142, 167$	$0.3, 10.0, 20.5$
Kristiansund	**Obs:**	$714, 1094, 2521$	$131, 167, 226$	$-0.7, 7.8, 16.2$
	RCP 8.5:	$1440, 2051, 2829$	$153, 192, 230$	$1.9, 9.6, 18.0$
Marseille	**Obs:**	$310, 533, 840$	$35, 49, 64$	$4.1, 15.2, 26.2$
	RCP 8.5:	$250, 492, 767$	$33, 50, 68$	$7.3, 18.0, 30.6$
Trondheim	**Obs:**	$669, 965, 1256$	$117, 150, 173$	$-6.1, 6.3, 17.9$
	RCP 8.5:	$853, 1176, 1599$	$133, 163, 196$	$-1.4, 8.6, 19.2$

4.2.2 Downscaling models and workflow

4.2.2.1 Data aggregation and processing

The historical data were aggregated two by two from $1\ min$ resolution (and accordingly $6\ min$) to more than 1 d resolution in order to capture a part of the uncertainty linked to the estimation of the parameter of the models. The aggregation was done for each possible time steps: all multiples of 2 smaller than $1500\ min$ (as there are $1440\ min$ in a day). During the process of aggregation, both the weights, Eq. 4.1, and the rainfall continuity indicator, Eq. 4.2, measuring the proportion of high weight on the side of the highest neighbouring depth were computed. $j \in [1..750]$ a timescale in minutes, $i \in [0..N_{2j}]$ a time step with N_{2j} the number of time steps at scale $2j$, and $d_{i,2j}$ a rainfall depth, the weight $w_{i,2j}$, and the indicator $S_{i,2j}$ of the side of the neighbour were calculated according to:

$$w_{i,2j} = \frac{\min(d_{2i,j}, d_{2i+1,j})}{d_{2i,j} + d_{2i+1,j}} \in [0; 0.5] \tag{4.1}$$

$$S_{i,2j} = \begin{cases} 0, & \text{if } (d_{i-1,2j} = d_{i+1,2j}) \cup (d_{2i,j} = d_{2i+1,j}) \\ 1, & \text{if } (d_{2i,j} > d_{2i+1,j} \cap d_{i-1,2j} > d_{i+1,2j}) \cup (d_{2i,j} < d_{2i+1,j} \cap d_{i-1,2j} < d_{i+1,2j}) \\ 2, & \text{if } (d_{2i,j} > d_{2i+1,j} \cap d_{i-1,2j} < d_{i+1,2j}) \cup (d_{2i,j} < d_{2i+1,j} \cap d_{i-1,2j} > d_{i+1,2j}) \end{cases} \tag{4.2}$$

4.2.2.2 Downscaling process

The MRC downscaling process consists of transforming daily rainfall depths to rainfall depths at lower timescale, e.g. 1 min, by means of successive distribution of the depth of a parent time steps between its two children time steps. The process is repeated by iteration until the desired timescale is reached. Figure 4.1 describes the downscaling process. In practice, the downscaling started at $1440\ min$ $(1d)$ time step with eight iterations to reach a time step of $5.625\ min$. The results were interpolated and scaled to a $6\ min$ time step for comparison with observed data. The final time step of $6\ min$ was chosen based on the resolution of original datasets in Lyon and Marseille. Three steps are necessary to downscale a parent time step to two children time steps. The occurrence of a zero weight, i.e. the probability to assign all the water from the parent time step to only one of the children time steps (Figure 4.1, centre left), is tested. This property is especially important and acknowledged by other studies. If a zero-weight does not occur, a non-zero-weight $w_{i,2j} \in]0, 0.5]$ is generated from a probability distribution (Eq. 4.3b). It distribute the depth from the parent time step between the two children time steps, as illustrated in Figure 4.1, center right. Finally, the weights $w_{i,2j}$ and $1 - w_{i,2j}$ have to be assigned to the children time steps. The occurrence of S_W (Eq. 4.4), i.e. allocating the highest weight to the children with the neighbour with the highest depth, is tested (Figure 4.1, bottom).

$$u_{0,i,2j} \sim \mathcal{U}([0,1]),$$
$$\text{if } u_{0,i,2j} < P(W=0|S_{time}=2j, D=d_{i,2j}, T=T_{i,2j}), \text{ then } w_{i,2j}=0 \tag{4.3a}$$
$$\text{else, } w_{i,2j} \sim \mathcal{N}_{[0,\frac{1}{2}]}(\frac{1}{2}, \sigma(S_{time}=2j)^2) \tag{4.3b}$$

$$P(S_W=1), \text{with } S_W \in \{0;1\} \tag{4.4}$$

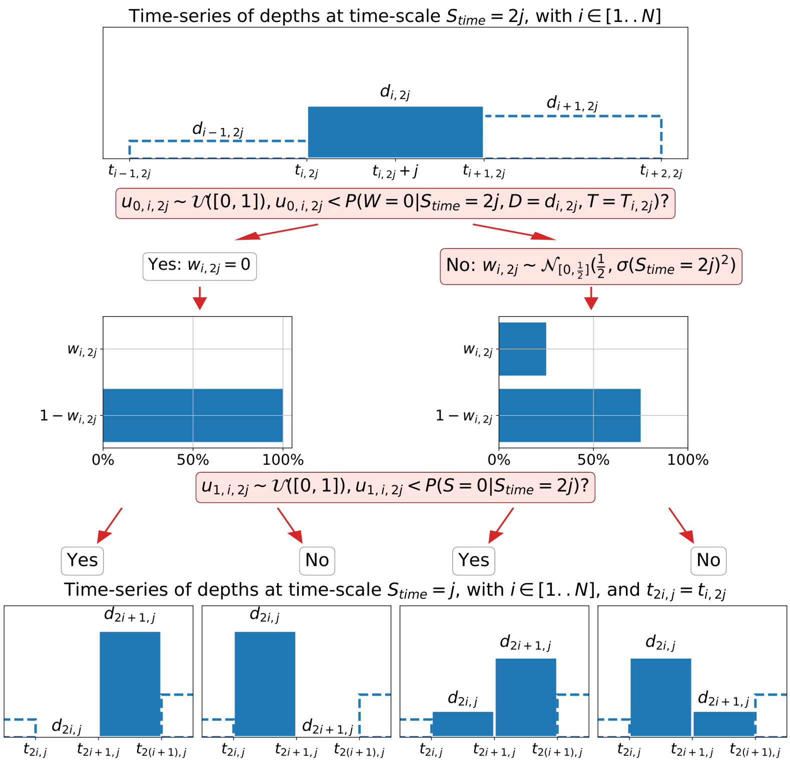

Figure 4.1: Workflow for downscaling to transfer a depth from time-step T to time-step $\frac{T}{2}$. The red boxes involve the generation of a random number. The process starts with $1440\ min$ time-step to reach $5.625\ min$ an interpolation is then done to reach $6\ min$ time-step. [Paper E - (Pons *et al.*, 2022a)]

4.2.2.3 Downscaling models conceptualization and calibration

Based on the observed data, six different MRC models were developed. Different mathematical expressions and probability distributions, detailed in Appendix A, were defined to represent Eqs. 4.3a, 4.3b and 4.4, depending on the hypothesis inherent to the later described models (Table 4.3). The models consist in three generators: a zero-weight generator, a nonzero-weight generator and a stochastic element permutation generator (SEP generator). Each of the zero-weight and nonzero-weight generators (Eqs. 4.3) were considered to vary with timescale (indicated with S in the

Table 4.3: Nomenclature of the models and various quantities taken into account by each model depending on the process considered; S is the time-scale, D the rainfall depth/intensity, T the temperature and N the close neighbour. [modified from Paper E - (Pons *et al.*, 2022a)]

Model	$P(W=0)$				$P(W\|W \neq 0)$				$P(S_W = 1)$				Number of parameters
	S	I	T	N	S	I	T	N	S	I	T	N	
$\mathrm{MRC_S}$	x				x								8
$\mathrm{MRC_{S-SEP}}$	x				x				x			x	13
$\mathrm{MRC_{SI}}$	x	x			x								14
$\mathrm{MRC_{SI-SEP}}$	x	x			x				x			x	19
$\mathrm{MRC_{SIT}}$	x	x	x		x								13
$\mathrm{MRC_{SIT-SEP}}$	x	x	x		x				x			x	18

model naming). The letter I in the nomenclature indicates a depth/Intensity for the zero-weight generator (Eq. B.2). The temperature dependency for the zero-weight generator Eq. B.3 was indicated by the letter T in the nomenclature. The temperature dependency was added in an attempt to improve the robustness of the model toward climate change under the hypothesis that the change in rainfall pattern would be correlated to the shift in temperature and that the existing observed datasets already carry the necessary information for calibration. In the models $\mathrm{MRC_{S-SEP}}$ $\mathrm{MRC_{S-SEP}}$, $\mathrm{MRC_{SI-SEP}}$ and $\mathrm{MRC_{SIT-SEP}}$ (Table 4.3) the weights generated were permuted stochastically depending on the neighbour (indicated with SEP, Eqs. 4.4 and B.5), while the $\mathrm{MRC_S}$, $\mathrm{MRC_{SI}}$, and $\mathrm{MRC_{SIT}}$ model considered equal probability (0.5) to permute the two children weights.

Similarly to Rupp *et al.* (2009), the generators of the MRC models include timescale dependency through analytical formulas. In practice it means that there is a single set of parameters per generator and not a different set at each cascade step. It ensured a relatively parsimonious number of parameters compared to other recent works on microcanonical MRC where a set per cascade step is often used (e.g. 12 to 36 total parameters by Bürger *et al.* (2019) or from 6 to 224 parameters per cascade step by Müller-Thomy (2020)). It should be noted that based on dataset analysis and as advised by Serinaldi (2010), despite the fact that universal and canonical MRC represent the most parsimonious approach parameterwise, their microcanonical counterpart was preferred. This choice of model that deviates from the hypothesis of multifractal scale invariance was supported by several other studies (Koutsoyiannis and Langousis, 2011; Veneziano *et al.*, 2006). The number of parameters can be lower with the use of universal MRCs which were excluded from this study due to lack of flexibility (Serinaldi, 2010). It also allows the model to be used with any desired initial resolution lower than $1500\ min$. Homogeneity of the resolution in the input datasets was not required for calibration and data processing (i.e. the model can be calibrated using multiple datasets with different resolutions between $1\ min$ and $1\ d$). The parameters of each generator of MRC models and each location required calibration.

A single-step calibration, based on the processed data, was sufficient for generators with only timescale dependency. A multiple-step calibration with data manipulation was necessary for generators with depth/intensity, temperature dependency, and for the non-zero-weight generator. This choice was motivated by the development of the model through data analysis and conceptualization of the model. Especially, the steps and calibration of the three generators were chosen to avoid compensation between processes using a bottom-up approach (i.e. starting from local properties and then add dependencies to progressively upscale the model). Additionally, the choice of regression over timescale was used to avoid parameter sets that lead to the correct distribution of precipitation intensities without temporal consistency. Later studies can further improve the procedure to make it more easily calibrated. The optimizations were based on non-linear least squares in the standard library scipy.optimize with default parameters in `Python` (Virtanen *et al.*, 2020).

- The parameters of zero-weight generator with only timescale dependency (Eq. B.1) followed a single-step calibration against observed zero-weight proportions by non-linear least squares.

- The parameters of the zero-weight generator with timescale and depth dependency (Eq. B.2) followed a two-step calibration: (i) for each timescale, the proportion of zero-weight depending on depth was evaluated using a weighted running window to compensate for rare occurrence of extreme depths. The proportion of zero weight depending on depth was then fitted to a function (Eq. B.2a). (ii) The functions modelling the parameters depending on timescale were then calibrated by least squares (parameters of Eqs. B.2b, B.2c and B.2d).

- The parameters of zero-weight generator with timescale, depth and temperature dependency (Eq. B.3) followed a similar calibration procedure. (i) Using running windows of temperature, the proportion of zero-weight depending on depth was fitted by least squares for different temperatures (Eq. B.3a). (ii) Given a timescale the parameters depending on temperature were fitted to a Gaussian function (Eq. B.3b). (iii) The parameters of the Gaussian function depending on timescale were then fitted to set of functions by least squares (Eqs. B.3c, B.3d and B.3e)).

- The non-zero-weight generator consisted of a truncated normal distribution on [0, 0.5] with $\mu = 0.5$ (Eq. 4.3b) and a function σ depending on timescale (Eq. B.4). It was chosen against more commonly used beta distributions (McIntyre *et al.*, 2016) after a goodness-of-fit test was applied to the historical data. The calibration was done in two steps. (i) σ was evaluated by non-linear least squares for each timescale. (ii) The parameters of Eq. B.4 were calibrated against the evaluated σ depending on timescale by least squares.

- The parameters of the SEP generator (Eq. B.5) followed a single-step calibration by least squares with processed proportion of high weight on the side of highest neighbour depending on timescale.

4.2.3 Green infrastructure modelling

The green infrastructure model used in this chapters consists in the green roofs models presented in CHAPTER 2. Namely the extensive green roof (E-Green roof) and the detention-based extensive green roof (D-Green roof). The reason for choosing those 2 roofs is dual. First, the model developed based on extreme precipitation showed high reliability under both low and high flow. Second, the two roofs have different behaviour and are sensitive to different events. The E-green roof has a very thin layer of substrate so is therefore sensitive to short duration intense rain, while the D-green roof has enough storage in the detention layer to attenuate them. The D-green roof is more sensitive to medium duration rains with peak toward the end.

4.2.4 Evaluation of the downscaling models

For each location, the observed precipitations were aggregated to daily resolution and downscaled to obtain 200 time series of $6\ min$ time step. They were used to model the extensive and detention-based extensive green roofs in parallel. It should be noted that irrigation needs and snow periods were neglected since the primary objective of the study was to evaluate the produced time series. There were 10 projections available in Norway for the RCP 8.5 and 12 in France with the EURO-CORDEX project. Each projected time series was downscaled 20 times (200 simulations for Norwegian locations, and 240 simulations for French locations) to capture the following: (i) the variability between the projections and (ii) the variability due to the nature of the downscaling model. The number of simulations per location and per period was chosen to ensure reasonably low simulation time and represent the stochastic uncertainty inherent to the downscaling process. The stability of the percentile estimator with 200 simulations was verified against 1000 simulations in one model and one location to validate the choice.

To evaluate the performance of the downscaling model and the projected performance of green roofs, different indicators were used:

- The lag-1 autocorrelation depending on timescale was evaluated. It was chosen to assess the temporal structure of the produced time series. The autocorrelation depending on lag time for timescale 6, 48 and $180\ min$ were used for an in-depth analysis.

- The survival distribution of precipitation and discharge from both roofs were assessed at $6\ min$ time steps. This approach is similar to the use of flow duration curves recently applied to green roofs by Johannessen *et al.* (2018). The exceedance probabilities were presented with a log axis to account for extreme probabilities. The median, 5^{th} and 95^{th} percentiles of the downscaled time series were represented. The survival distribution of discharge from the roofs with downscaled time series compared to the distribution based on observed data indicates the applicability of the downscaled time series as an input for green infrastructure modelling.

- Along with the survival distribution, a performance indicator derived from the Kolmogorov–Smirnov (KS) distance was used. The KS distance was indeed not relevant for the survival distributions where the extreme probabilities are of prime importance. The authors did not find a standard indicator for such cases in the literature; therefore the following indicator, which penalizes more errors for extreme probabilities, was developed:

$$KS_{rel} = max(\frac{Distrib_{Sim,median} - Distrib_{Obs}}{Distrib_{Obs}} \quad (4.5)$$

- Three different discharge thresholds were used to report exceedance frequency on different operating modes: 1 L s-1 ha-1 for small events, 10 L s-1 ha-1 for major events and 100 L s-1 ha-1 for extreme events. Those thresholds were chosen in common for all roofs to facilitate comparison. They represent a compromise to have the same operating modes for each location even if the occurrence of those modes differs due to different climate conditions. Small event durations were counted in days per year, major events in hours per year and extreme events in minutes per year.

- The distribution of dry periods and the retention fraction were computed. They are not expected to be affected by the downscaling process since the dry periods affecting the roofs can be observed on daily resolution, and the retention fraction can be estimated with conceptual models using daily time-step data. However, they provide additional information to analyse the behaviour of the roofs.

4.2.5 Hybrid event-based downscaling

In order to assess the applicability of downscaled time series to predict the future performance of green infrastructure, the methods were compared to the current recommended practice in the locations: the use of an event-based design method based on IDF curves with a climate factor (CF) (Kristvik *et al.*, 2019). In particular, the variational method (Alfieri *et al.*, 2008) is applied. It consists, given a return period, in considering the constant-intensity rainfall leading to the highest discharge. It should be noted that the comparison intended to follow the recommended design method and not to follow the guidelines of a specific city since they can differ in terms of regulation. For instance, in Trondheim a threshold for maximum discharge has to be fulfilled (Trondheim Kommune, 2015), while in Lyon the first $15\ mm$ of a 20-year return period has to be retained, and beyond those $15\ mm$ a threshold is set for maximum discharge from the parcel (Greater Lyon council, 2020). The longest available time series, which originated from Trondheim, was the most adequate for this example. For 2-, 5- and 10-year return period rainfall and runoff events, three approaches were compared: (i) peak runoff of runoff events based on an observed precipitation time series (reference), (ii) peak runoff of rainfall events based on variational method, the IDF curves and with and without climate factor (typical design approach), and (iii) a hybrid approach based on downscaling 105 rainfall events with a daily depth based on the return period curves with and without climate factors. This last approach used the $\mathrm{MRC}_{\mathrm{SIT-SEP}}$ model, the initial water content was set to the most probable value based on analysis of a long time series. According to the current recommendation in Norway for Trondheim municipality, a climate factor of 1.4 was applied (Dyrrdal and Førland, 2019).

4.3 Result and discussion

4.3.1 Analysis of climates properties

Figure 4.2 presents the zero-weight proportion depending on timescale, depth and temperature for two different datasets (Bodø and Hamar). In Figure 4.2a the proportion of zero-weight decreases with increasing timescale for Bodø. In Hamar the proportion decreases until $45\ min$ and increases for higher timescales. Based on this observation, two types of datasets were identified in terms of zero-weight occurrence. For data from Bodø, Bergen, Kristiansund and Trondheim, the proportion of weights that equalled zero decreased with increasing timescale. For the data from Hamar, Lyon, Marseille and Kristiansand, the proportion decreased until $45\ min$ timescale and increased afterwards (Figure B.1a). Given a timescale, the proportion of weight equal to zero was not uniform depending on the weights (e.g. Bodø and Hamar Figure 4.2b with a timescale of $48\ min$). Therefore, the monotony or nonmonotony of the proportion of weights equalling to zero depending on timescale can be explained by different distributions of depth in the observed data. The proportion depended on depth, which is consistent with previous work (Rupp *et al.*, 2009). It should be noted that a high proportion of zeroweight is linked to shorter and more intense rainfall events. It could explain why the proportion is higher in Lyon than in Bergen (cf. Figure B.1a).

In Figure 4.2b, the zero-weights proportion decreases with increasing depth for the case of Bodø. In the case of Hamar, it increases for depth higher than $2\ mm$. Figure 4.2c and d show that a temperature dependency may explain this behaviour. In Bodø, the proportion depending on depth gives similar results for different ranges of temperature at $48\ min$ resolution (Figure 4.2c). On the contrary, in Hamar, the subsets with lower temperature lead to a lower proportion of weights being equal to zero, compared to subsets with higher temperature (Figure 4.2d). Moreover, the higher depths were observed in subsets with higher temperature. The increase observed in Hamar can be explained by the distribution of observed values. It is consistent with the observation of different temporal distributions of rainfall for different temperature ranges such as convective rains (Berg *et al.*, 2013; Zhang *et al.*, 2013). If, given a depth of $10\ mm$ at resolution of $48\ min$, the probability to have a weight equal to zero is higher, then there is a higher probability to have an intense rainfall. The non-homogeneity of observed datasets and the shift in temperature with climate change might lead to inconsistency in time series produced by the downscaling methods that exclude depth and/or temperature dependency. The $48\ min$ timescale was chosen to exemplify these properties. The same properties can be observed for different timescales, but the magnitude differs and tends to lower with higher timescale (Figure B.1b, c and d). Developing a model without temperature dependency might prevent comparability of parameters between locations and does not necessarily lead to parameter parsimonious models. Moreover, a model such as $\mathrm{MRC_{SI}}$ can result in overfitting when used with datasets like Hamar. The functions necessary to represent the behaviour without considering the temperature dependency are more complex and less explanatory. Based on this analysis it was possible to add the temperature dependency and conceptualize a more explanatory model ($\mathrm{MRC_{SIT}}$, with Eqs. B.3) with more robust results for the influence of climate change. This underlies the hypothesis that the information about the correlation between rainfall and precipitation will be expressed in the same way through those variables in the future.

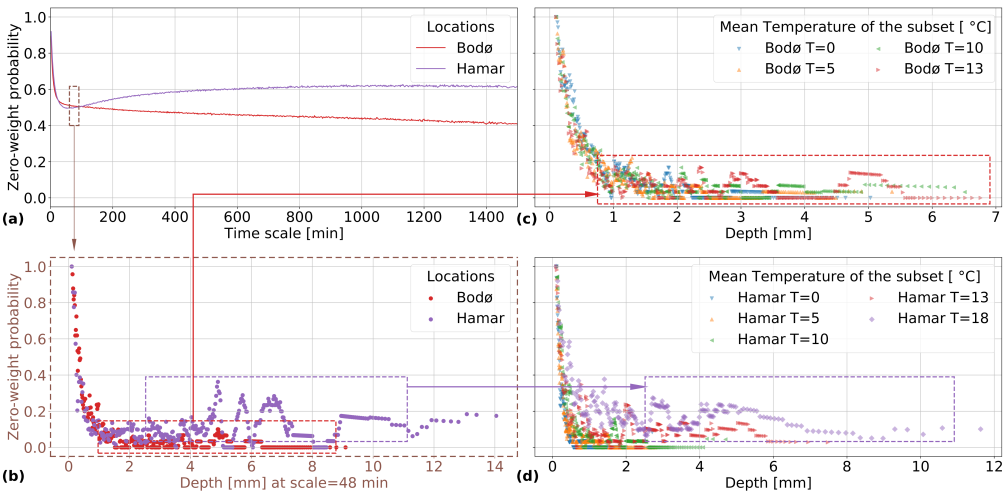

Figure 4.2: Dependency of the probability to have a weight equal to zero on: time-scale (a), rainfall depth (b) and temperature (c and d) for datasets observed in Bodø and Hamar. b, c, and d are based on data at 48-minute resolution. [Paper E - (Pons *et al.*, 2022a)]

4.3.2 Evaluation of the downscaling methods

An overview of the performance of the downscaling and green roof models in Bergen is presented on Figure 4.3. All the downscaling models performed similarly in terms of dry period distribution and slightly underestimated the dry periods in observed data (Figure 4.3b). The dry periods were directly linked to the zero-weight probability. In green infrastructure modelling, the length of the dry periods influences the retention performance as it can lead to water stress hindering evapotranspiration. However, dry periods leading to water stress can be also evaluated with daily time-step series (there is no need for minute time-step series). Therefore, dry periods longer than the initial daily resolution are not significantly affected by downscaling.

The distribution of precipitation (Figure 4.3a) was properly reproduced by $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$ ($KS_{rel} = 1$ in this case, indicating that the maximum distance has the same order of magnitude in data and model results) models, while $\mathrm{MRC_{S}}$ and $\mathrm{MRC_{S-SEP}}$ underestimated low precipitation and overestimated high precipitation depths ($KS_{rel} = 10^2$ meaning that the maximum distance reached 2 orders of magnitude). This was expected as the time steps with high depth have higher probability to not be split in the observed data. This is not the case for $\mathrm{MRC_{S}}$ and $\mathrm{MRC_{S-SEP}}$ models, for which probability is uniformly distributed. In Bergen, the observed precipitations were within the range of 90% coverage interval for $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$. For the four later mentioned models, the discharge of the D-Green roof was underestimated by 1 order of magnitude with a KS_{rel} of 1.7×10^1 (Figure 4.3c), due to the behaviour of the roof with rare high discharge. The hyetographs produced by downscaling probably tend to generate less favourable hyetographs for this roof. Although the discharge of the E-Green roof did not fall in the 90% coverage interval, it can be considered as slightly underestimated since the magnitude is similar with a KS_{rel} of 2.0 (Figure 4.3d). However, this was not the case for all locations, as in Hamar the most extreme precipitation tended to be underestimated, while the discharge from both roofs had the same order of magnitude as the observed data but tended to be overestimated. These findings could suggest inconsistency in the temporal structure of rainfall. This hypothesis can be confirmed by the autocorrelation (Figure 4.4) being overestimated at $6\ min$ time step.

The autocorrelation was underestimated by $\mathrm{MRC_{S}}$ and $\mathrm{MRC_{S-SEP}}$ models. The use of the rainfall continuity indicator increased the lag-1 autocorrelation for all models but did not improve the overall performances. The models $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$ underestimated the lag-1 autocorrelation between 48 and 300 min timescales, but an in-depth analysis with different lags at 48 and $180\ min$ timescale shows that despite that underestimation for lag-1 the general behaviour of the observed time series is reproduced. Similar observations were done for other locations.

To evaluate the produced time series it is necessary to compare the discharge with observed time series to the discharge with downscaled time series. For most of the locations, the predicted range of precipitation or discharge deviated for lowest probabilities from the values obtained with observed time series: (i) when the precipitation range matched with the observed distribution, the discharge tended to be overestimated; (ii) when the precipitation was underestimated, the discharge with observed data tends to lie in the range obtained from downscaled time series. While the downscaled time series suffer from some limitation when compared to results obtained from the observed time series, the raw discharge time series might as well not be suitable for robust decision making in green infrastructure implementation as it does not represent the natural variation of performance of green infrastructure.

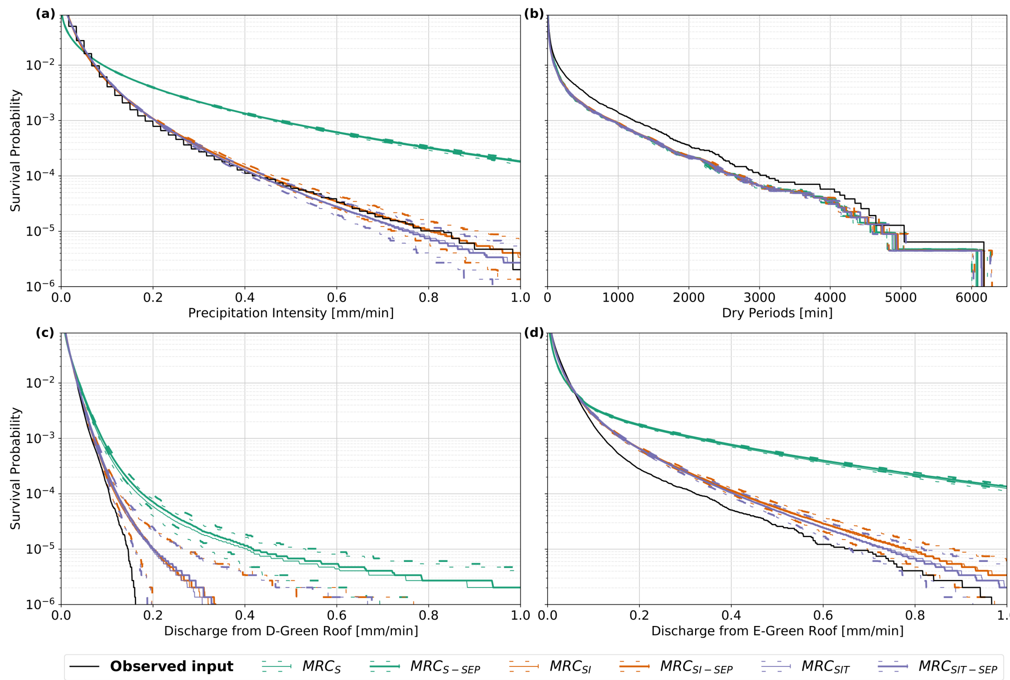

Figure 4.3: Models performance with data from Bergen current climate for MRC_S, MRC_{S-SEP}, MRC_{SI}, MRC_{SI-SEP}, MRC_{SIT}, and $MRC_{SIT-SEP}$ with a range from 5^{th} to 95^{th} percentiles. Observed input represents the fine-resolution observed time-series or simulation using this time-series as input. [Paper E - (Pons *et al.*, 2022a)]

In order to evaluate the potential of discharge from downscaled time series to approach the range of performance linked to natural variability, a 3-year moving window was used on precipitation and discharge time series resulting from observed precipitation. The resulting 5^{th} and 95^{th} percentiles of the annual duration exceeding 1, 10 and 100 L s-1 ha-1 are presented in Figure 4.5 to evaluate the time series in different operating modes of the roofs. It is compared to the stochastic variability (5^{th} and 95^{th} percentiles) from the six models. Each horizontal line in Figure 4.5 represents the range between 5^{th} and 95^{th} percentiles for the threshold and model considered. The different thresholds represent the discharge for respectively small events, for major events and extreme events. In Figure 4.5, the thresholds correspond to 0.006, 0.06 and 0.6 $mm \cdot min^{-1}$. A good estimate is defined by a complete or partial overlap between the observed natural variability and the stochastic variability range; the order of magnitude of the estimates should be similar. For instance, in Bergen (first column), the observed range of the E-Green roof higher than $100\ L \cdot s^{-1} \cdot ha^{-1}$ (third row) is predicted, based on observed input, from 4 to 10 min; the $\mathrm{MRC_S}$ model provided values around 200 min; it is not a good estimate as there is no overlap and the order of magnitude varies; the $\mathrm{MRC_{SI}}$ model resulted in a range from 10 to 20 min. It is a good estimate as the ranges are overlapping, and the orders of magnitude are similar. The $\mathrm{MRC_S}$ and $\mathrm{MRC_{S-SEP}}$ models tend to underestimate the order of magnitude of

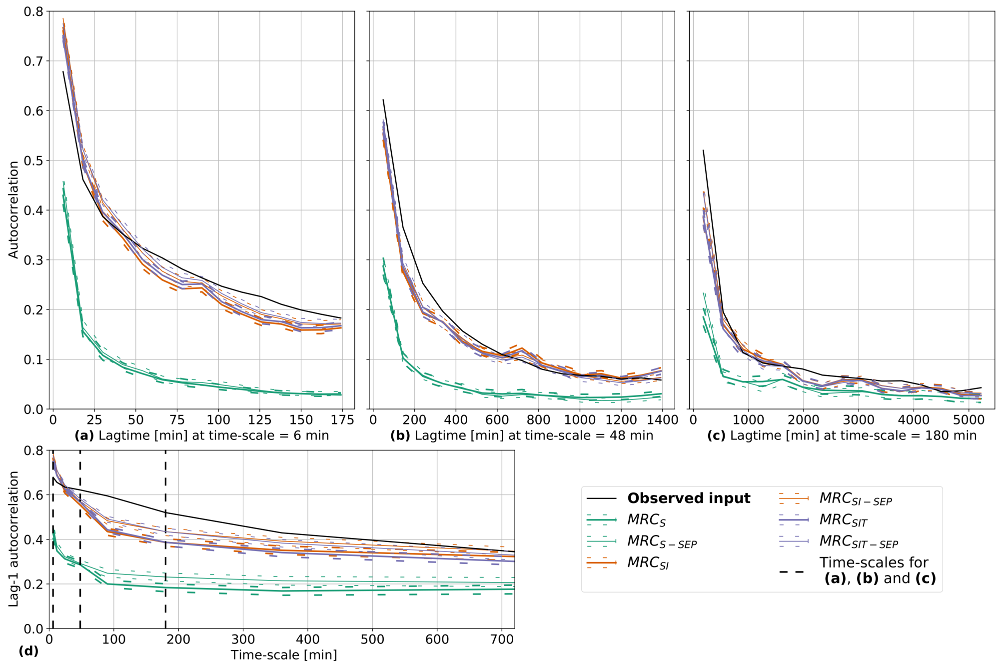

Figure 4.4: Autocorrelation with data from Bergen current climate for MRC_S, MRC_{S-SEP}, MRC_{SI}, MRC_{SI-SEP}, MRC_{SIT}, and $MRC_{SIT-SEP}$ with a range from 5^{th} to 95^{th} percentiles. Autocorrelation with different lags for $6\ min$, ,$48\ min$ and $180\ min$ timescales, and lag-1 autocorrelation depending on time-scale. They are compared to the observed input which represents the fine-resolution observed time-series. [Paper E - (Pons *et al.*, 2022a)]

the range of exceedance frequencies of the small events ($1\ L \cdot s^{-1} \cdot ha^{-1}$) (in Bergen, Hamar and Marseille) but tend to overestimate major ($10\ L \cdot s^{-1} \cdot ha^{-1}$) (Hamar) and extreme events ($100\ L \cdot s^{-1} \cdot ha^{-1}$) (Bergen, Bodø, Hamar and Marseille). The other models gave mostly good estimates for each of the thresholds (Figures 4.5 and Figure B.2). In Marseille, the models $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$ tended to underestimate the higher bound of the extreme event precipitation with values lower than $50\ min \cdot yr^{-1}$, whereas the observed time series led to a maximum of $90\ min \cdot yr^{-1}$. However, those models kept the order of magnitude, while $\mathrm{MRC_S}$ and $\mathrm{MRC_{S-SEP}}$ models estimated it higher than $10^2\ min$. The same behaviour was observed with Hamar (Figure 4.5) and Lyon datasets (cf. Figure B.2). This suggests that the models performed worse for dryer locations, possibly due to the calibration procedure since fewer wet days are available for calibration. $\mathrm{MRC_{SI}}$ and $\mathrm{MRC_{SIT}}$ performed similarly, but due to its structure, $\mathrm{MRC_{SI}}$ may overfit to the calibration data. It could result in an inaccurate prediction in the case of significant temperature shift between the calibration and prediction datasets. To conclude, $\mathrm{MRC_S}$ and $\mathrm{MRC_{S-SEP}}$ lead to overestimation of the natural variability, while $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$ give more accurate estimates.

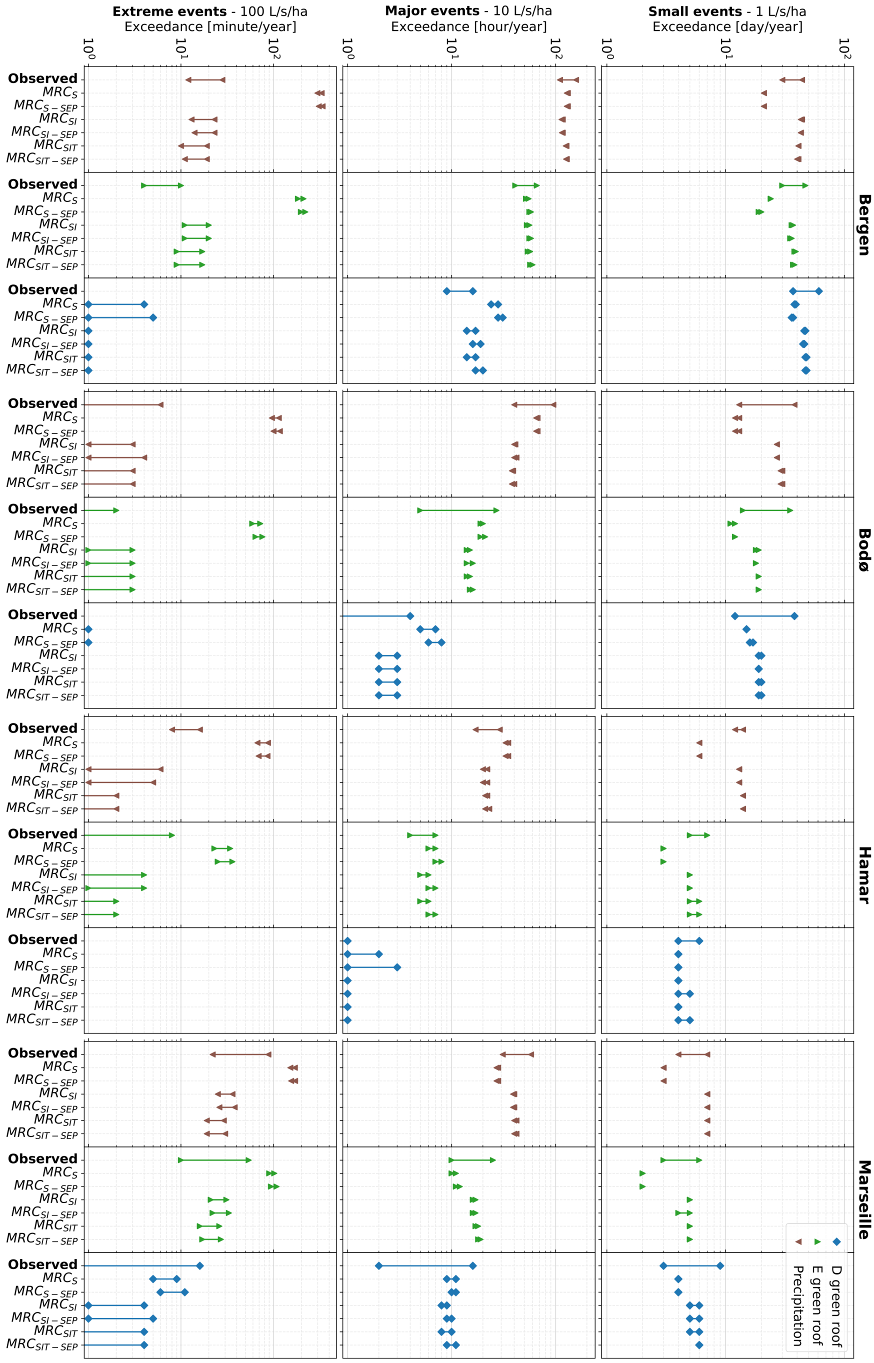

Figure 4.5: Performance of the downscaled time-series in Bergen, Bodø, Hamar and Marseille; exceedance frequency for small events, major events and extreme events. The stochastic variability linked to the downscaled time-series is evaluated with the 5^{th} to 95^{th} percentiles. $Observed$ represents the fine-resolution observed time series or simulation using this time series as input; The 5^{th} to 95^{th} percentiles was estimated with a 3-year moving window. Due to log axis, occurrences lower than 10^0 are not visible. [Paper E - (Pons *et al.*, 2022a)]

4.3.3 Assessment of green roof future performance

All six models were used to assess the performance of green roofs for future climate as illustrated for Bergen in Figure 4.6. It was nevertheless acknowledged that $\mathrm{MRC_S}$ and $\mathrm{MRC_{S-SEP}}$ models gave less accurate estimates. The four model $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$ lead to similar results in Bergen (Figure 4.6). The difference in estimates between the models with coherence indicator ($\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT-SEP}}$) and without ($\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT-SEP}}$) was negligible in comparison to the stochastic uncertainty inherent to the models and the variability linked to the different projections available under RCP 8.5 (Figure 4.6). In Bergen, according to the projections, the performance of the two solutions is likely to lead to worse performance: under the current climate, the $100\ L \cdot s^{-1} \cdot ha^{-1}$ exceedance was lower than $1\ min$ for the D-Green roof; according to the $\mathrm{MRC_{SIT-SEP}}$ model it might reach between 5 and $19\ min$ in future climate. It suggested a shift in the order or magnitude from 10^0 to more than 10^1 min. Similarly, the E-Green roof might have a $100\ L \cdot s^{-1} \cdot ha^{-1}$ exceedance shift from 10^1 to $10^2\ min$. It means that the threshold would regularly be reached. As illustrated by Figures 4.7 and B.3, the performance shift depends highly on the location. While the $100\ L \cdot s^{-1} \cdot ha^{-1}$ exceedance of the green roofs was likely to get worse in Bergen, it was found to stay stable despite a small increase in Bodø and to improve in Hamar and Marseille. The increase of exceedance frequency in the Norwegian cities was due to an increase in precipitation (Table 4.2). However, the increase in temperature led to an increase in potential evapotranspiration and therefore might have attenuated or even counterbalanced the effect of rainfall increase by lowering the initial water content in the roofs at the beginning of a rainfall event. The Table 4.4 shows that the retention fraction was likely to decrease in Bergen, Bodø, Hamar, Kristiansand and Kristiansund. It was found to increase more significantly in Lyon, Marseille and slightly in Trondheim. The models with temperature dependency performed similarly to the model with only depth dependency in most of the locations. However, in Lyon and Marseille, the $100\ L \cdot s^{-1} \cdot ha^{-1}$ exceedance or precipitation predicted differed from 16–27 to 21–$50 min$ (14–30 to 14–43 in Marseille). This suggests that some locations are more sensitive than others to temperature-dependent patterns. The models $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$ allow the evaluation of shift in performance for the different roofs using exceedance range.

4.3.4 Design perspectives

The potential of downscaling models to improve the current practices was investigated. Figure 4.8 presents results based on continuous simulation, on the variational method and on the hybrid approach with downscaled events. It shows that the variational method underestimated the peak runoff with observed data, and the distribution from the hybrid approach covered them. It suggests that the variational method might not be enough conservative when compared to peak runoff from runoff events instead

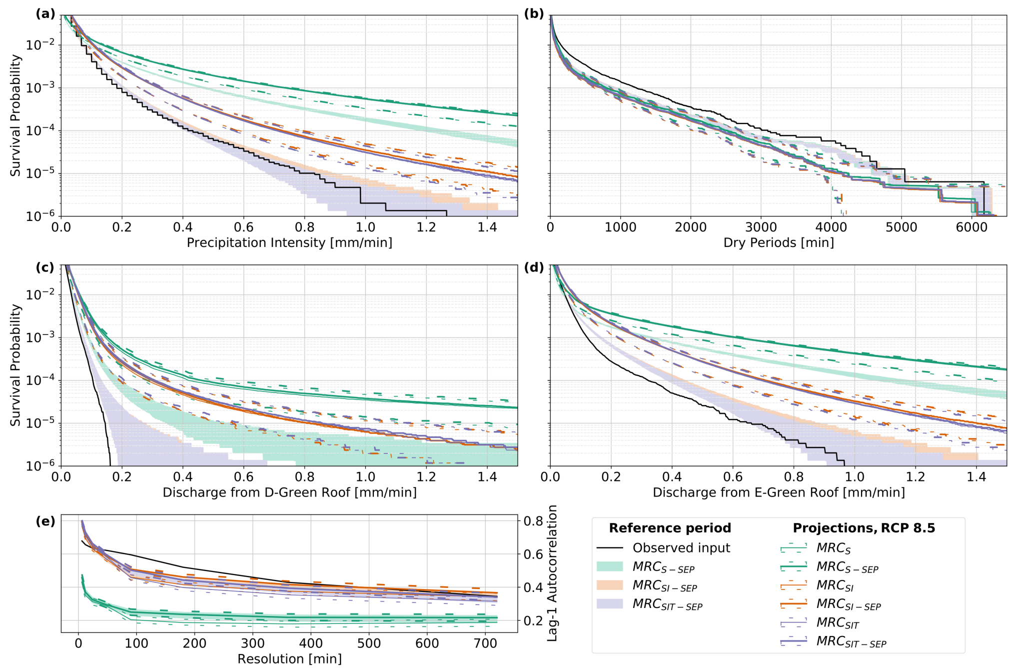

Figure 4.6: Comparison between performance under current climate and future climate in Bergen for the MRC_S, MRC_{S-SEP}, MRC_{SI}, MRC_{SI-SEP}, MRC_{SIT}, and $MRC_{SIT-SEP}$ with a range from the 5^{th} to 95^{th} percentiles. They are compared to Observed input which represents the fine-resolution observed time-series or simulation using this time series as input. [Paper E - (Pons *et al.*, 2022a)]

of rainfall events. Even if the results from the hybrid event-based downscaling lead to realistic distribution based on probable rainfall events, the downscaling models might need a different calibration or conceptualization to be optimized specifically for extreme events. Moreover the initial water content for the events remains a limitation of this method. The observed peaks show a range of possible outcomes, which highlights the limitations of the variational method with a single estimate, whereas the hybrid downscaling-event based method, leading to a range of probable outcomes, gave promising results that can lead to more robust design and decision making. Due to its characteristics, the shift in performance between current climate and future climate is higher for the E-Green roof than for the D-Green roof. This is due to the detention layer in the D-Green roof which is not saturated by a 10-year return period event (Hamouz *et al.*, 2020b).

Table 4.4: Retention fraction in the different locations defined as the sum of outflow divided by the sum of precipitation. [modified from Paper E - (Pons *et al.*, 2022a)]

Location	Bergen		Bodø		Lyon		Hamar	
Period	Obs.	Proj.	Obs.	Proj.	Obs.	Proj.	Obs.	Proj.
D-Green roof	0.20	0.17	0.21	0.20	0.43	0.47	0.47	0.40
E-Green roof	0.19	0.16	0.21	0.20	0.39	0.44	0.44	0.38
Location	Kristiansand		Kristiansund		Trondheim		Marseille	
Period	Obs.	Proj.	Obs.	Proj.	Obs.	Proj.	Obs.	Proj.
D-Green roof	0.24	0.22	0.25	0.20	0.27	0.30	0.41	0.47
E-Green roof	0.22	0.20	0.24	0.20	0.26	0.29	0.36	0.42

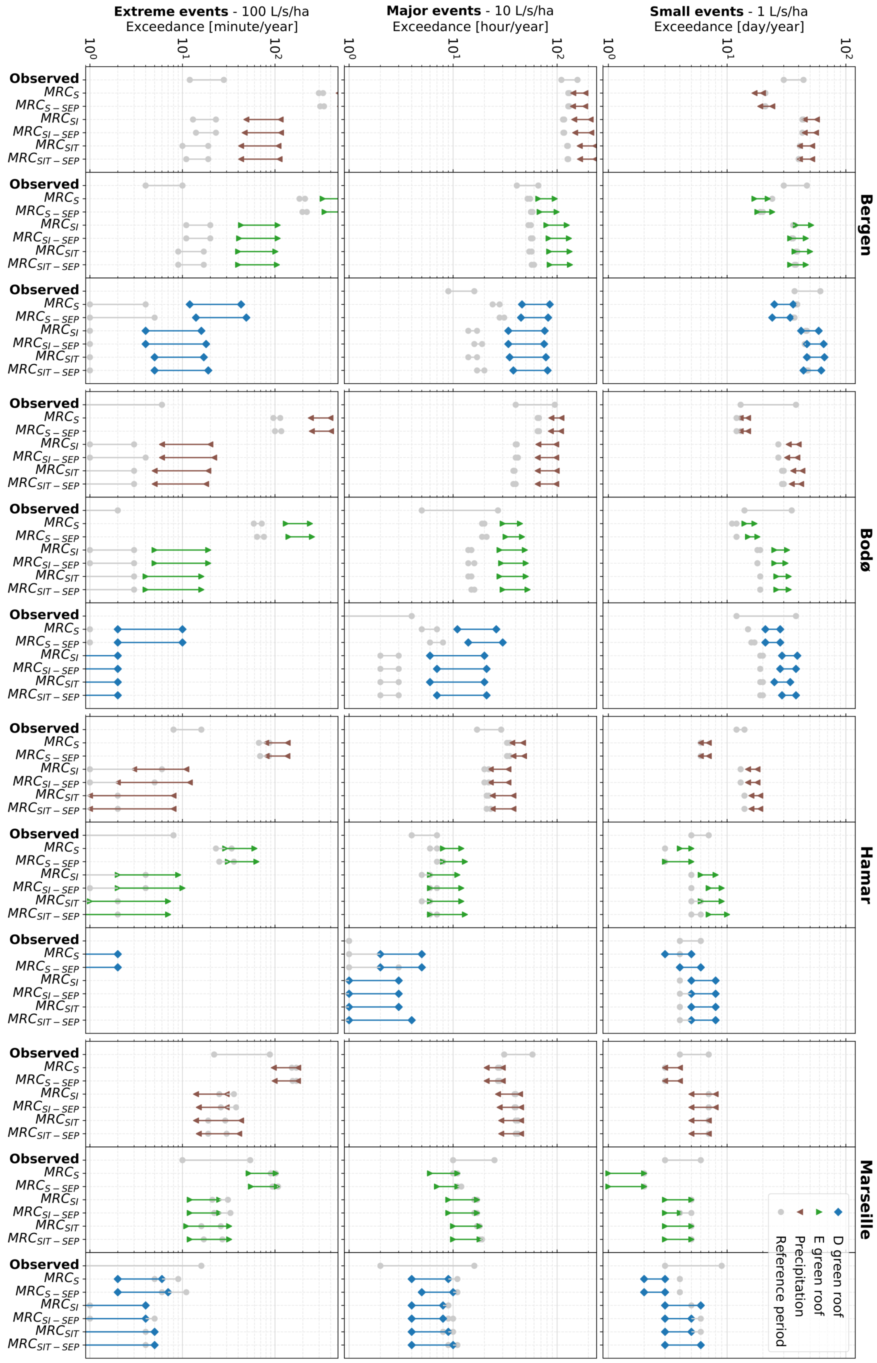

Figure 4.7: Future performance of green roofs (D and E) in Bergen, Bodø, Hamar and Marseille; exceedance frequency for small events, major events and extreme events. The stochastic variability linked to the downscaled time-series is evaluated with the 5^{th} to 95^{th} percentiles. $Observed$ represents the fine-resolution observed time series or simulation using this time series as input; The 5^{th} to 95^{th} percentiles was estimated with a 3-year moving window. Due to log axis, occurrences lower than 10^0 are not visible. [Paper E - (Pons *et al.*, 2022a)]

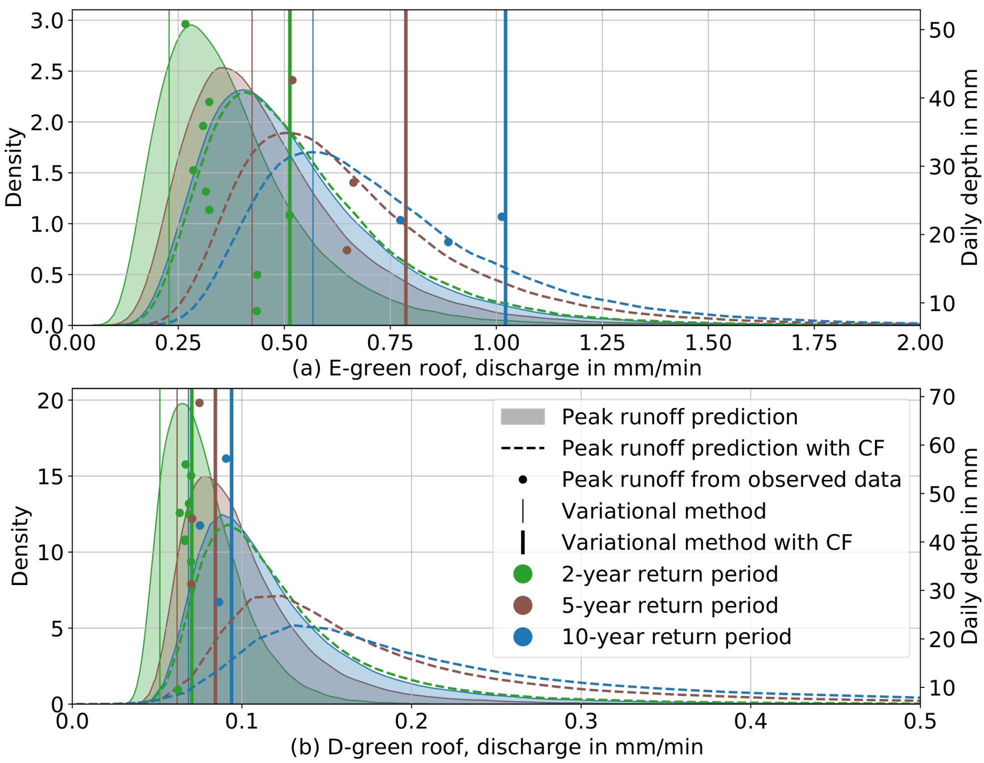

Figure 4.8: Performance depending on the return period in Trondheim for the extensive green roof (top) and the detention-based extensive green roof (bottom). The transparent coloured area (resp. dotted line) is the distribution based on the hybrid event-based downscaling under current climate (resp. with CF); the points represent the peaks runoff of runoff events from observed precipitation; the vertical lines the results found based on the VM. 2, 5 and 10-year return period are displayed. [Paper E - (Pons *et al.*, 2022a)]

4.4 Conclusions

In this chapter, multiplicative random cascades models with different variable dependency were developed. They were based on a study of timescale, depth, and temperature characteristics of the datasets to ensure a consistent structure in the view to apply them to daily-resolution climate projections. The applicability of the synthetic time series to be used as input for performance modelling of green infrastructure was evaluated. They were used to predict the shift in runoff exceedance under a future climate.

Six downscaling models were developed: two models with only timescale dependency ($\mathrm{MRC_S}$ and $\mathrm{MRC_{S-SEP}}$), two models with timescale and depth dependency ($\mathrm{MRC_{SI}}$ and $\mathrm{MRC_{SI-SEP}}$), and two models with timescale, depth and temperature dependency ($\mathrm{MRC_{SIT}}$ and $\mathrm{MRC_{SIT-SEP}}$). The models $\mathrm{MRC_{S-SEP}}$, $\mathrm{MRC_{SI-SEP}}$ and $\mathrm{MRC_{SIT-SEP}}$ include a rainfall continuity property with the intention of improving the temporal structure of the rainfall. The parametrization of the models ensures the continuity of the different properties modelled and a low number of parameters.

The $\mathrm{MRC_S}$ and $\mathrm{MRC_{S-SEP}}$ were not sufficient to predict the future performance of green infrastructure as they lead to an overestimation of runoff; the $\mathrm{MRC_{SI}}$, $\mathrm{MRC_{SI-SEP}}$, $\mathrm{MRC_{SIT}}$, and $\mathrm{MRC_{SIT-SEP}}$ lead to better performance: it was possible to predict runoff exceedance frequency with similar order of magnitude as the estimate of the natural variability of performance based on observed time series. The structure of the $\mathrm{MRC_{SI}}$ and $\mathrm{MRC_{SI-SEP}}$ models makes them more vulnerable to overfitting than $\mathrm{MRC_{SIT}}$ and $\mathrm{MRC_{SIT-SEP}}$, which makes them less reliable for future performance estimates. However, the differences between them were negligible compared to the variability linked to the different outcome of climate models, the variability inherent to the model and its accuracy. The $\mathrm{MRC_{S-SEP}}$, $\mathrm{MRC_{SI-SEP}}$ and $\mathrm{MRC_{SIT-SEP}}$ add an equation to improve the temporal structure of downscaled rainfall. The models predicted higher runoff from the detention-based extensive green roof, which is consistent with their properties; however the change in performance was not significant compared to stochastic uncertainty.

Using the RCP 8.5, the different downscaling and the green roof models suggest that the performance shift due to climate change highly depends on the location. The runoff exceedance is likely to increase in Bergen while slightly decreasing in Lyon and Marseille and keeping the same order of magnitude in the other locations. The results were compared to one of the current practices: the use of the variational method with a climate factor. It highlighted the limitation of this practice that provides a singular estimate and underestimates the observed peaks. A hybrid method using downscaling on extreme events led to promising results by estimating a distribution of performance of peak runoff.

The models performed well in the eight locations and four different climates. The use of a more advanced calibration procedure with Bayesian methods should improve the results. Similarly, a sensitivity analysis could improve the parametrization, especially for the models with depth and temperature dependency in order to fix non-behavioural parameters. The current study does not include irrigation, and snow modelling a study centred on green infrastructure modelling is therefore needed to extend the results. In order to be applied in practice on event-based simulation for design perspectives, the downscaling models need to be improved with a calibration procedure developed for extreme events and not on the complete spectrum of observation as in the current study.

5

Revising green roof design methods with downscaling model of rainfall time series

But I spoke hastily. We must not be hasty. I have become too hot. I must cool myself and think; for it is easier to shout "stop!" than to do it.

Treebeard,
J.R.R. Tolkien,
The Lord of the Rings

Foreword

The current chapter is based on the preprint of Paper D which resulted in a published paper (Pons *et al.*, 2022b). In particular some figures have been modified from the preprint and an informal sensitivity analysis has been added based on Communication F.

The right grey bar in the margin is used to inform the reader that the work is similar to one of the direct contribution to the thesis. Similar is defined as reformatted to fit to the chpter structure. Minor modifications of the text are done in order to fit to the structure of the current PhD thesis. When a major modification was necessary, the section or paragraph is not quoted.

Abstract

Historically, green infrastructure for stormwater management has been event-based designed. This study aims to realign the green infrastructure design strategies with principles for robust decision-making, through the example of green roofs design with the variational method and exemplified using the Norwegian context of the 3-step approach (3SA) for stormwater management. The 3SA consists of planning solutions to handle day-to-day rain at site scale through infiltration (step 1) and detention (step 2), and extreme events with safe floodways (step 3). An innovative framework based on downscaling of rainfall time series is suggested as follows: (i) long duration continuous simulation for retention variation and day-to-day discharge, corresponding to step 1 in the 3SA; (ii) intensive sampling of local extreme events to estimate reliability and robustness of solutions, corresponding to steps 2 and 3 in the 3SA. Comparing the traditional variational method to Highly-Informed-Design-Evaluation-Strategy (HIDES), it was found that the variational method possibly leads to incorrect decisions while the suggested novel approach was found to give more informed and reliable results by suggesting a design based on both operating mode and failure mode. It allows embedding solutions within the urban water system by facilitating the link between the steps of the 3SA. Such a framework was found to be data-wise applicable in the Norwegian context.

Contents

5.1 Introduction

In Norway, stormwater management follows a 3-step approach (3SA) (Lindholm *et al.*, 2008). Different solutions at different scales (site-scale, neighbourhood scale, catchment-scale) are designed to cope with events of different magnitudes and return periods (RP). The approach is similar to many other countries around the world aiming to infiltrate small events, detain larger events and safe passage of larger more extreme events (e.g. 3PA in Denmark (Fratini *et al.*, 2012)). There is still no consensus in Norway on which RP thresholds to apply to which steps (Paus, 2018). However, designing solutions according to this philosophy requires quantification of their robustness and resilience (Liao, 2012), which means studying their behaviour under failure condition (i.e. under rainfall events larger than the design events). Ultimately, the objective of the 3SA approach is to provide a decision-making-support framework to select robust or adaptative solutions to cope with increasing urbanization, climate change, and deep uncertainty (Walker *et al.*, 2013).

The hydrological benefits for local green infrastructures (GIs), such as green roofs, lie in restoring the natural water cycle through retention (infiltration and evapotranspiration), detention, and efficient urban space management. Although some green roofs can be used to attenuate high RP events (e.g. 20-year RP) (Hamouz *et al.*, 2020b), they are usually not designed to cope with larger events.

Green infrastructures and green roofs are often sized using methods with design events (Kristvik *et al.*, 2019; Trondheim Kommune, 2015) based on Intensity Duration Frequency (IDF) curves. These methods rely on design hyetographs that may be based on historical events or on predefined shapes such the Chicago-type hyetograph, the Blue hyetograph or constant intensity events (e.g., the rational method, RM, or the variational method, VM) (Alfieri *et al.*, 2008). The design methods using such type of events typically rely on a single hyetograph or a limited number of hyetographs. This design approach, selected to facilitate design with limited climate data (IDF curves and climate factors), is therefore not consistent with the 3SA for several reasons: (i) it investigates neither day-to-day rainfall (only detention according to a design rainfall event) nor rainfall lying in the failure domain (i.e. larger than design RP), (ii) it does not investigate long-term retention performances, and (iii) it does not provide information on the robustness of the solution.

Statistical temporal downscaling models allow generating weather time series and especially precipitation time series. Some multiplicative random cascade models also include temperature dependence in order to improve the robustness of the models under climate change (Bürger *et al.*, 2014, 2019; Pons *et al.*, 2022a).

This study aims to improve the green infrastructure design strategies through a method that realigns with robust decision-making principles. It is here exemplified for green roofs, in the Norwegian context of the 3-step approach as a case study, by proposing a framework including performance assessment for future climatic conditions using a downscaling model of rainfall time series. The new design framework will be demonstrated by addressing the following aspects: (i) Evaluating the limits of the

VM by sampling local events to evaluate the distribution of performance depending on the RP and performing continuous simulation, (ii) Comparing the performance and robustness of different solutions similar in terms of VM-design, (iii) Suggesting additional steps to design practice to restore consistency with the 3SA.

5.2 Methodology

The methodology used in this work includes the following steps:

i. Input data generation: design rainfall events, stochastic extreme rainfall events and future stochastic rainfall time series,

ii. Input data applied to two different green roofs: extensive green roof (E-Green roof) and detention-based green roof (D-Green roof)),

iii. Performance analysis depending on the type of input,

iv. Analysis of four different scenarios similar according to design rainfall events.

5.2.1 Downscaling model and event sampling strategy

A climate-change-robust downscaling model based on multiplicative random cascades was developed to generate rainfall time series for different cities in Norway and France (Pons *et al.*, 2022a). In this chapter, the model calibrated for Trondheim was used together with IDF curves to generate random extreme events for each RP (Local Event Sampling, LES). A climate factor of 1.4 was used to account for climate change (Dyrrdal and Førland, 2019). The depth corresponding to 24-hour precipitation with each RP was downscaled from 1 day to a 6-minute time step. The process was repeated to obtain 10^5 hyetographs for each RP.

5.2.2 Green roof model

Similarly to (Pons *et al.*, 2022a), two green roofs were modelled in this chapter: an extensive green roof (E-Green roof) and a detention-based extensive green roof (D-Green roof). The model is based on a non-linear reservoir. In order to increase the robustness of the model and its range of validity under extreme events, the model was calibrated using data from extreme tests previously performed on a large scale pilot roof (Hamouz *et al.*, 2020b). Three parameters control the discharge function of the roof: (i) WC_K represents a characteristic water content value in the transition toward a linear increase of outflow, (ii) S_K represents the transition from a dry roof to wet roof, (iii) K represents the slope of the outflow curve when the roof is wet ($water\ content > WC_K$. The E-Green roof consists of a 30-mm layer of substrate with a 10-mm layer of storage. It was represented with a single discharge function. The D-Green roof consists of one 100-mm layer of clay aggregates and one 30-mm layer of substrate. It was represented by the sum of two discharge functions, one for each layer. Further details can be found in Chapter 2.

5.2.3 Performance evaluation

The regulations of Trondheim municipality (Trondheim Kommune, 2015) were used to set thresholds for appropriate comparison. The regulation for local stormwater management set the peak discharge allowed to be released in the sewer system during a 20-year RP rain event. When connected to a separate sewer system, the threshold is $6.4\ L/s$ for an $800\ m^2$ area. When the area is connected to a combined sewer system, the threshold is stricter, $1.65\ L/s$ for $300\ m^2$. Those two thresholds were used as references for two possible regulations in this chapter. For comparison purposes, they are converted and normalized as $0.48\ mm/min$ and $0.33\ mm/min$. Three performance evaluation strategies were used:

- The variational method (VM) (Alfieri *et al.*, 2008) to account for strategies with a low number of events. It consists in using the constant intensity rainfall leading to the worst peak runoff according to each IDF curve.
- A continuous simulation (CS) to i) evaluate performances based on runoff distribution, and ii) estimate the mean annual duration of runoff above threshold accounting for natural variation of the climate. It also allows evaluating the annual retention. A 29-year long time-series was used for this simulation.
- Local Event Sampling (LES) to sample a large number of probable hyetographs $(N = 10^5)$ according to the location and downscaling model properties. It allows estimating the probability of coping with a RP rain under future climate conditions in accordance with the guidelines.

5.2.4 Scenario comparison

To analyse the consequences, in terms of hydrological performances, of sizing a solution with the VM, four different scenarios for the E and D green roofs were designed to cope with a 20-year RP in Trondheim according to the VM (Table 5.1). The resulting solutions were then evaluated using the LES and CS methods. The first scenario is based on the D-Green roof and an impervious area. The minimal fraction of roof necessary to meet the discharge requirement was chosen. The second scenario was based on the E-Green roof with an extra storage layer. The third scenario was based on a combination of both the E and the D green roof. The minimal proportion of D-Green roof meeting the requirement was chosen. The fourth scenario was based on the E-Green roof, with an outflow controller with limit set to, and an extra storage in the substrate media. The depth was set to the minimum depth, ensuring no overflow.

5.2.5 Framework for robustness assessment: Highly Informed Design Evaluation Strategy (HIDES)

The different solutions designed through the VM can be analysed with the framework presented in Figure 5.1. The approach is divided into three complementary approaches: (i) the long term simulation answering the question *'How is the solution going to behave in operating state?'* and corresponding to the first step of the 3SA (i.e. assessing the benefits that the solution is supposed to provide, retention and

Table 5.1: Details of the different scenarios designed using the VM to cope with a 20-year RP rain even. [modified from the preprint of Paper D - (Pons *et al.*, 2022b)]

Solution	Scenario 1 (Det)	Scenario 2 (Spl)	Scenario 3 (Mix)	Scenario 4 (Sto)
E-Green roof	-	100% of the area 7.75 mm of extra storage	47% of the area	100% of the area
D-Green roof	29% of the area	-	53% of the area	-
StU	-	-	-	Discharge constrictor: $0.33\ mm/min$ Equivalent storage: $1.33\ mm/m\ 2$
Impervious area	71% of the area	-	-	-

mild rain detention), (ii) the event based simulation to answer the question *'How is the solution going to behave under failure state?'* corresponding to steps 2 and 3 of the 3SA, and (iii) the climate change robustness answering the question *'Is the behaviour of the solution expected to be stationary?* corresponding to the philosophy behind the 3SA.

5.3 Result and discussion

5.3.1 Green roof performance analysis

The comparison between VM and LES is shown in Figure 5.2 for current climates (opaque distributions) and future climate projections (transparent distributions) through the use of a 1.4 climate factor (Dyrrdal and Førland, 2019) according to different RP (2-year on top to 200-year at the bottom). The performances of the E-Green roof (left) and the D-Green roof (right) are displayed. The VM led to single point estimates (blue dots). In the case of the D-Green roof, VM tends to estimate a lower peak runoff than the mode of the LES distribution. For the E-Green roof, similar observations appeared only for the 2-year RP events. It indicates that the VM is not necessarily conservative since, depending on the solution, a significant proportion of hyetographs led to higher peak runoffs than the VM. For the D-Green roof and a 20-year RP event in a current climate, 96% of the simulated events led to a peak runoff less than the 0.33 mm/min threshold (resp. 79% with climate factor). For the E-Green roof only 10% of the peak runoff values were less than the threshold (resp. 0.5% with climate factor).

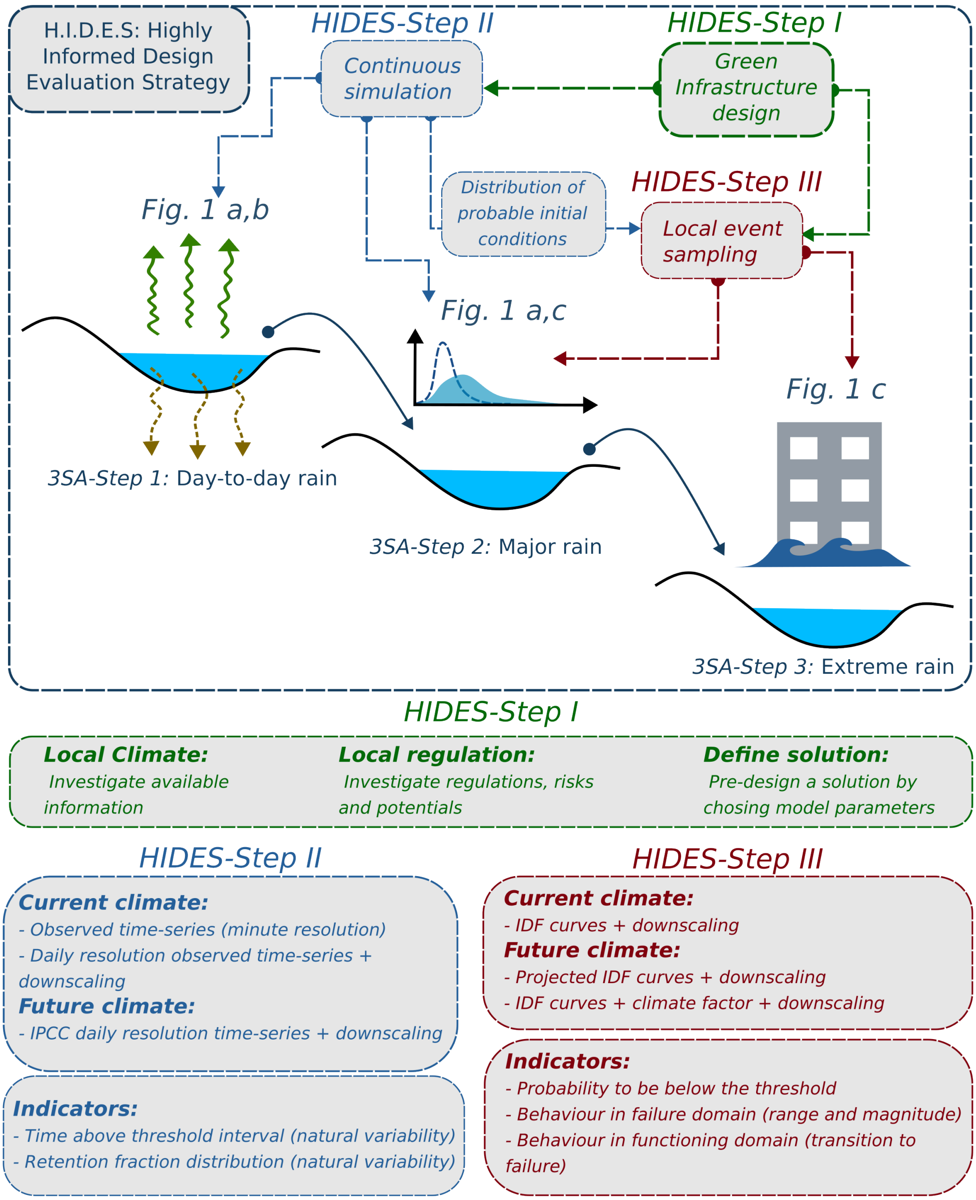

Figure 5.1: HIDES framework for performance estimation and robustness assessment of designed solution, the red dotted line relates to climate change assessment. IPCC: Intergovernmental Panel on Climate Change, GCM: Global Circulation Model. [modified from the preprint of Paper D - (Pons *et al.*, 2022b)]

The robustness and reliability of a solution in terms of hydrological performance can be defined with regard to the distributions displayed in Figure 5.2. A distribution with similar orders of magnitude of deviation under different return periods and climate factors is considered reliable, indicating no shift in the performance range. A solution that meets the target under a large range of return periods and climate factors is robust (static robustness as defined by Walker *et al.* (2013)). Considering the 0.48 mm/min threshold, the E-Green roof is reliable, but not robust. It has a deviation range from 0.17 to 0.45, and under high RP it can deal with fewer than 10% of the events. On the contrary, the D-Green roof is robust as it can handle more than 50% of the events up to a 200-year RP with a 1.4 climate factor, but not reliable as the order of magnitude of its standard deviation changes from 0.02 to 0.5 with larger return periods.

Return periods larger than 20-year can be considered as the failure domain of the roofs in the second step of the three-step approach. The roofs are not designed to cope with those events; however, quantifying their behaviour within this failure domain can help to make a more informed decision when dealing with the next steps. Since the VM cannot estimate the reliability and robustness of the solutions, it can result in wrong decisions or missed opportunities.

Table 5.2 shows the probability of reaching the target depending on the green roof type, the return period and the method used. For example, considering the D-Green roof, the probability of reaching the target under a 200-year RP with a 1.4 climate factor was only 0.33 with LES contrary to 1 using the VM. Table 5.2 highlights that the VM does not allow the user to take a well-informed decision due to the nature of boolean estimates. They provide a deterministic value for each return period, while the solution behaviour differs depending on the hyetograph. Moreover, it should be pointed out that the shape of the hyetograph based on the VM (e.g. constant intensity rainfall) does not depend on the location. On the other hand, the LES method provides more robust estimates of the performance because a larger diversity of events likely to occur in the specific location are sampled. For instance, in Trondheim, among the events sampled, some may trigger the E-Green roof and some others the D-Green roof. In previous studies (Hamouz *et al.*, 2020b), the D-Green roof was found sensitive to specific types of hyetographs, which supports the use of LES method. The VM does not include such hyetographs, which leads to low representativeness of the estimates. For comparison, a CS allows estimating mean annual runoff duration above threshold, which would be lower than 4 minutes per year in the case of the E-Green roof, and 0 minutes for the D-Green roof. The CS method is highly dependent on data availability, but directly estimates frequency of exceeded thresholds without using IDF curves or events.

Table 5.2: Probability to reach the $0.33\ mm/min$ target depending on the green roof, the return period and the method used. [modified from the preprint of Paper D - (Pons *et al.*, 2022b)]

	E-Green roof				D-Green roof			
RP	LES		VM		LES		VM	
2-year	0.45	1	0.14	0	1	1	0.98	1
5-year	0.26	0	0.04	0	1	1	0.88	1
10-year	0.16	0	0.01	0	0.98	1	0.79	1
20-year	0.10	0	0.005	0	0.96	1	0.68	1
25-year	0.09	0	0.003	0	0.95	1	0.65	1
50-year	0.05	0	0.001	0	0.90	1	0.53	1
100-year	0.03	0	0	0	0.84	1	0.41	1
200-year	0.01	0	0	0	0.77	1	0.33	1

5.3.2 Scenario robustness and reliability analysis

Figure 5.3 shows the cumulative distribution of peak runoff for different return periods based on the LES method for each of the solutions (Table 5.1). For the 2-year RP, 90% of the events were below 0.33 mm/min for the scenario 3 against only 50% of the events for the scenario 2. The figure also shows the proportion of events sampled above the VM estimates (dotted lines). For the 50-year RP rainfall, the VM-estimate was above 70% of the events for scenario 3 and 4 against $30–40\%$ for scenario 1 and 2. For the 20-year RP, the value of the VM-estimate is equal to $0.33\ mm/min$ for each scenario, since the solutions were designed using the VM.

According to the LES method and previously defined criteria, the scenario 3 is the most robust and reliable solution. It relies on a combination of both types of green roofs, and since each type of green roof is sensitive to a different type of rainfall, using both types of green roofs in a combined solution results in a solution that is able to cope reasonably well with most of the possible hyetographs. Such a property could not be demonstrated using the VM. The scenario based on a fraction of D-Green roof (scenario 1) shows a great robustness to low return periods ($< 10 - year$) but behaved similarly to scenario 2 for larger return periods. The D-Green roof had a larger storage capacity, which can handle a high volume of water without high runoff, but when the water content reaches the critical parameter $WC_{K,subs}$ the discharge increases rapidly. Table 5.3 shows the probability of reaching the threshold $0.33\ mm/min$ for each scenario depending on the return period, including the 20-year RP for which the different scenarios have been designed. The table also shows the duration above threshold (ADT) in minutes calculated from the CS on an annual basis. For scenario 1 the ADT was found to be between 4 and 104 minutes, indicating a regular exceedance of the threshold value. On the other hand, the annual durations above the threshold value for the other scenarios are all below 10 minutes. The use of

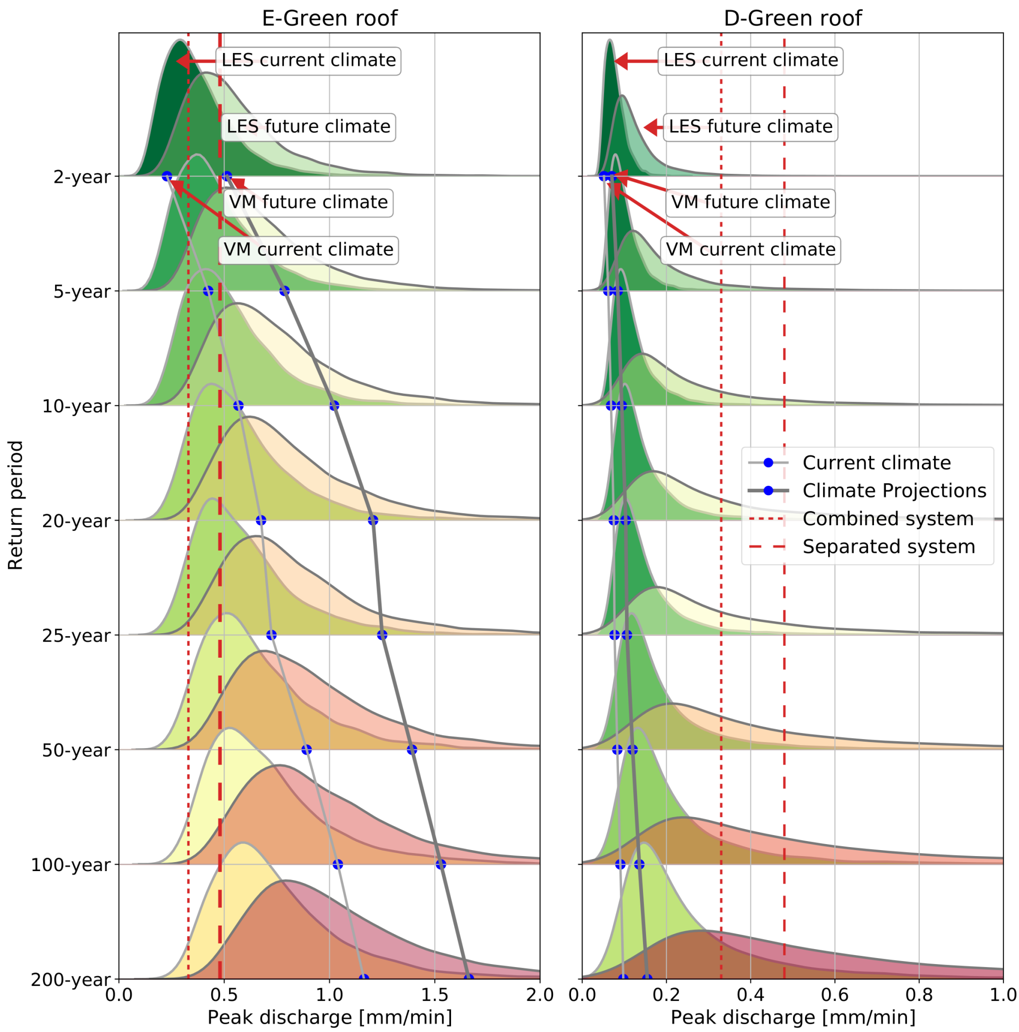

Figure 5.2: Predicted peak runoff of the E-green roof (left) and the D-green roof (right) using variational method (thick grey line with blue dot markers) and local event sampling (distributions) under current climate (light grey) and projected climate RCP 8.5 (dark grey). The colour of distribution is conditioned by the centroid value: green for low, yellow for medium and red for high. [preprint of Paper D - (Pons *et al.*, 2022b)]

a continuous simulation shows the capacity of the roof under operational conditions, where the D-Green roof has a long detention time and therefore a higher risk of not being drained before the next event occurs (Hamouz *et al.*, 2020b). Table 5.4 shows the 95% shortest coverage interval (i.e. the shortest interval including 95% of the values, similar to a deviation-based confidence interval but more appropriate for skewed distributions). According to the coverage intervals, Scenario 3 is robust and reliable. Scenario 2 was less robust and Scenario 1 is less reliable.

Figure 5.4 shows the results of the different scenarios based on CS. This allowed

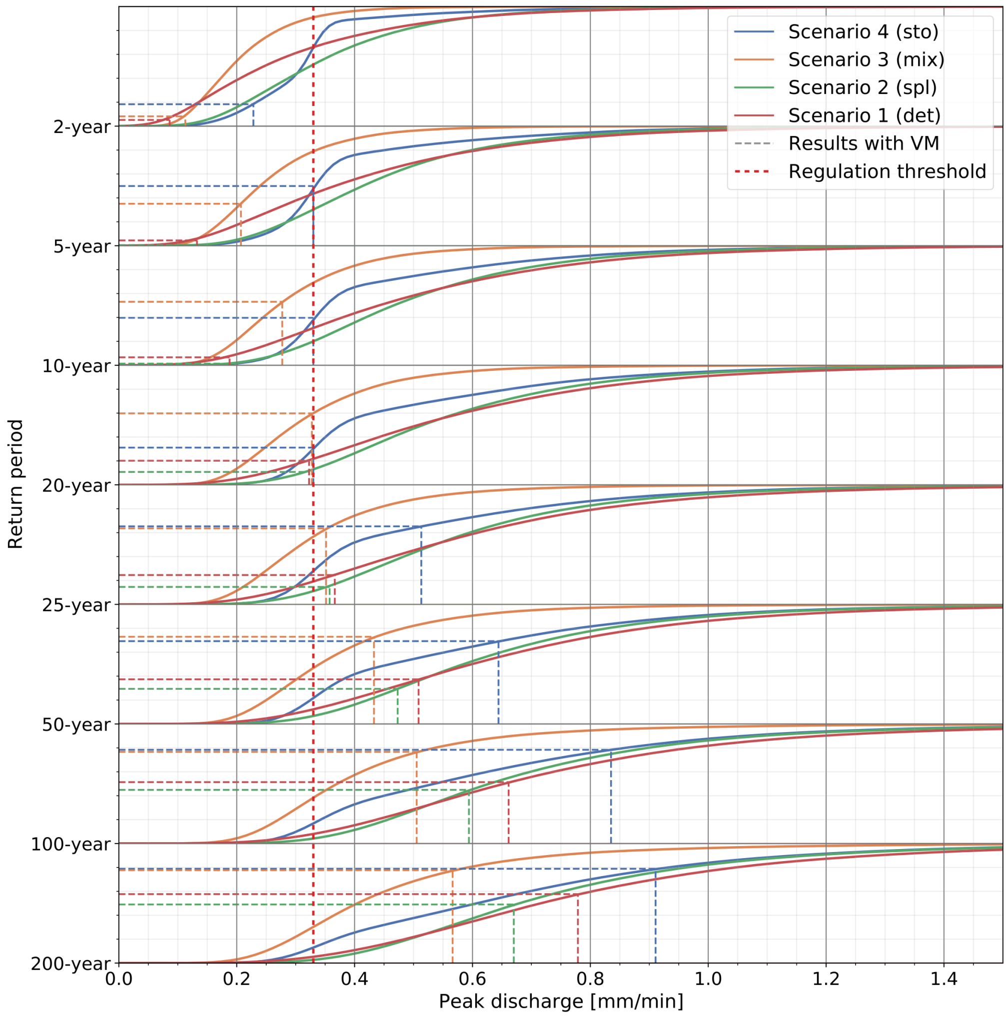

Figure 5.3: Cumulative distribution functions for the four scenarios with the proportion of events below the estimate based on the variational method for different return periods. [preprint of Paper D - (Pons *et al.*, 2022b)]

to estimate both retention metrics (e.g. retention fraction) and detention metrics (e.g. extreme values of discharge). The left plot with survival distributions can be used similarly to flow duration curves, allowing estimation of the exceedance duration frequency. The probability for the discharge to exceed the threshold was found to be reasonably low for Scenarios 2, 3, and 4, but as stated in Table 5.3, the probability is higher for Scenario 1 (i.e. the ADT). It can be explained by the characteristics of the D-Green roof. The water is detained in the roof for a longer time, which makes this roof more sensitive to antecedent rain events. This also demonstrates the necessity of CS: the event-based methods used in this chapter do not take into account antecedent rain.

Table 5.3: Probability to reach the $0.33\ mm/min$ target for each of the scenario and depending on the return period based on the LES method. Annual duration above thresholds (ADT), based on continuous simulation. [modified from the preprint of Paper D - (Pons *et al.*, 2022b)]

	det	spl	mix	sto
2-year	0.67	0.52	0.91	0.67
5-year	0.44	0.30	0.79	0.50
10-year	0.31	0.19	0.69	0.40
20-year	0.21	0.12	0.60	0.31
25-year	0.19	0.10	0.57	0.29
50-year	0.11	0.06	0.74	0.21
100-year	0.07	0.03	0.39	0.16
200-year	0.05	0.02	0.30	0.12
ADT (min)	4-104	0-4	0-4	0-8

In the context of CS, i) a solution is more reliable than another if the standard deviation is smaller, and ii) a solution is more robust than another if the mean performance is better. The right plot in Figure 5.4 shows that the retention fraction for Scenario 1 was lower, with a smaller deviation than with other scenarios. It is the less robust scenario but the most reliable. The roof covers only 29% of the area, which directly affects the retention fraction. On the opposite, Scenario 2 with an E-Green roof and extra storage layer results in a higher retention fraction; however, the deviation of this retention fraction is higher than with other scenarios (ranging from 0.2 to 0.6 with a mode at 0.4), which indicates a lower reliability.

Table 5.4: 95% shortest coverage interval for each of the scenario and depending on the return period based on the LES method. [modified from the preprint of Paper D - (Pons *et al.*, 2022b)]

	det	spl	mix	sto
2-year	0.05, 0.72	0.10, 0.70	0.08, 0.39	0.12, 0.6
5-year	0.09, 0.95	0.15, 0.87	0.10, 0.48	0.16, 079
10-year	0.09, 1.05	0.18, 0.98	0.12, 0.54	0.19, 0.92
20-year	0.12, 1.18	0.19, 1.09	0.13, 0.61	0.21, 1.05
25-year	0.14, 1.22	0.21, 1.12	0.13, 0.64	0.21, 1.07
50-year	0.17, 1.34	0.23, 1.22	0.16, 0.73	0.25, 1.21
100-year	0.20, 1.44	0.27, 1.31	0.16, 0.81	0.26, 1.28
200-year	0.22, 1.55	0.28, 1.41	0.17, 0.92	0.30, 1.41

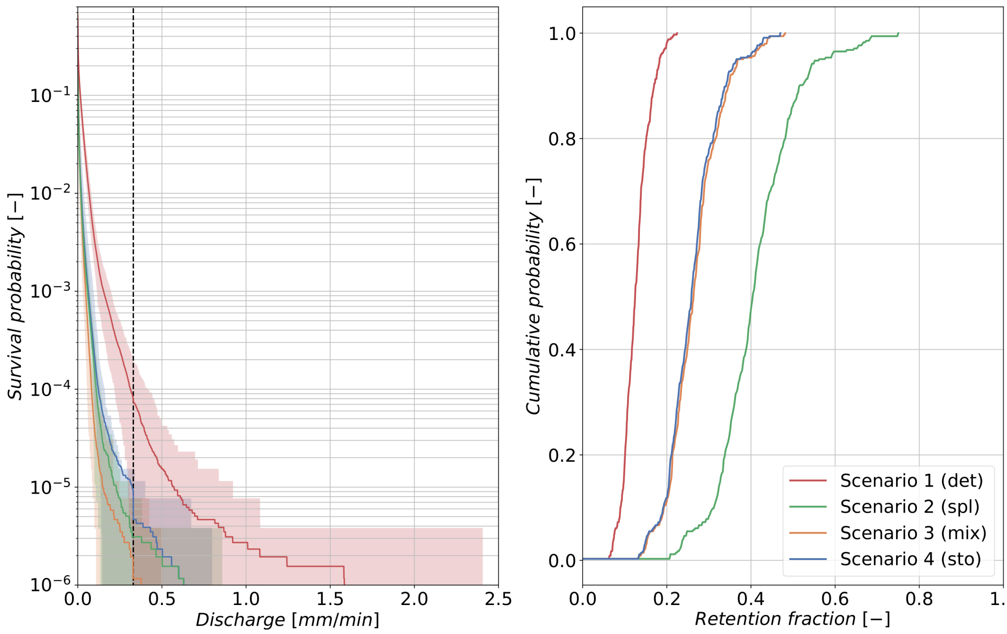

Figure 5.4: Comparison of scenario using continuous simulation (CS). Survival distribution of discharge 5th and 95th percentile distribution using a 3-year moving window (shaded area) and 29-years long time series (full line) (left). Cumulative distribution of Retention fraction (right). [modified from the preprint of Paper D - (Pons *et al.*, 2022b)]

5.4 Design application potential

The proposed HIDES framework for green roof design is depicted in Figure 5.1. The framework includes CS and LES of solutions that are designed with a single hyetograph and will guide the user to select the most robust and reliable design. The CS will provide the basis for decision-making in step 1 of the 3SA and will require either long time series with higher temporal resolution or a downscaling model and long daily resolution time series. Since the distribution of retention fraction can be estimated based on a 1-year-long moving window with a step of 1 month, a minimal duration of 20 years leading to a distribution estimated with kernel density based on more than 200 points is suggested. The local event-based approach will provide a basis for decisions related to steps 2 and 3 in the 3SA and will require IDF curves and a downscaling model. The proposed framework is especially relevant in cities subject to increasing urbanization and climate change. In Norway, a downscaling model has already been developed for six large cities, and daily time series or projections are often available (Dyrrdal *et al.*, 2018). In the case where no downscaling model is available, using a downscaling model calibrated in a similar area might add some uncertainty, but can still help understand the behaviour of the solutions. It would therefore result in a more informed design than the one achieved through VM.

In order to evaluate the applicability of such a framework for design potential, several parameters needs to be investigated:

- The influence of the number of extreme events sampled.
- The influence of the initial water content in the GI.
- The influence of the temperature on the hyetographs sampled and therefore on the GI performance.
- The influence of the calibration site for the downscaling model.

5.4.1 Sensitivity to number of events and convergence

One limitation to the application of a method such as Local Event Sampling is the need to sample a large quantity of events. Indeed, while models such as reservoirs for single GI units do not need intensive computation, hydro-dynamic models (such as HEC-RAS or Mike Flood) consist in fully distributed models that require significant computational power for each model evaluation. The Figure 5.5 shows the influence of the number of events sampled on the distribution of peak runoff for the E-Green roof. It should be noted that the value of the maximum outflow allowed by the municipality influences directly the accuracy of the estimate, since the uncertainty is not constant along the distribution. Another important remark is that the influence of the number of events also depends on the infrastructure considered.

The example given in Figure 5.6 represents the convergence of the probability estimate. It shows that with 10 events the E-Green roof could have been estimated to fail only in 40% of the events while the process converge to 90%. Using 100 events, the estimate for the D-Green roof is between 0 and 12%. It is between 80 and 95% for the E-Green roof. This seems sufficient to give an order of magnitude of the probability at approximately $\pm 5\%$ for those 2 solutions.

It is not realistic to advise on a number of events to use since this number is directly related to the accuracy needed. The accuracy required has to be defined in accordance with decision makers, discussing which threshold is acceptable. However, in the context of engineering application, it is possible to give boundaries for recommendation. It has been seen that 10 events or fewer, chosen randomly within the set of events that can be sampled with the downscaling model, can hardly be enough to provide an estimate of an order of magnitude. Therefore, as a rule of thumb, a number of 100 events is advised as a strict minimum, when no further information is available, and with all the above-mentioned limitations. The number of events selected has to be chosen in accordance with the available computational power. If computational power is a limitation, it is advised to consider a strategy similar to the one advised in the GUM for Monte Carlo Simulation (BIPM *et al.*, 2009). It consists of successive sampling batches of events and comparing the convergence.

Further studies are needed to be able to sample representative events, and to be able to do the same in future climate. One limitation to consider for those studies

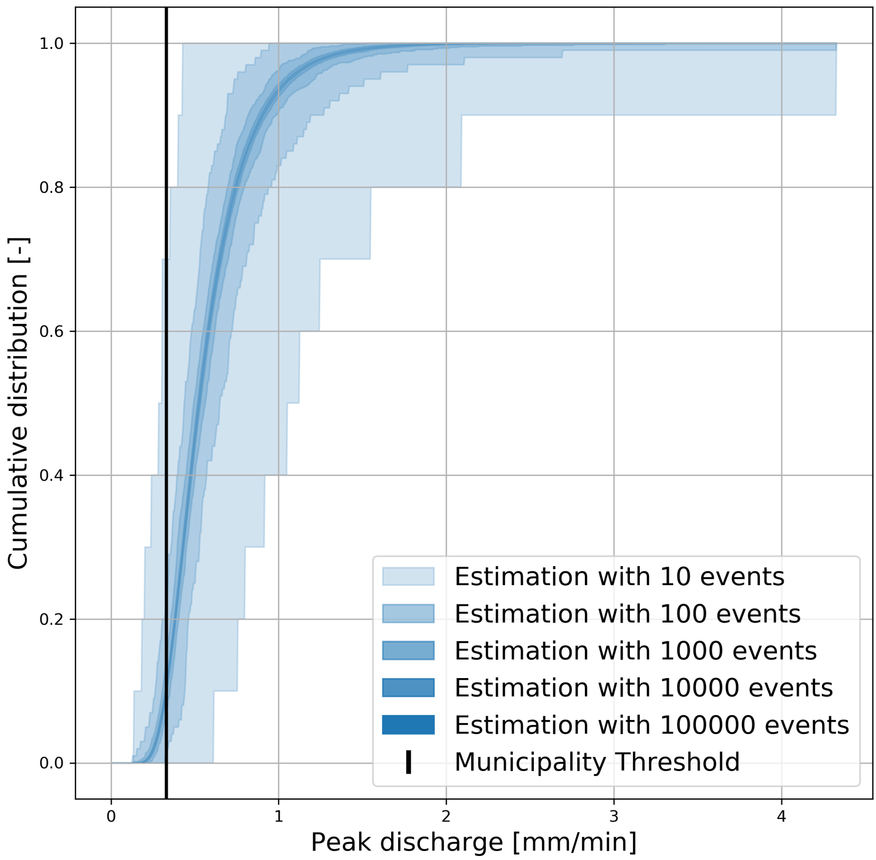

Figure 5.5: Influence of the number of events sampled on the survival distribution of peak discharge for the E-Green roof and a 20-year RP curve.

is that the representativity of an event also depends on the sensitivity of the infrastructure to a type of hyetographs. Another approach could consist in developing metamodels to estimate the probability with fewer simulations.

5.4.2 Sensitivity to initial conditions

The figure 5.7 presents a qualitative assessment of the different hypothesis used to set initial conditions for the method of Local Event Sampling. Given 100 000 events sampled, several setups are compared:

a. Using the mean initial water content for the green roofs based on a 20-year long continuous simulation and that mean temperature for event sampling on

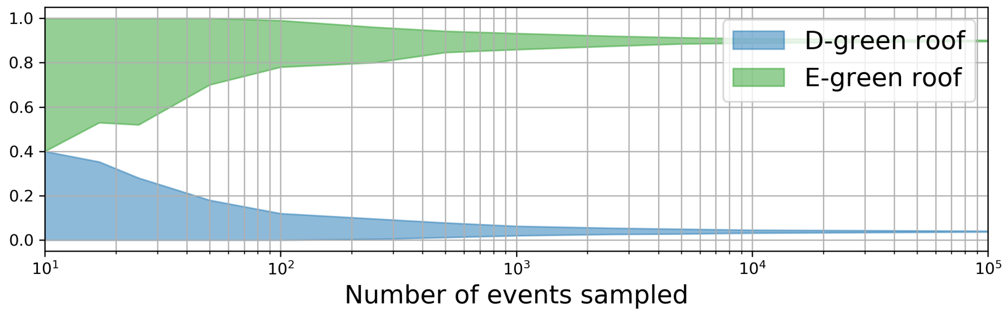

Figure 5.6: Convergence to the probability of exceedance of the municipality threshold for a 20-year return period curve.

the same 20-year long period.

b. Using the distribution of initial water content from the above-mentioned time-series and the mean temperature.

c. Using dry condition for initial water content and the mean temperature.

d. Sampling from the distribution for both initial water content and temperature.

For the E-Green roof only the scenario d lead to a shift in the distribution, which remains negligible compared to the range due to the 100 events sampled. The shift can be explained by the occurrence of high temperature which lead to sampling of hyetographs closer to convective storms which can trigger the roof more intensely. For the D-Green roof 3 groups are obtained. It shows that using dry condition has an influence on the distribution and similarly, the temperature, therefore the hyetographs, influence the performance. Based on those results, it seems that the hypothesis to take into account depends on the accuracy needed. Ideally, both a distribution of initial water content and temperature should be used, but in the context where only a limited accuracy is required, those effect can be neglected and using the mean value seems sufficient. It should be reminded that different design can lead to different sensitivity to those hypotheses.

5.4.3 Sensitivity to model calibration site

Another major drawback of such a method is the availability of a downscaling model in the location considered. Indeed, in the current PhD thesis only 8 $MRC_{SDT,SEP}$ models have been made available. To further investigate that limitation, the 8 models have here been used with the climate information of Trondheim (mean temperature, mean water content, IDF-curves). The results are presented in figure 5.8 depend on the roof considered. For both roofs, the use of the model from Marseille led to a distribution of peak runoff that dropped out of the range of peak runoff distribution based on the limited events from Trondheim (100). It suggests that this climate

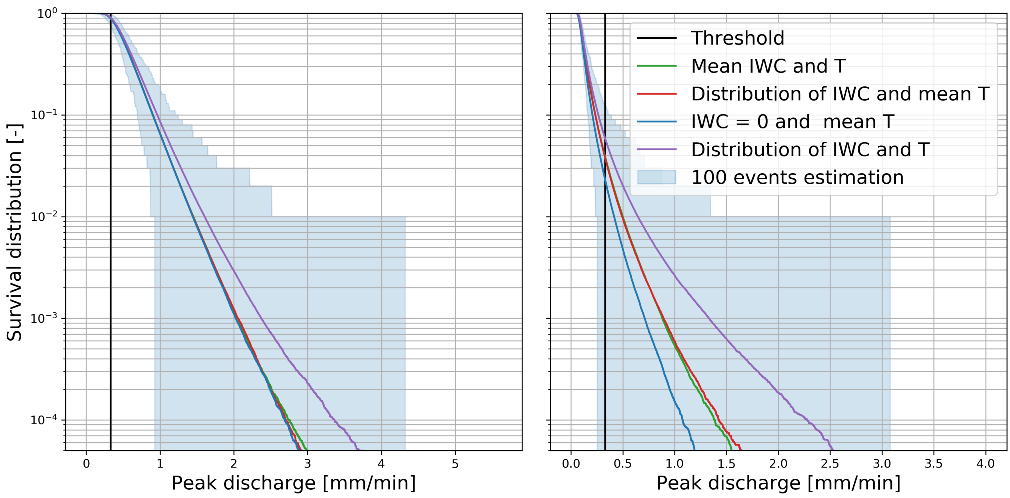

Figure 5.7: Influence of initial condition, i.e., initial water content in the roofs and temperature for the rainfall event sampling, on the survival distribution of peak runoff, compared to the range generated with 100 event sampled.

is too different from the one in Trondheim. It can be understood based on the difference both in climate and weather patterns. For both roofs, it can be seen that the downscaling models from Throndheim, Bodø and Kristiansund give close results which is consistent due to their close climates. It is not possible to further conclude without more models and a regionalization of parameters. However, two points can be drawn out of this study:

- The future availability of other downscaling models / weather generators will improve the accuracy of the method.
- The use of a downscaling model, even if it is not linked to the considered location, can provide valuable information on the GI behaviour and from that perspective, is still a clear gain considered to traditional approaches

The future availability of other downscaling models / weather generators will improve the accuracy of the method.

5.5 Conclusions

The VM was compared to LES and CS. The VM was found to fail to provide reliable estimates due to its single-estimate nature. The method was found to not necessarily be conservative depending on the roof, the return period and the climate condition. It demonstrated that in order to achieve a robust decision-making following the 3SA philosophy, the method needs to be improved.

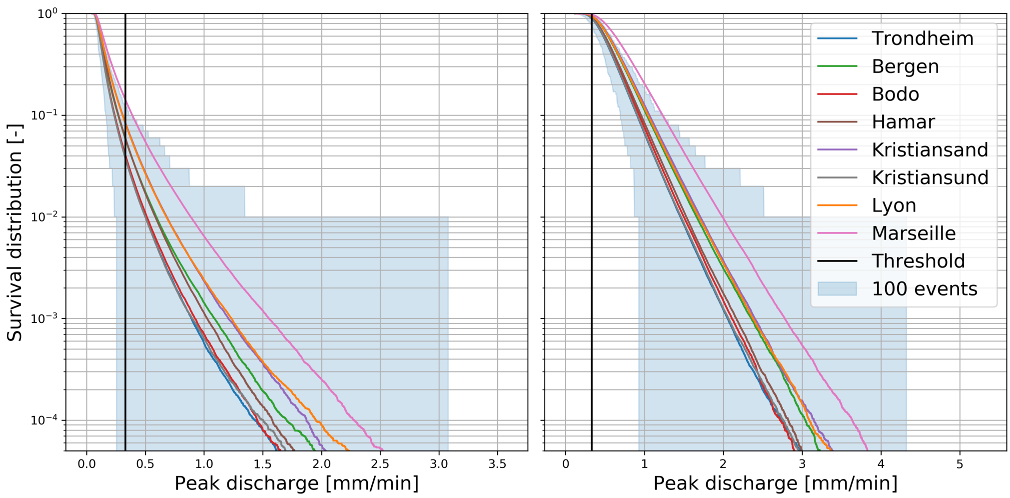

Figure 5.8: Influence of the location used to calibrate the downscaling model on the survival distribution of peak runoff, compared to the range generated with 100 event sampled.

Four scenarios were designed to cope with a 20-year RP in Trondheim, based on the VM. They were found to have significantly different hydrological behaviour, which cannot be captured using the VM. Following the 3SA philosophy and aiming for robust decision-making, the four designed solutions were evaluated using a CS approach (for step 1) and the LES approach (for steps 2 and 3). The different solutions can be ranked according to different criteria and be used as the basis for a multi-criteria decision analysis depending on factor prioritisation (e.g. reliability and robustness).

The solution based on a mix of the two types of green roofs was found to be robust in terms of extreme events. The LES method demonstrated its robustness by sampling probable events. Both roofs being sensitive to different extreme events, the mixed solution could cope with a larger range of events (static robustness).

In countries such as Norway, sufficient data is freely available to apply such a design method, based on improving the VM with CS and LES to restore consistency with 3SA. The method proved to significantly improve the reliability and robustness of green infrastructure design.

While a methodology such as HIDES can be considered heavy in terms of modelling for design application, it was shown to be more reliable than single event-based design. Therefore, the recommended approach is to consider it necessary and to justify in case it is considered unnecessary to apply it. It should be evaluated to which extent the methodology can be simplified. The idea behind the framework being to convey the information linked to climate variability into the performance indicators, simplifying the methodology should still consider those aspects in order to stay aligned with the principles of robust decision-making. Some efforts in that direction were done. In particular, it was studied in the Section 5.4.1 the impact of the number of event sampled, the account of temperature and initial moisture conditions. Therefore, within a decision-making framework, the level of accuracy required may allow for simplification of the framework use.

The last point of discussion that should be mentioned will be further discussed in Chapter 6. In the current chapter, the methodology was applied to site scale GIs. A few units consisted of a combination of GIs, but it remains a site scale. It is therefore questioned how to apply such a framework to a neighbourhood scale, and what information from site scale can be upscaled to neighbourhood scale.

6

Green infrastructure and scales

That doesn't make sense to me. But, then again, you are very small.

Treebeard
J.R.R. Tolkien,
The Lord of the Rings

Foreword

This chapter is not directly based on any publication. However, several studies, other than the one used as basis for the previous chapters, contributed indirectly to its conceptualization. In particular, Paper C (Le Floch *et al.*, 2022), Communication A, Communication D, Communication F, and Poster C can be considered as contribution to the current chapter.

The current chapter is divided in 3 parts. First, based on an in-depth analysis of the results of Paper C, knowledge gaps in the practice of upscaling green infrastructure models at catchment scale are identified. Then, a theory to conceptualize the interdependencies between green infrastructure is presented. Finally, the potential of passive coupling of green infrastructure is investigated through a modelling-based informal sensitivity analysis at neighbourhood scale.

Abstract

Evaluating the performance of green infrastructure has to be linked to its potential benefits in urban areas. It means that the (up)scalability of green infrastructure performance should be studied to verify their potential from site scale to city scale. In the current chapter, the concept of active and passive coupling of green infrastructure were developed. Passive coupling consists in combining the benefits of green infrastructure in order to achieve robust design at system scale. Active coupling, consists in decentralized real time control (e.g., interconnected water reuse for irrigation). The concept of passive coupling is studied more in details. In particular, several green infrastructure units are designed with the variational method for a 20-year return period. Based on this set of solutions, several random implementation scenarios are generated. The variety of units for solution at system scale is found to lead to a possible improved robustness. The solutions at system scale are also found to be sensitive to permutation of solution. In terms of consequence for regulation, it suggests that unit scale implementation should be completed with system scale assessment. It also suggests that the requirement per location should depend on the local context, since green infrastructures are often implemented sequentially following urbanization dynamics.

Contents

6.1 Introduction

6.1.1 What happens at site scale - summary of previous work and limitations

In the current thesis, the previous chapters have been dedicated to data collection (Chapter 2) or data generation (Chapter 4) data for the evaluation of climate change adaptation measures. This data was then turned into relevant information through the conceptualization of performance indicators (Chapter 3) and the development of a framework for aligning green infrastructure (GI) objectives and stormwater management strategies (Chapter 5). The objective in the current chapter in therefore to upscale this information in terms of both spatial scale and nature: what knowledge can we draw out of the previously developed tools at neighbourhood scale?

It should be reminded at that stage that the downscaling models developed in this thesis will be interchanged in the future with more accurate models. In order to remain useful, they should have a stochastic nature which allows for Local Event Sampling. They should also be robust to climate change. Similarly, the green roofs and retention basin models used should be changed with relevant models: both other geometries, other types of GI (e.g., bioretention cell), and encompassing other processes (see Chapter 1 e.g., drought induced mortality, snowmelt processes, clogging, etc.). However, such a model should provide reliable results for both high and low flow (see Chapter 2) in order to be useful for both current and future climate, and both under daily and extreme events.

To some extent, the following chapter provides, in a more theoretical approach, perspectives in order to upscale from information to knowledge. The reason for the choice of a theoretical approach is that an applied perspective would remain centred on the study case, while the current approach aims at providing a frame that can be transferred to other contexts. It aims at keeping the added information learnt from the previous chapters.

6.1.2 What happens at catchment scale - what is general and what are the limitations ?

While Paper C (Le Floch *et al.*, 2022) is not directly used in the current thesis, it constitutes one of the main motivations for the current paper.

One of the key aspects of that study is that, due to available information, the calibration of the model has not led to high NSE values (< 0.9 for most events). As a result, it was decided to use an ensemble of models for prediction. It could have been chosen to try a more advanced modelling approaches by i) increasing the number of parameters to calibrate and therefore the degree of freedom, ii) improving the space discretization (subcatchments), iii) collecting more field data, or iv) accounting for more hydrological processes. However, in the timeline of the study, it was decided to investigate the information that can be gained based on a model with limited performances. Indeed, municipalities often rely on limited resources for stormwater management (Cousins and Hill, 2021). Consequently, they may not have enough budget to develop, calibrate and test an accurate stormwater model. One of the limitation in the investigation of the relationship between GI and scale is that at city scale, the available information is often limited. Applying advanced methods when a lot of hypotheses are necessary and when different sources of uncertainty are ignored may therefore be counterproductive. The decision taken based on ignored uncertainty should be avoided (Walker *et al.*, 2013), which motivated the modelling choices made in (Le Floch *et al.*, 2022).

Despite the high level of uncertainty, the study could draw insightful outcomes that should be accounted for. Green infrastructures have several hydrological objectives which are: i) reducing the volume of runoff discharged in the sewer, ii) attenuating rainfall according to a predefined maximum discharge threshold and a probability of exceedance iii) contributing when the rainfall magnitude exceeds the GI design. Those hydrological objectives can be evaluated both at site and city scale, however, the upscaling has different implications depending on the objective. In particular, reducing the volume of runoff discharged in the sewer, does not depend directly on spatial implementation. On the opposite, reducing the risk and magnitude of flooding in some dedicated area of the city directly depends on where the infrastructure is located. For instance, it was found that GI placed close to the outlet have a local effect on flooding that evenly distributed GI don't have. Such a statement has to be balanced by the context of the study. Only 2 designed of solutions were used (green roofs and permeable pavements). The tool used, SWMM, may not be appropriate to represent all processes involved. Finally, only a few events were used for simulations. Qin *et al.* (2013) showed that the hyetograph can strongly influence the performance variation, which confirms that approaches based on a single or few hyetographs are limited.

Several types of studies investigate the relationship between GI and catchment/city scale (Ferrans *et al.*, 2022). More specifically, they investigate "How much?", "Where in general?", and "Where exactly?". While trying to answer to the "How much?" type of question, many studies have investigated the influence of increasing GI implementation at catchment scale (Hamouz *et al.*, 2020a; Hernes *et al.*, 2020; Palla and Gnecco, 2015). More specifically, they look at the number of GI measures to be implemented in order to have a noticeable effect. Palla and Gnecco (2015) recommended at least 5% in their study. Hamouz *et al.* (2020a) mentioned 11% of the roofs retrofitted in green roofs to have a substantial reduction. Those 2 studies were based on SWMM engine and with event-based studies, so suffer similar limitation as Le Floch *et al.* (2022) which investigated how much GIs are needed under increasing urbanization and climate change. Other studies investigated the effect of GI density in a Norwegian context, for instance Hernes *et al.* (2020) or Skaugen *et al.* (2020). Zellner *et al.* (2016) found 10% go GI to help to capture small storms, but bigger storms would require to double the proportion.

"Where in general?", and "Where exactly?" are two distinct questions in the current chapter. The first tries to find general knowledge about the influence of GI placement at catchment scale, while the later one aims at optimizing a multi-objective problem, which is "Which implementation plan is optimal?". Giacomoni and Joseph (2017) investigated the robustness of the hypothesis that increasing the amount of GIs leads to reduced peak flow. They also found, using Monte Carlo sampling, that upstream catchment should be targeted for hydraulic footprint residence (area and duration of flooding through the downstream segment) while downstream catchment should be targeted for peak reduction. This is in agreement with Le Floch *et al.* (2022) that concluded that different objectives lead to different choices of implementation. Yao *et al.* (2020) found it efficient, in terms of hydrological performance, to retrofit green roofs directly connected to the drainage network instead of connecting them to infiltration units. Similar findings were presented by Liang *et al.* (2020). They found that implementation close to the outlet helps to reduce peak runoff. Hou *et al.* (2020) found cost-efficient to place GI close to sensitive areas in order to reduce flood risks. Ercolani *et al.* (2018) found that spatially heterogeneous implementation may increase efficiency. In practice, by heterogeneous, they mean targeting a specific area, such as the one where drainage system capacity is prone to exceed its capacity (by opposition to evenly implemented GIs). Zellner *et al.* (2016) developed a synthetic catchment in order to explore the effect of GI at neighbourhood scale ($4\ km^2$) differently from other studies, they found homogeneous implementation to be more efficient to reduce flooding. This can be due to the different scale used, and the other scenarios used for comparison. In practice, it is complicated to have generalized conclusions, and several limitations of those approaches due to their modelling nature should be accounted for when discussing the results. However, most of the approaches agree that, implementing green infrastructures helps to mitigate peak flows and that different strategies seem optimal depending on the hydrological objective.

6.1.3 Discussion on the practice of GI scaling - direction and objectives

Ward *et al.* (2019) highlighted some issues linked to governance level and green infrastructure. Indeed, the ownership of GI constitutes a barrier to their maintenance. A limited maintenance may directly influence their performance and therefore their reliability (Comby *et al.*, 2019). It should be investigated if this specific issue constitutes a direct limitation to the applicability of methods for green infrastructure placement at city scale. Indeed, by essence, a decentralized approach to stormwater management may not easily be centralized at the operational level. Rather, while it may be possible to optimize subcatchment objectives at a centralized strategic level, it may be more relevant to investigate the placement influence at subcatchment/ neighbourhood scale. In particular, that scale may allow for using more advanced modelling approaches due to lower computational power requirement per model evaluation. In practice, lower computational power requirement means that sampling methods for uncertainty quantification, that cannot be afforded at city scale (Section 6.1.2), may be applicable. It may also allow investigating how different infrastructure may interact at the neighbourhood level.

In that sense, the current chapter aims at investigating the interaction of green infrastructure at the neighbourhood scale. Passive coupling (juxtaposition of solutions to enhance the overall system) and active coupling (coupling dynamically several infrastructures to enhance the overall system), similarly to the definition of active and passive systems by Webber *et al.* (2022), will be conceptualized. In particular, the concept of passive coupling and its potential for aligning stormwater management strategy and operational implementation will be investigated in-depth.

6.2 Theory and evidence

6.2.1 The missing scale - interdependencies between GI

One of the aims of the current chapter is to present evidence and potential of 2 types of coupling of green infrastructures, namely passive coupling and active coupling. In the previous chapters, Green infrastructure has been studied at site scale. In Paper C, GI has been studied at city scale, assuming that they could be scaled linearly. However, the infrastructure studied at site scale can present complex behaviour, as shown in Chapter 5. Indeed, the performance of the combination E and D green roofs performed better than the E-Green roof or the D-Green roof alone, while they were both designed following the same procedure.

6.2.1.1 Passive coupling

Passive coupling of green infrastructure is here defined as the system of green infrastructure performing next to each other without direct interaction between them. From a resilience point of view, if the two infrastructures have the same performance profile, the resulting system may resist to a high degree to a certain type of events. However, it also means that they may share the same conceptual weaknesses (Figure 6.1a). For instance, with the case of infiltration based solution, if they are installed at the same time and share similar conditions, they may clog at similar time. It would result in the failure of both solutions, therefore of the entire system considered for now. If we consider instead similar green roofs, a particularly intense summer drought may result in plant mortality on both roofs. Those two examples present theoretical resilience losses of individual solutions at system scale. If now we consider a system with an infiltration-based solution located next to a green roof. It is more likely that one fail at a different time as the other, especially because they do not share the same risks of failure. As a drawback, different infrastructure may require different maintenance procedures, which are yet to be systematized (Langeveld *et al.*, 2022).

In the previous paragraph, the theoretical case consisted in a parallel placement of two infrastructures. If we consider the case of a network, two exactly similar infrastructures located close enough to face the same precipitation may have the same peak of runoff. However, their peaks of runoff might not contribute to the network's discharge at the same time and location. Studying passive coupling of green infrastructure means studying how infrastructures designed independently contribute together at system scale. It also consists in assessing if an interdependent design of those infrastructures could have led to a better system scale performance. That question of interdependent design is especially relevant if we consider that often the solutions are not designed at the same time. It also suggests an ownership shift of GI from the individual to the community. This could be a desirable property since it keeps the decentralized properties of green infrastructure but ensure their interconnection.

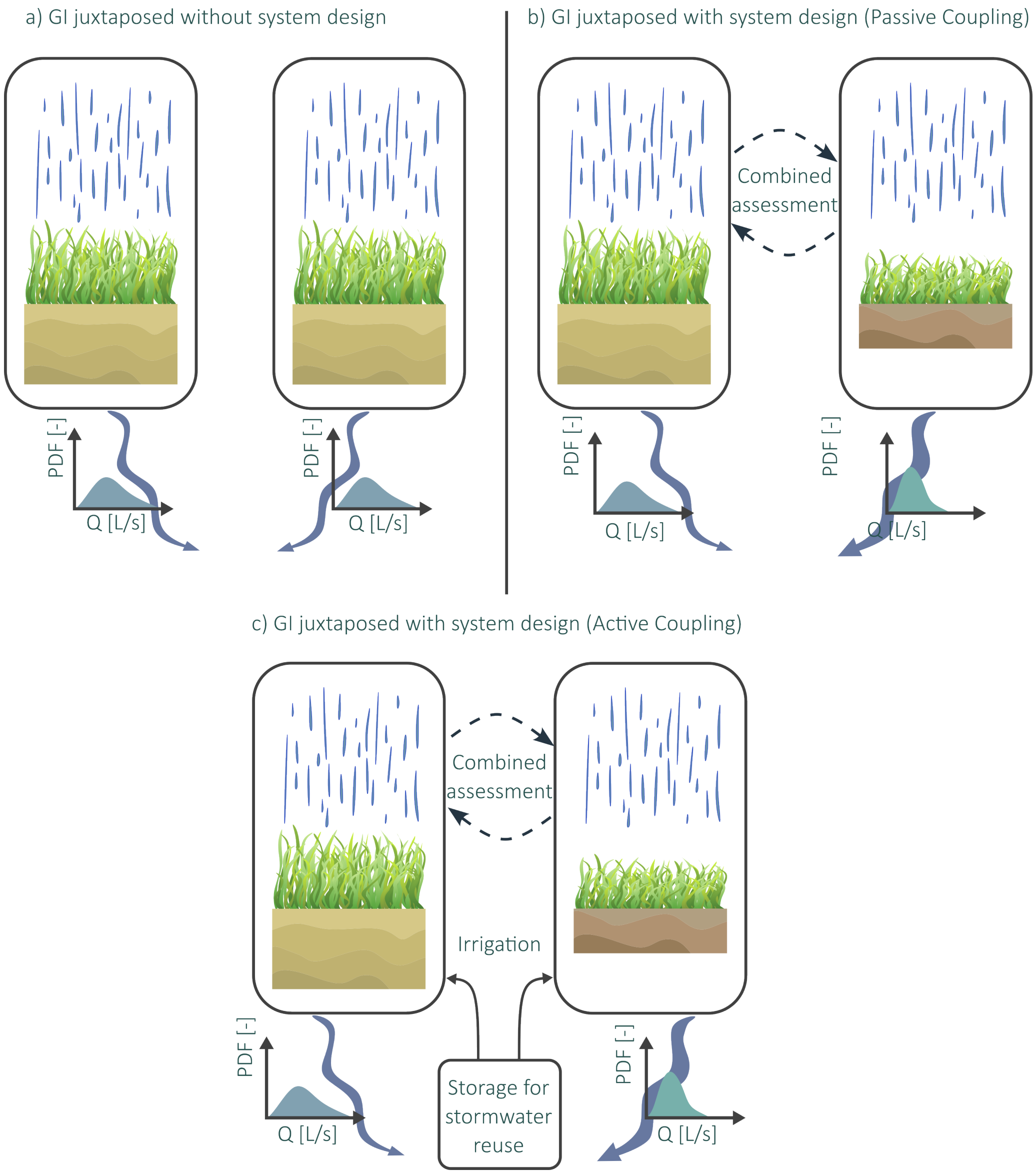

Figure 6.1: Conceptual view of GI designed without system-thinking, b) system-based design with passive coupling, and c) system-based design with active coupling.

6.2.1.2 Active coupling

Compared to passive coupling, active coupling goes one step further. It consists in dynamically connecting the infrastructures together to enhance their performance at system scale (by decentralized real time control). One example is to redirect the flow of a saturated green roofs to an unsaturated infiltration trench. That hypothesis can be brought further by considering water reuse. If a green roofs discharge into a storage tank, the rainwater collected can be used to irrigate the roof in case of drought (Poster C). As discussed in CHAPTER 1, the current green infrastructure models ignore mostly the modelling of the consequences of drought, even though evidence shows that under long periods of hydric stress, the evapotranspiration drops (Nagase and Dunnett, 2010). Under extended drought periods, the vegetation may die (Mencuccini *et al.*, 2015). One easy method to avoid that risk of retention failure is to irrigate the vegetation (Hill *et al.*, 2017). However, periods where irrigation would be mostly required are also the ones where the available water is the more limited. In consequence, municipalities are likely to implement regulations to prevent the use of drinking water for vegetation watering. The reuse of stormwater by coupling a green roof to a storage tank in order to keep stormwater for irrigation is a way to couple those infrastructures. The coupling can be even considered at system scale. If a sufficient volume of runoff from green roofs discharges into the same tank, it can be prioritized how to allocate water resources. For instance, let us consider N roofs. Each has access to a volume V of water from their individual storage tank. If we assume that a volume V is not sufficient to keep the roof in its functioning state, all the roofs will fail. A better approach to prioritization is to consider that the N roofs have access to a total volume of $N \times V$. Based on that assumption, it would be possible to prioritize based on prediction if it is better not to irrigate a subset of the roofs in order to keep a subsystem functioning. Such an optimization makes sense at system scale because the GIs owned by individuals are benefiting the system and not necessarily the individuals directly.

In that sense, the active coupling of green infrastructure is directly related to decentralized real time control. This close relationship with those concepts helps to draw a clear line between passive and active coupling, similarly to Webber *et al.* (2022) definition of active and passive system. Active coupling requires a dynamic activation, while passive coupling does not. Both systems benefit from maintenance and monitoring, but active coupling requires more equipment and should therefore only be applied only when evaluated necessary. It would mean that: i) a passive coupling appears insufficient to achieve mandatory objectives, ii) active coupling would be reliable and robust enough to achieve those objectives.

6.3 Methods

6.3.1 Data and site

The historical climate time-series from Trondheim were used. Climate projections were extracted from $1 \times 1\ km$ gridded data (Dyrrdal *et al.*, 2018). A downscaling model $\mathrm{MRC}_{\mathrm{SIT-SEP}}$ from (Pons *et al.*, 2022a) was used. In particular, the HIDES framework developed in (Pons *et al.*, 2022b) was used and upscaled to neighbourhood scale.

The site used for the study was a neighbourhood of 20 houses varying from $80\ m^2$ to $150\ m^2$. The neighbourhood, even though based on satellite pictures of a real neighbourhood, is synthetic and for demonstration purpose. The delay to the outlet of the residential area varied from 1 to 4 minutes, depending on the location of the house.

In order to provide an example of the previously theorized passive coupling, several GI units were used:

- A detention-based green roof (D-green roof) and extensive green roof (E-green roof) resulting directing from the model presented in (Pons *et al.*, 2022a). Those two GI units models were not altered in order to match a specific design criteria. It implies that the D-green roof, is too efficient for the design criteria of Trondheim municipality, and the E-Green roof is undersized according to the criteria.
- A storage unit (StU) with discharge controller based on the URBIS model (e.g., Sandoval *et al.*, 2019) was used and designed according to Trondheim municipality's requirements. It was considered $1\ m$ deep, the parameter adjusted for design was the relative area.
- An E-Green roof unit was designed with the storage depth as a parameter.
- A D-Green roof unit with relative area as design parameter was sized. It means that given an area, a part was kept impervious, discharging into the D-Green roof.
- A unit based on a combination of unmodified E-Green roof discharging into a Storage unit was designed. The design parameter was the relative area.

The last possibility consisted in having no functioning GI unit on-site. In practice, it consists in discharging the precipitation volume in the network pondered by the area without losses, since the surface is impervious. While this hypothesis may be limiting, it was considered sufficient for this theoretical example, since the area of the houses was between $80\ m^2$ and $150\ m^2$.

The idea behind the choice of those solutions is to provide units with a variety of individual performance in order to trigger different system scale performance. No solution with infiltration was chosen for computation reason at this stage, but should be investigated in further work.

6.3.2 Neighbourhood scenarios

Two categories of scenarios were considered, the reference scenarios, and the stochastic scenarios. The reference scenarios consist of using the same unit for each house of the neighbourhood. The stochastic scenarios consist in sampling a unit for each house randomly, based on a subset of the units. The different scenarios and their subset description are as follows:

- Scenario A0: All types of units can be used (both designed and unmodified), absence of units can also be used. This is the most general scenario.
- Scenario A1: All types of units can be used (both designed and unmodified), but there has to be a unit implemented. This scenario is used for comparison with A0 to see the influence of unit absence. Unit absence can stand for a house that has not been retrofitted, or for a unit that has not been maintained or is malfunctioning.
- Scenario B: Only unmodified units are used. In particular, it means that the configurations consist of a mix of undersized and oversized solutions. This scenario aims at investigating the influence of absence of design from unit scale to system scale.
- Scenario C: A variation of scenario B also allowing the storage unit. This scenario investigates the influence of a resistance-based solution. A resistance-based solution tends to overflow abruptly when the storage capacity is exceeded. It is defined by opposition to solution that have a gradual transition when it comes to failure. The storage unit StU is a resistance-based solution.
- Scenario D0: Only designed units are allowed, the absence of unit is allowed. This is the complement of scenario B. It investigates how in a timescale only having locally designed units results at system scale.
- Scenario D1: Only designed units are allowed, the absence of unit is not allowed. Similarly to scenario A1 associated to A0, D1 is associated to D0. It investigates the influence of absence of unit. It should be noted that this scenario is what the current guidelines tend to build, while D0 is representing a transient state before all housing implement a unit.

Table 6.1 summarizes the objectives behind the elaboration of the different scenarios.

Table 6.1: Summary of the objectives of the different scenarios comparison

Objective of the scenario comparison	Scenarios
Influence of the absence of units	A0 compared to A1, D0 compared to D1
Unit-based design compared to system-scale objectives	D0 compared to B
Targeting property of units to enhance a system	C compared to B
Influence of a large variety of solution on the system	A0 compared to D0, A1 compared to D1, C compared to B
Influence of resitance-based solutions on scenario robustness	Single-unit scenarios with a StU compared to all others
Influence of the timeline of implementation of solution or failure of solutions	A0 compared to A1, D0 compared to D1

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6.3.3 Sampling and computation procedure

For each of the units, the method of Local Event Sampling was used (Pons *et al.*, 2022b). The return periods of 5, 20 and 100-year were selected. For each of the return period, 10^4 events were sampled. The initial conditions were taken as a mean value from continuous simulation since in the case of Trondheim, sampling from the moisture distribution did not lead to a large difference in results (Chapter 5).

In the current form, the neighbourhood consists of a directed acyclic graph. The pipes link the units only apply a delay and no attenuation. In this particular case, the neighbourhood scale model therefore consists in a summation of time-series with respect to delay. It makes it particularly convenient to avoid expensive computation. The 500 configurations for each of the stochastic scenarios were generated.

6.3.4 Informal sensitivity analysis

The analysis realised below consists in an informal qualitative analysis. The choice of such an analysis over formal and quantitative methods, such as computation of Sobol indices (Section 1.1.3), was motivated by the context of the study.

The analysis of the influence of the permutation aims at quantifying if the permutation of the configuration influences or not the outcomes. Therefore, it does not consist in discriminating the variance attributed to different factors. For that reason, and due to computation time, a qualitative analysis was realised. 15 different configurations of GI were generated randomly. They were then shuffled 50 times. The use of several starting configurations aims at avoiding a sensitivity conditioned by the configuration itself.

For the scenarios, using a formal SA measuring the influence of each GI units on the outcome was not considered relevant since the goal is to demonstrate the concept of GI passive coupling and not measure in a case study the influence of the individual units at neighbourhood scale. An informal qualitative sensitivity analysis was preferred to favour discussion.

6.4 Result and discussion

6.4.1 Application of HIDES to a neighbourhood scale

Figures 6.2, 6.3, and 6.4 show the results of applying the framework HIDES to the single events scenarios and the 500 configurations from scenario A0. On Figure 6.2, the survival distributions of discharge are displayed. It was concluded in Chapter 3 that the climate variability should be accounted for in survival distribution of discharge. Indeed, in order to achieve robust decision-making, this information of the variability of performance is important. Given two solutions with the same survival distribution of discharge over 30 years, one may conclude that they have similar performance with respect to the 1^{st} step of the 3SA. However, while they may have the same frequency of exceedance over 30 years, the variability of their frequency and magnitude of exceedance may be different. The framework HIDES initially includes the representation of this annual variability as presented in Chapter 5. However, in the current chapter, the survival distributions are presented without considering annual variation for readability purpose. The aim is to present the variation due to configurations for the different scenarios. By graphical read, it can be shown that the frequency above $0.25\ mm/min$ range from $4 \cdot 10^{-7}$ to $2 \cdot 10^{-5}$ which differs by two orders of magnitude. It shows that a particular attention should be given to the effects at system scale, since the variability in performance is large. One can see that the envelope of the scenario A0 remains within the boundaries set by the different units. It can be noted that the designed storage units do not exceed the threshold of $0.33\ mm/min$. However, for lower flows this solution has one of the highest frequency (e.g., between $0.01\ mm/min$ and $0.2\ mm/min$).

The retention fraction cumulative distributions are displayed on Figure 6.3. The designed storage unit does not have retention. That information also explains the high frequency of low flow (Figures 6.2). This solution can be used to limit the peak flow, but not to limit volume. The envelope of scenario A0 ranges from 80% of years, with retention lower than 12% to 35%. It could be discussed if the result of the simulation for the scenario with designed E-GR is realistic or not, since the increase of storage depth may not increase evapotranspiration ratio to that extent. However, for comparison purpose it was kept since that unit shows a different behaviour with one of the highest frequency of flow above $0.33\ mm/min$ on Figure 6.2. The median of A0 configurations shows that favouring high volume reduction is a choice and has to be accounted for at system scale.

While Figures 6.3 and 6.2 are mainly investigating the neighbourhood scale effect of scenario A0 according to step-1 and to some extent step-2 of the 3SA based on continuous simulations, Figure 6.4 investigate their probability to reach the target of $0.33\ mm/min$ under different return periods (5, 20 and 100-years) through the use

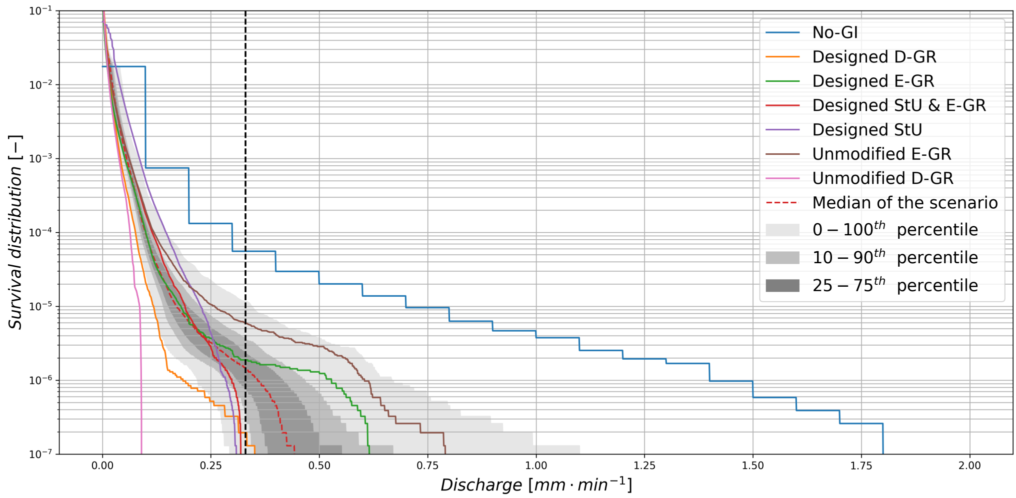

Figure 6.2: Survival probability of discharge for the scenario A0.

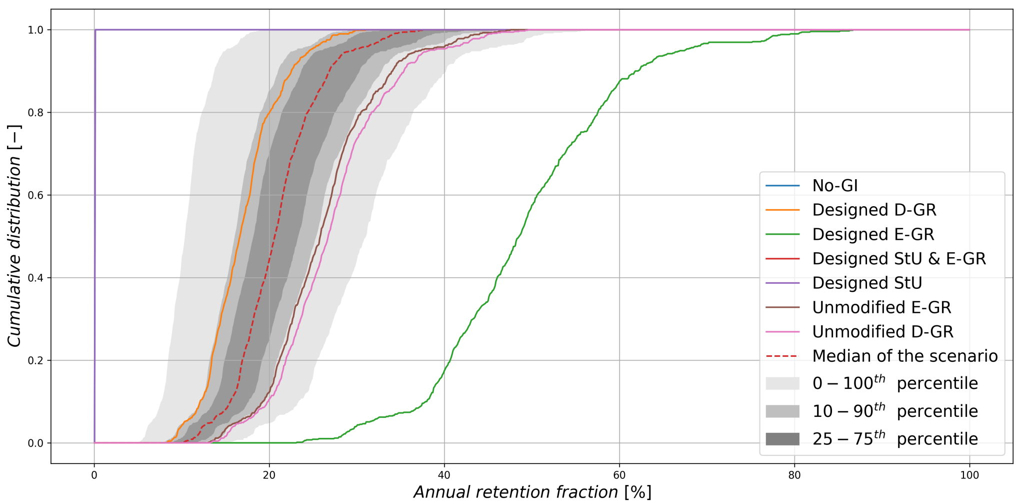

Figure 6.3: Cumulative distribution of retention fraction for the scenario A0.

of local event sampling. It also helps to understand the behaviour under failure and addresses step-2 and 3 of the 3-SA. The median A0 scenario reaches the target for 5-year return period with a probability of 0.35, 0.15 for 20-year (the design return period), and 0.05 for 100-year. The decrease in probability can be explained by the increasing magnitude of the events, but the probability of meeting the target remains low for the designed return period. However, the envelope shows that it is possible to find a more robust combination of solutions (maximum probability of 0.4 among the 500 configurations for the design return period). From a qualitative point of view, the figure shows that some configurations lead to performance distributions without heavy tails. Such a property is desirable since it means that in case of failure, the magnitude of the flow is expected to increase relatively less than a configuration with a heavier tailed distribution. In particular, as detailed in the resistance analysis in section 6.4.4, the reference scenarios solely based on storage units have a higher probability to reach the target but a heavier tail. Moreover, the heaviness of the tail seems to increase with the return period to converge to the peak rainfall distribution. This can be explained since once the tank is full, the solution lets the rainfall overflow directly, while the models of the green roofs describe a smoother behaviour.

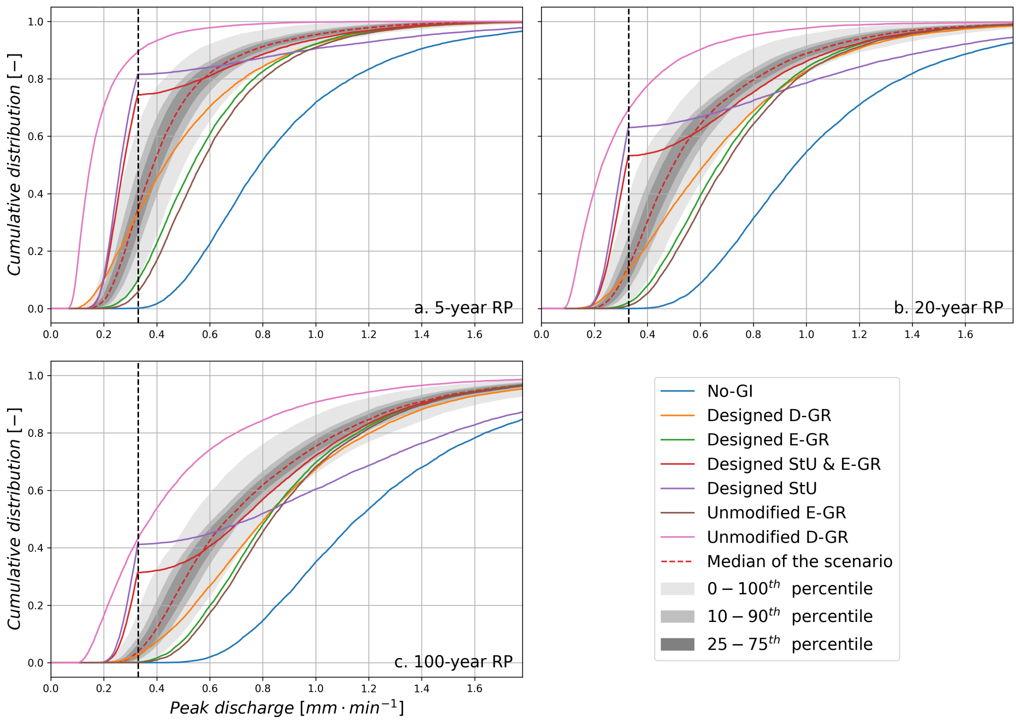

Figure 6.4: Cumulative distribution of peak runoff for: 5-year, 20-year, and 100-year return period.

6.4.2 Configuration and permutations

One important question to study is the influence of permutations of a given configuration. More precisely, it should be assessed if, at such a local scale, the spatial variation in the configuration affects the performance indicators. In order to assess that effect, an informal qualitative sensitivity analysis was performed. For 15 configurations, 50 permutations were generated and the variation of performance indicators due to the permutations was compared to the variation of performance due to the configurations. The range of variation due to permutations divided by the range of variation between the median of configuration was used as an indicator. A ration close to 0 would mean a negligible influence, and a ration higher than 1 a major influence. For a 5-year return period, the ratio is between 0.21 and 0.65. For the 20-year return period, it is between

0.13 and 0.86. For a 100-year return period, it is between 0.04 and 1.29. For the discharge of the 99.5^{th} percentile, it is between 0.18 and 0.47. Evaluating a quantitative indicator would require higher computational power since each configuration requires a 30-year time series, and, 10000 events for 3 different return periods. However, the indicator gives a qualitative estimate of the contribution of permutation to the performance linked to a configuration. It is possible to conclude that the configuration tends in most of the cases to be influenced by the permutations. Indicators relying on extreme events may be more influenced than indicators based on milder events. On the other hand, Figure 6.5 shows probability distributions of meeting the target for 5, 20 and 100-year return periods. It shows that the absolute range of variability due to permutations is lower for higher return period. For configuration $\#10$, the range of probability to meet the target for a 5-year return period ranges from 0.4 to 0.67, while it ranges from 0.06 to 0.14 for a 100-year return period. The question of the necessary accuracy in the estimation of the probability of a risk event is directly linked to a decision-making process. However, in that specific case the risk event is the same: exceeding $0.33\ mm/min$, but while the probability of exceedance is lower for a 100-year RP rain event, its magnitude of exceedance is expected to be higher than for a 5-year RP. It suggests that planning to face extreme events may require a site-scale modelling when allocating green infrastructures. The conceptual knowledge that those simulations suggests, from an applied perspective, should be further evaluated. Indeed, a municipality may consider applying a high-resolution green infrastructure multi-objective optimization algorithm at catchment scale in order to make a plan. However, if they were to modify the plan at the operational level, they would need to reevaluate the plan since the system's sensitivity to permutations.

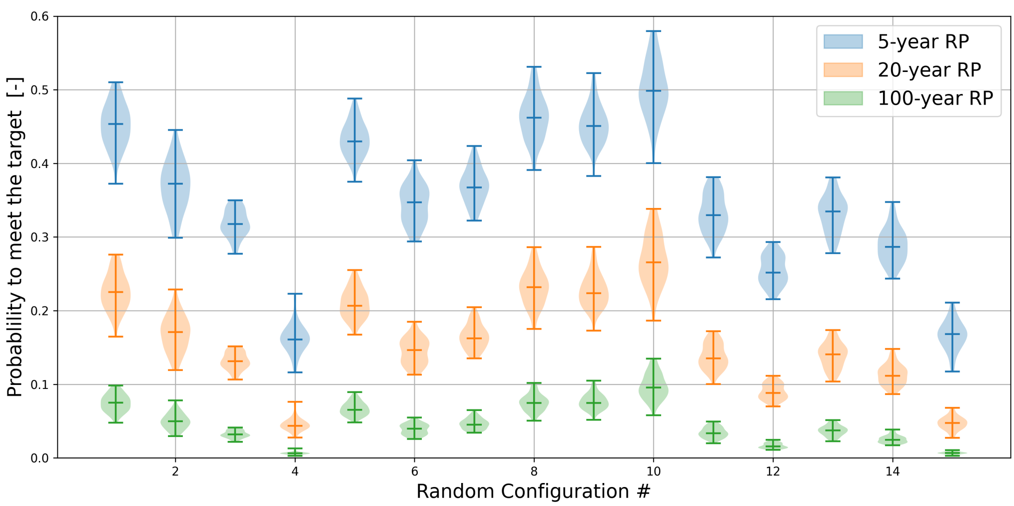

Figure 6.5: Distribution of probability to meet the target for 50 permutation of 15 randomly generated configurations.

6.4.3 Neighbourhood scenario

Continuous simulations (Figure 6.6 and 6.7) and local event sampling for a 20-year return period (Figure 6.8) were run for each of the scenarios. Retention, presented in Figure 6.6, is not affected by the permutation in the case of passive coupling. The resulting performance distribution is simply a mixture of the performance distribution of the different units. It means that storage units or absence of green infrastructure tend to lower the performance of the system. In particular, the performance of the unmodified E and D green roof being similar, the variation due to configurations in scenario B is small compared to other scenarios. The configurations with the highest performances are the ones related to scenarios allowing for the designed E-green roof, since this unit has the highest performance. However, it should be kept in mind that high retention performance and high detention performance are not linearly correlated.

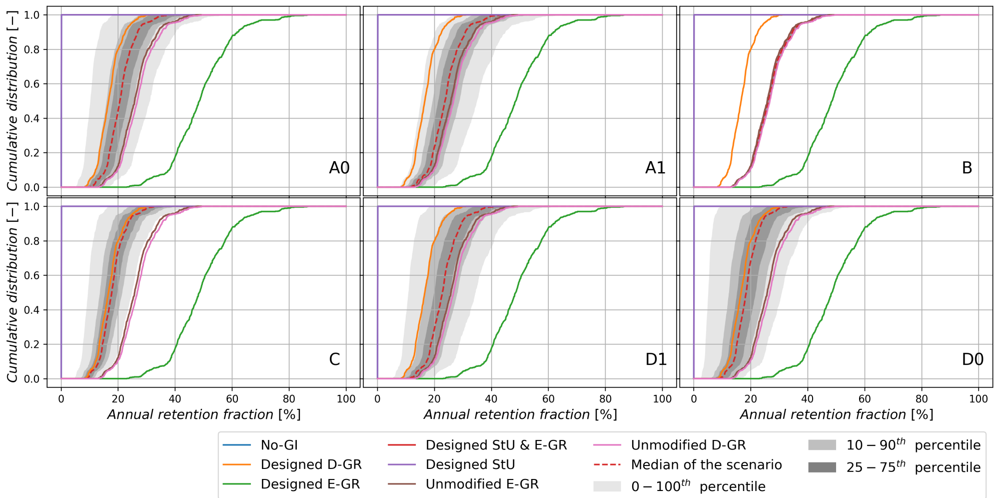

Figure 6.6: Cumulative distribution of retention fraction for the different random scenario configurations for a 20-year return period rain.

In terms of continuous simulations and survival discharge (Figure 6.7), the scenarios with the worst low range of performance are the ones allowing for GI absence (A0 and D0). The scenarios with the best high range of performance are the ones allowing for unmodified D-green roof (B and C in particular). Another Important observation based on scenario D1, where only designed units are used, is that the threshold of $0.33\ mm/min$ can be exceeded. This can be due to the fact that the designed E-green roof is not robust enough in the context of continuous simulation and has a higher chance of failure.

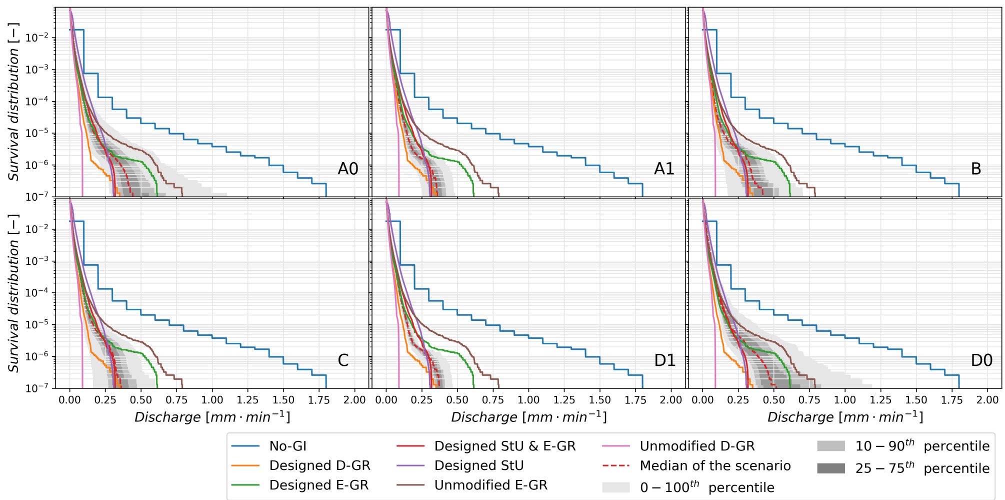

Figure 6.7: Survival distribution of the discharge for the different random scenario configurations for a 20-year return period rain.

6.4.4 Resistance and Robustness to extreme events

Figure 6.8 presents the cumulative distribution of peak discharge for each of the scenarios for a 20-year return period with a climate factor of 1.4 in Trondheim municipality. The vertical dotted line shows the design threshold of $0.33\ mm/min$. Similarly to the unit scale case presented in (Pons *et al.*, 2022b), fulfilling the design criteria with the variational method doesn't mean fulfilling the design criteria for a large range of 20-year return period events. Moreover, fulfilling the criteria at unit scale doesn't mean fulfilling it at system scale.

When only storage units are used, 50% of the 20-year return period events peak discharge are below the municipality's requirement. However, as showed by the cumulative distribution function, they fail abruptly with a different trend in discharge increase. It can be shown by the heaviness of the tail of the distribution. This type of failure mode characterizes solutions designed to resist. To some extent, it should be discussed if such a property should be avoided. Indeed, the issue with such a property is that for most events no overflow will happen, which is desirable, but if failure occurs it is likely to be a failure of large magnitude. In a context of flood management, a city with regular activation of floodways gets the citizens more informed of how to behave in case of flooding, since it leads to a flood memory. Flood memory plays an important role in human risk perception (Ridolfi *et al.*, 2020), but can be affected by culture and high migration rate in the population. A more progressive increase of peak discharge may make the citizens more aware of the behaviour of the system under failure. It means that, from a risk management perspective, a solution without resistance pattern and a lower probability of meeting the target may be more desirable.

We see on Figure 6.8 that the unmodified units represent the envelope of the scenarios. In particular, scenario B which is a combination of E and D green roofs shows the same median probability to reach the target than scenario D1 with only designed units, but has a higher robustness with a thinner tail. The scenario C, which allows for storage units, shows similar performance but with a higher probability of meeting the target. This result is interesting because all the units have a different behaviour. However, in terms of retention (Figure 6.6), it leads to lower robustness than the scenario B which has a thin range among configurations and higher performance. To conclude, the robustness of scenarios to extreme events requires using solutions with different behaviour, but high robustness to extreme events does not imply high robustness in terms of retention performance.

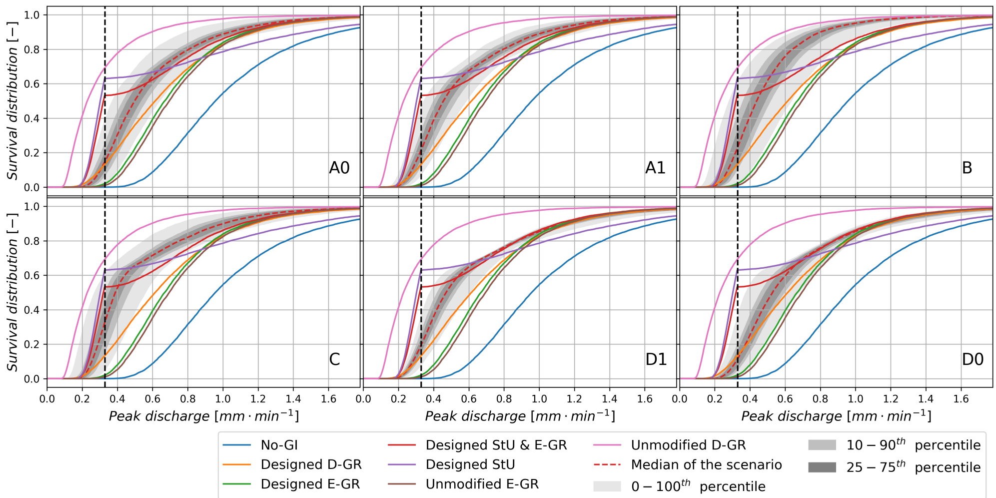

Figure 6.8: Cumulative distribution of peak runoff of the different random scenario configurations for a 20-year return period rain.

6.5 Conclusion

In the current chapter, two different approaches of system-based design for green infrastructure have been conceptualized, namely passive and active coupling. While the latter has not been investigated in the current chapter due to limitation in the current state-of-the-art of GI models (i.e., GI models not accounting for infrastructure failure induced by ageing or drought), the concept of passive coupling has been investigated. The framework HIDES has been applied at catchment scale. It showed that a combination of solutions allows for selection of performance according to different steps of the 3SA. In particular, solutions based on resistance, while they seem to give a high probability of meeting the target, are not able to reduce volume and therefore have a high frequency of low flow. It was also showed that the heavy tail in their response to extreme events may not be desirable. Analysing the scenarios, it was shown that a combination of solutions, not necessarily designed at local scale and including both storage units and green roofs ensures a better global performance in terms of retention, detention, and behaviour under extreme events.

Through the comparison of permutations of configurations, it was shown that the performance may vary in case of permutation. It means that modelling at site scale implementation can have an effect even on a small neighbourhood. It questions therefore the relevance of city scale green infrastructure multi-objective placement optimization. Furthermore, it suggests that it may be more efficient to proceed with sequential scaling approaches in design strategy. It would be similar to IAM (strategical, tactical and operational): establishing from city-scale to catchment-scale performance target, from catchment-scale to neighbourhood-scale and finally from neighbourhood-scale to unit-scale. The reason behind that necessity is that the computational power may not be sufficient to directly apply a framework such as HIDES at city scale for optimization. This approach, similarly to IAM, does consist neither of a top down nor a bottom-up approach: it includes bidirectional interaction between scales.

The last conclusion of upscaling HIDES to neighbourhood scale is that simplistic hydrological approaches cannot represent the complexity of interaction between green infrastructure. Simplistic approach refers here to the use of single rainfall events, and a coarse resolution lumping a group of LID into a single unit. As detailed above, such a resolution can be applied once its accuracy has been assessed at higher resolution in a bottom-up approach. The interaction between infrastructures may have a significant impact on the hydrological performance of the system with respect to volume reduction, peak flow attenuation, failure probability and behaviour under failure. Neglecting those interactions, though a misuse of available climate information, and uninformed modelling approach may lead to misleading performance indicators. Poorly defined and estimated indicators may result in wrong decision-making.

General conclusion

End? No, the journey doesn't end here.

Gandalf,
J.R.R. Tolkien,
The Lord of the Rings

Contents

Thesis conclusions

It may be tempting to justify the use of green infrastructure (GI) through an *appeal to nature*, especially when changing the practices takes a long time. However, such a fallacious rhetoric should be avoided when it comes to a decision-making process under deep uncertainty, such as adaptation to climate change. Moreover, while *an appeal to nature* is a rhetoric process that claims that a thing is good because it is "natural", it could be discussed if green infrastructures, so-called nature-based solution, always qualify to be considered as natural. The substrate or filtration medium in GI often consists of an engineered soil designed for its properties in order to deliver a service. The vegetation is carefully selected, and nutrients are added in order to maximize evapotranspiration rates. Unwanted weeds are removed, and grass-based roofs are sometimes mowed. Such a human-controlled environment can hardly be considered as natural. This rhetoric of green infrastructure as the solution to stormwater management and climate change adaptation is one of the main motivations of this thesis: Can green infrastructure deliver the services we attribute them in our rhetoric?

In practice, around that main motivation, the objective of this thesis, is to develop a framework to evaluate the future hydrological performance of green infrastructure. At that point, it should a highlighted again that hydrology alone is not the only dimension to be considered when it comes to green infrastructures. And it is complex to predict their hydrological performance without accounting for other dimensions. For instance, the vegetation selection, for biodiversity purpose and the placement of the GI within a green corridor may not be the ideal solution in terms of hydrology. The governance of GI, which are inherently part of the stormwater management system, is complex since it can be owned by a private person or be considered as a public green space. This governance aspects will influence the maintenance aspects. The use of GI to mitigate heat island effect will also influence the choice of the placement and the design. And finally, last but not least, the social aspects around green infrastructure will influence their placement and their maintenance.

Those complex relationships between fields and dimensions led to a deep level of uncertainty in order to predict the performance of green infrastructure. In that context, the current thesis aims at developing adaptable tools and framework in order to better guide performance estimation. Indeed, it is not yet possible to account for all types of interdependencies and their direct consequences of the performance, but it is possible to provide estimations within the current state of knowledge and more importantly to develop indicators that can account for the uncertainty that needs to be considered.

Climate change adaptation and data

The question of available data and desirable data is central when it comes to climate change adaptation. It was shown in the current thesis that the data needed to model green infrastructure can be more efficiently collected though experiments than through monitoring campaigns. Indeed, the models that are required for future performance estimation may require observation outside the range that is currently likely to be observed. Therefore, approaches to artificially collect those data can help to collect crucial data in a short time. Indeed, due to their nature, extreme events rarely occur, therefore it is likely that a long monitoring campaign is necessary in order to collect those data. The collection of specific data was also found to help with both model conceptualization and "data-frugal" calibration process. Indeed, the calibration of the detention equation of the models of the E-green roof and the D-green roof only required one day of minute resolution data. The retention equations, on the other hand, do not require such high-resolution temporal data but require longer time-series. Those approaches of experiment-based data-targeting are also desirable for machine learning approaches, since it provides higher boundaries to avoid the need to extrapolate from a black-box model.

The other source of data that needs to be addressed in the context of hydrological performance estimation in the context of climate change adaptation is the climate projections available. At the beginning of the PhD work, only the data from the 5^{th} CMIP was available, but it is now possible to use the data from the 6^{th} CMIP. This reminds that, regularly, new projections are made available. The results presented in this thesis are based on the CMIP5, but they should be updated as new inputs are made available (e.g., with the CMIP6).

The nature of climate inputs also brought several points of discussion. The first was "How to bring those results to the desirable resolution?" and the second was "How to include the uncertainty inherent to those datasets?". One of the first aspects is the cascade of uncertainty. Indeed, the datasets results from Socio-Economic scenarios driving greenhouse gases emission and concentration scenario. Those scenarios are used as input for global climates models that feed regional climate models through dynamical downscaling. The results of this chain of models were still too coarse to be used as input, they are therefore statistically downscaled, and bias corrected. The resulting datasets, have daily resolution and a spatial resolution of 1 to 12 km. While the thesis does not rely on gridded data, it is important to mention the final resolution, since regionally downscaled data aim to represent local climate. The fact that a dataset represents well the global climate does not mean it represents well the local climate (smoothed extremes at local scale should be avoided for hydrological performance evaluation). Those datasets were used as available and accessible data. The question of accessibility remains central, since climate change adaptation is at the interface between several fields of science. It is therefore important to pay attention to data accessibility and availability.

In order to bring the input data to the desirable resolution, Multiplicative Random Cascades have been used. The model was made robust to climate change through the hypothesis that the temperature-rainfall dependency could be used to drive prediction. This hypothesis could be discussed, especially when convection-permitting models start to be available. However, the output of the models was found sufficient to simulate the performance of green infrastructures. Their nature of weather generator was found to be a key property for performance estimation, accounting for climate variability and uncertainty. To conclude, while better climate models and better statistical downscaling models may become available in the next years, their use as weather generators will remain relevant, especially to evaluate performance in non-stationary conditions.

From data to information: the hydrological performance of green infrastructures

Stormwater management strategies coupling centralized and decentralized solutions are often used in cities with an existing sewer network. Modern stormwater management in cities consists in partitioning water management depending on the type of event. For instance, the 3-step approach in Norway, consists in managing the day-to-day rains at the source, mainly through evapotranspiration or infiltration. The goal is to reduce the annual volume released into the sewer network. Major rains that cannot completely be retained by decentralized solutions are supposed to be attenuated in order to lower the stress on the sewer system, which is designed for that type of events. Finally, extreme events, defined here as events of higher magnitude than the one used to design the main stormwater system (i.e., GI and sewer system), are supposed to be attenuated at best by the system under failure. The problem turns for such events in a risk prioritisation approach. The main stormwater system is failing because it is not designed to stop extreme events. Consequently, the roads are flooded and activate their secondary floodway function. Since the main system is likely to fail, the risk prioritisation approach should aim at quantifying the magnitude of the failure as well as its probability. Then acting on the floodway system should aim at reducing risks in highly sensible areas (e.g., school) and place risk reduction measures plan (e.g., pedagogic plan).

From the perspective of the previously presented stormwater management strategy, designing and evaluating the performance of green infrastructure should aim at quantifying retention, detention, probability of failure and behaviour under failure. Moreover, as it has been explained earlier, the input climate data contains several sources of uncertainty, and notably climate variability, which should be aimed to be represented in the performance indicator. For that purpose, the framework HIDES was developed. It argues that GI solutions should be evaluated for each of the steps of the 3SA approach. The use of HIDES showed that the current design methods are not reliable. It allowed to quantify the probability of failure of GI solutions. It also helped to show evidence that solutions with similar design (i.e., designed according to the same regulation) can have different behaviour and, more importantly, different robustness to climate change. Especially, sampling local extreme events with the downscaling models showed that a combination of solutions can face a larger range of rainfall than a single one if the solutions are carefully chosen. To conclude, the framework HIDES suggests which input data to used and how. It shows also how to transform the output data into relevant information that are metrics of robustness of solutions in terms of retention, detention, failure, and behaviour under failure. Its use and conceptualisation helped to build knowledge of the robustness of combinations of GI.

Upscaling information: green infrastructures interdependencies

The last objective of this PhD thesis was to conceptualize how to bring the knowledge about GI hydrological performances to another spatial scale. The main direction to approach that problem has been to question the relevance of green infrastructure placement, and the relevance of local design. The investigation started from the conclusions, based on HIDES, that approaches based on a single or small number of rain events can lead to misleading performance estimation at unit scale. It was argued that it is likely that using the same approach at catchment scale (i.e., GI optimization at catchment scale based on single events) can lead to misleading decisions. Therefore, it was investigated how GI can interact at neighbourhood scale. Two forms of GI coupling were conceptualized, by opposition to Non-coupling (GI implemented according to regulation without accounting for the local context). Passive coupling consists in choice of GI in accordance with neighbouring GI in order to achieve a specific performance target at neighbourhood scale. Active coupling consists in actively and dynamically combining GI functions to enhance the system though interaction. The definition is similar to the one used by Webber *et al.* (2022) to define passive and active system. For instance, linking several infrastructures to a main storage tank in order to reuse water for irrigation can help to maintain the vegetation vital functions in case of drought. It can in more severe cases be used to prioritize which infrastructure should be maintained.

The relevance of passive coupling was then investigated in details by upscaling HIDES at neighbourhood scale. It was found that even in a small neighbourhood of 20 houses, the same configuration is sensitive to permutations, i.e., the same infrastructures placed differently affect the performance and especially the probability to reach a target at system scale. It was also showed that local design does not mean reaching the target at system scale. Some scenarios based on a combination of low and high performance solutions were found to be more robust than some configurations based on designed solution only. The main conclusion and new knowledge brought through that modelling approach is that design of GI should not solely be based at site scale, but also at system scale. More advanced modelling practice based on long term simulation and local event sampling should be used to assess the robustness of systems when designed. If the use of a framework such as HIDES is here recommended, it is acknowledged that it requires availability of a downscaling model. On the other hand, it was found that the use of a model in a neighbourhood city could be sufficient to have estimates. To conclude, the different tools developed during this PhD, helped to provide evidence of the necessity to account for uncertainty and climate variability both during modelling and when translating models outcome into meaningful information. They are also considered as relevant tools in order to convey information about climate variability and GI upscaling.

Thesis perspectives

As detailed previously, the current PhD can be considered as follows. Given the cascading uncertainty from stemming from climate data and green infrastructure models, how to turn model outcomes into useful knowledge conveying critical information. While some tools were developed for that purpose, some methodological points need to be mentioned and further discussed. The climate data used are collected from the 5^{th} CMIP in the 5^{th} assessment report of the IPCC and after statistical downscaling and bias correction method through the EURO-CORDEX project. While the global climate models are becoming more finely gridded, starting to permit convection process, the reliability of the predictions will increase. It means that when more accurate projections are available, it will be possible to substitute them to the one used in the current thesis. The downscaling multiplicative random cascade models, used in the thesis, are an attempt to convey information about climate change though the use of temperature as a predictor. In the future, more reliable downscaling will be available. However, the use of those downscaling models was presented in the current thesis as weather generator. The use of those weather generators is one of the keys used in this thesis to convey the information about climate variability. The approach of extreme event sampling, to the knowledge of the author, is novel and still needs investigation, especially to permit to reduce the number of events needed for simulation. Indeed, applying local event sampling at catchment scale cannot be achieved by municipalities without large computational power. Another limitation and development perspective from the current results in to add a spatial dependency to the weather generators used for HIDES. It would, indeed, allow using the framework at city scale.

The approach used for model calibration, which consists in targetting critical data outside the observed range, is also one of the key outcomes that should be used to improve the green infrastructure models at a low monitoring cost. Therefore, the methodology used in this thesis could be transferred to other types of green infrastructures in order to improve their conceptual models. The concept of "data-frugal" model brought in the 2^{nd} chapter of this PhD and the idea of passive coupling explores the possibility to achieve climate robustness with a limited amount of data. In a context where the tendency is to intensify monitoring and ML-approach, it to put in perspective the efficiency of those approaches in terms of resources and as climate adaptation measures.

On an applied level, the framework HIDES should be tested, and its real applicability evaluated. One step toward this direction is to make its use easier. It is acknowledged that a framework such as HIDES requires a paradigm shift in the design practice. Indeed, it is a probability based framework. On the one hand, it is considered as necessary to make this shift in design paradigm in order to convey information about climate variability and uncertainty to achieve robust and resilient design plan. On the other hand, it is also acknowledged that, in its current form, HIDES requires a change of methods and skills in design while its use might not be necessary for some every design cases. However, it should be reminded that prior to the application of HIDES it might not be possible to estimate the necessity of its use for a case study. Further investigation of the need for such a framework and in which case it can be avoided should be investigated.

Concerning the question of scale, green infrastructure coupling was introduced here on a theoretical level. Research should be carried on with inputs linked to green infrastructure maintenance and regarding the possible non-stationarity in model parameters. The modelling results presented here should be confronted with other modelling approaches and monitoring results. One central question yet to be assessed is whether the interdependency-processes and non-stationarities that were not modelled in the current thesis are sensitive processes when upscaling at city scale. *In other terms, for decision-making, [To which extent] can we rely on the current city scale approaches in terms of hydrological modelling?*

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Appendices

And look! More lembas bread.

Samwise Gamgee,
J.R.R. Tolkien, The Lord of the ring

Contents

A Performance under extreme rain

The following table present the data collected during the experiments on the D-Green roof at Høvringen pilot station.

A.1 Soil characteristics

Table A.1: Summary of the soil characteristics. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

	Unit	Expanded clay 0-6 mm	Method
Particle density	g/cm3	0.92±0.03	*Porous plate
Particle density	g/cm3	0.89	Calculated
Bulk density	g/cm3	0.43±0.00	*Porous plate
Bulk density	g/cm3	0.39±0.06	**FLL
Porosity	% v/v	53.7±1.5	*Porous plate
Porosity	% v/v	56.2±0.3	**FLL
Wilting point	% v/v	6.5±1.5	*Porous plate
Field capacity	% v/v	9.1±0.5	*Porous plate
Maximum water holding capacity	% v/v	30.1±1.8	**FLL
Hydraulic conductivity	cm/h	105.2±28.3	***Darcy's law

* Porous plate apparatus method, laboratory of the Norwegian University of Life Sciences, Ås
** (FLL, 2008)
*** Flow of a fluid through a porous medium

A.2 Performance tables

Table A.2: Performance depending on hyetographs. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

Start. Flow mm/min	IRWC mm	PRWC mm	PRu mm/min	PA -	T50 min	CD min	PDe min
TRO 2: 8x 16:00-min blocks with 1.0 mm/min intensity, mean=16.25, std= -							
0.00	8	23	0.04	96%	492	411	6
0.04	24	38	0.12	88%	79	92	3
0.11	37	48	0.30	70%	30	35	4
0.18	45	54	0.63	38%	13	16	2
0.21	49	56	0.76	25%	10	12	2
0.22	50	57	0.81	20%	10	11	2
0.23	51	58	0.84	17%	9	10	2
0.23	51	58	0.84	17%	9	10	2
TRO 2a: 7x 16:00-min blocks with 1.0 mm/min intensity, mean=15.73, std=0.12							
0.00	10	22	0.03	99%	480	421	20
0.03	24	36	0.10	96%	83	103	17
0.09	37	47	0.29	89%	31	39	16
0.15	44	51	0.48	82%	15	21	16
0.18	48	54	0.62	77%	11	14	15
0.20	51	55	0.67	74%	9	11	15
0.31	54	57	0.74	72%	7	7	15
TRO 2b: 8x 16:00-min blocks with 1.0 mm/min intensity, mean=15.80, std=0.06							
0.00	9	24	0.04	99%	702	483	6
0.03	24	38	0.12	95%	80	93	3
0.10	37	48	0.33	87%	28	34	4
0.18	45	54	0.69	74%	11	15	3
0.21	49	56	0.83	69%	9	11	3
0.28	51	58	0.95	64%	7	8	3
0.40	54	59	1.04	61%	5	6	3
0.74	57	59	1.22	54%	2	2	3
TRO 2c: 6x 16:00-min blocks with 1.0 mm/min intensity, mean=15.75, std=0.04							
0.01	23	38	0.08	97%	113	137	31
0.08	38	51	0.29	89%	33	37	10
0.18	48	58	0.73	72%	10	12	7
0.22	52	60	0.87	66%	8	8	6
0.25	54	61	0.96	63%	7	7	6
0.37	55	61	1.08	59%	5	5	4
TRO 2d: 6x 16:00-min blocks with 1.0 mm/min intensity, mean=16.15, std=1.16							
0.00	13	26	0.04	99%	361	454	3
0.04	28	39	0.12	95%	66	79	2
0.11	40	49	0.32	88%	32	34	3
0.19	47	54	0.62	77%	12	15	2
0.22	51	56	0.71	73%	10	11	2
0.37	54	57	0.81	70%	6	6	2

Table A.3: Performance depending on rainfall events. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

Start. Flow mm/min	IRWC mm	PRWC mm	PRu mm/min	PA -	T50 min	CD min	PDe min
TRO 1: 9x 7:00-min blocks with 1.7 mm/min intensity, mean=12.12, std=0.16							
0.00	2	12	0.01	99%	-	512	17
0.01	14	24	0.04	97%	188	352	6
0.04	25	35	0.10	94%	67	81	3
0.09	35	44	0.20	88%	31	36	2
0.16	44	51	0.47	73%	14	19	3
0.23	49	56	0.76	56%	8	11	2
0.22	50	58	0.78	55%	8	11	2
0.24	51	57	0.85	51%	7	10	3
0.24	52	58	0.88	49%	7	10	3
TRO 2: 8x 16:00-min blocks with 1.0 mm/min intensity, mean=16.25, std= -							
0.00	8	23	0.04	96%	492	411	6
0.04	24	38	0.12	88%	79	92	3
0.11	37	48	0.30	70%	30	35	4
0.18	45	54	0.63	38%	13	16	2
0.21	49	56	0.76	25%	10	12	2
0.22	50	57	0.81	20%	10	11	2
0.23	51	58	0.84	17%	9	10	2
0.23	51	58	0.84	17%	9	10	2
TRO 3: 10x 3:30-minutes blocks with 2.6 mm/min intensity, mean=9.26, std=0.01							
0.01	18	26	0.05	98%	120	176	3
0.04	26	34	0.09	97%	56	65	3
0.08	34	41	0.17	94%	29	33	3
0.14	41	47	0.26	90%	18	22	3
0.18	45	51	0.45	83%	11	14	4
0.18	46	52	0.45	83%	11	14	4
0.18	47	53	0.51	81%	10	13	4
0.19	48	53	0.50	81%	10	12	4
0.19	48	54	0.51	81%	10	12	4
0.32	54	57	0.82	69%	6	7	4
TRO 4: 6x 26:00-min blocks with 0.8 mm/min intensity, mean=19.83, std=0.75							
0.00	3	22	0.04	94%	786	458	5
0.04	22	38	0.15	81%	79	90	3
0.11	35	49	0.38	49%	28	36	3
0.17	42	52	0.52	31%	16	19	2
0.17	44	54	0.56	25%	15	18	2
0.26	50	56	0.67	10%	10	10	2

Table A.4: Performance depending on rainfall events. [reformatted from Paper A - (Hamouz *et al.*, 2020b)]

Start. Flow mm/min	IRWC mm	PRWC mm	PRu mm/min	PA -	T50 min	CD min	PDe min
OSL 1: 6x 16:00-min blocks with 1.7 mm/min intensity, mean=27.79, std=0.14							
0.00	8	33	0.10	94%	246	366	2
0.08	32	52	1.00	42%	25	39	2
0.22	46	58	1.55	11%	8	10	1
0.25	49	60	1.64	5%	8	9	1
0.19	48	61	1.59	11%	8	10	1
0.33	52	62	1.70	2%	7	7	1
OSL 2: 3x 44:00-min blocks with 1.0 mm/min intensity, mean=44.79, std=0.14							
0.00	7	47	0.26	75%	162	281	4
0.12	36	57	0.90	12%	23	35	2
0.20	48	60	1.01	2%	12	13	-2
BER 1: 6x 9:00-min blocks with 1.7 mm/min intensity, mean=15.98, std=0.62							
0.00	9	22	0.03	98%	821	436	17
0.03	24	37	0.10	94%	83	101	3
0.10	37	49	0.30	83%	31	37	4
0.19	46	56	0.92	47%	9	14	2
0.26	51	58	1.19	32%	7	9	2
0.38	54	60	1.40	21%	6	6	2
BER 2: 5x 24:00-min blocks with 1.0 mm/min intensity, mean=23.32, std=0.12							
0.00	14	30	0.07	93%	145	228	5
0.07	30	50	0.44	61%	40	49	3
0.23	44	56	0.85	16%	11	13	2
0.36	49	58	0.95	9%	7	7	1
0.45	51	59	0.98	3%	6	6	1

A.3 Green roof discharge model's pseudo-code

The algorithm of the discharge function of the two layer D-Green roof.

Algorithm A.1 d-green roof outflow for a timestep i

Input: the substrate parameters ($s_{k,subs}$, k_{subs}, and $wc_{k,subs}$), the detention layer parameters ($s_{k,det}$, k_{det}, and $wc_{k,det}$), and the water content in the roof wc_i at time-step i.

Set $wc_{0,det} = wc_{k,det} + \frac{s_{k,det}-1}{2\times k_{det}}$ ▷ start computing the outflow with the detention layer contribution

if $wc_{i-1} < wc_{0,det}$ **then** ▷ Logistic part of the detention layer's curve

    Set $q_{det} = \frac{s_{k,det}}{1+\exp(-\frac{4\times k_{det}}{s_{k,det}}\times(wc_i - wc_{0,det})}$

else ▷ Linear part of the detention layer's curve

    Set $q_{det} = k_{det} \times (wc_i - wc_{k,det}) + \frac{1}{2}$

end if

Set $wc_{0,subs} = wc_{k,subs} + \frac{s_{k,subs}-1}{2\times(k_{subs}-k_{det})}$

if $wc_{i-1} < wc_{0,subs}$ **then** ▷ Logistic part of the substrate layer's curve

    Set $q_{subs} = \frac{s_{k,subs}}{1+\exp(-\frac{4\times(k_{subs}-k_{det})}{s_{k,subs}}\times(wc_i - wc_{0,subs})}$

else ▷ Linear part of the substrate layer's curve

    Set $q_{subs} = (k_{subs} - k_{det}) \times (wc_i - wc_{k,subs}) + \frac{1}{2}$

end if

Set $q_i = q_{det} + q_{subs}$

Output: discharge q_i at timestep i

A.4 Green roof model testing

Tables A.5 and A.6 present the three largest events used to test the green roofs models. The last event presented in Table A.6 present a mismatch between precipitation and runoff. It can be explained by snowmelt or failure in precipitation collection. It result in an apparent NSE performance loss.

Table A.5: Details of the three largest events used to test the D-Green roof

starting date	intensity mm/min	depth mm	duration min	temperature $^\circ C$	max runoff mm/min	median NSE	max NSE
2019-09-18 03:29	0.013	56.5	4497	8.90	0.09	0.96	0.97
2019-09-13 01:53	0.012	39.5	3229	8.69	0.02	0.76	0.95
2019-09-15 07:43	0.010	29.5	3002	9.04	0.03	0.81	0.90

Table A.6: Details of the three largest events used to test the E-Green roof. The third event has suspected snow melt that may affect the model performance.

starting date	intensity mm/min	depth mm	duration min	temperature $°C$	max runoff mm/min	median NSE	max NSE
2017-06-17 16:49	0.012	59.6	4923	11.00	0.13	0.96	0.96
2017-08-19 13:41	0.014	57.7	4000	12.29	0.26	0.98	0.98
2017-04-20 19:06	0.005	35.6	7180	3.20	0.12	0.60	0.61

B Downscaling algorithm and model description

The following appendix section is relative to Paper E (Pons *et al.*, 2022a) and describes the algorithm, presents the model equations and supplementary material regarding data analysis, and models performance under 4 locations.

B.1 Algorithm pseudo-code

The algorithm of the Multiplicative Random Cascade is presented below.

Algorithm B.1 Multiplicative random cascade model

Input: Coarse resolution precipitation time series P_r, $ZeroGen$ function, $NonZeroGen$ function, and $SEPGen$ function

for $i = 0, \ldots, length(P_r$ **do**
  Draw $u_{zg} \sim \mathcal{U}([0,1])$
  if $u_{zg} > ZeroGen(R, P_{r,i}$ **then** ▷ Check occurence of a zero weight
    Set $w_i = 0$
  else ▷ Generate the main weight from the $NonZeroGen$ generator
    Draw $w_i \sim \mathcal{U}([0,1])$
  end if
  Draw $u_{SEP} \sim \mathcal{U}([0,1])$
  if $u_{SEP} > SEPGen(R)$ **then** ▷ high weight on the side of the highest neighbour
    $w_{i,high} = w_i$
    $w_{i,low} = 1 - w_i$
  else ▷ high weight on the side of the lowest neighbour
    $w_{i,high} = 1 - w_i$
    $w_{i,low} = w_i$
  end if
  Compute $P_{r,i,2j}, P_{r,i,2j}$
end for

Output: High resolution time series

B.2 Generators description

B.2.1 Zero-weight generator with only time-scale dependency

$$ZeroGen_S(S_{time}) = a_{14} \times \log(S_{time})^4 a_{13} \times \log(S_{time})^3 + a_{12} \times \log(S_{time})^2 + a_{11} \times \log(S_{time}) + a_{10} \tag{B.1}$$

B.2.2 Zero-weight generator with both time-scale and depth dependency

$$ZeroGen_{SI}(d_{i,2j}, S_{time} = 2j) = \\ = \begin{cases} \dfrac{1}{1 + d_{i,2j} - P_3(S_{time})}^{f_0(S_{time})} + \\ \left(1 - \dfrac{1}{1 + d_{i,2j} - P_3(S_{time})}^{f_1(S_{time}))}\right), & \text{if } d_{i,2j} > a_2 \\ 1, & \text{else} \end{cases} \tag{B.2a}$$

$$f_0(S_{time}) = \frac{S_{time}^{a_{00}-1} \times (1 + S_{time})^{-a_{00}-a_{01}}}{a_{02}} + a_{03} \tag{B.2b}$$

$$P_3(S_{time}) = b_{13} \times S_{time}^3 + b_{12} \times S_{time}^2 + b_{11} \times S_{time} + b_{10} \tag{B.2c}$$

$$f_1(S_{time}) = \begin{cases} A \times (1 - \frac{1}{1+\exp(-\frac{4\times B}{A} \times (WC_i - C - \frac{A}{2\times B}))}, & \text{if } S_{time} > C - \frac{A}{2\times B} \\ B \times (S_{time} - C), & \text{else} \end{cases} \tag{B.2d}$$

B.2.3 Zero-weight generator with time-scale, depth and temperature dependency

$$ZeroGen_{SIT}(d_{i,2j}, T_{i,2j}, S_{time} = 2j) = \frac{1}{1 + d_{i,2j}}^{gauss(T_{i,2j}, S_{time})} \tag{B.3a}$$

$$gauss(T_{i,2j}, S_{time}) = A_0(S_{time}) \times \exp\left(\frac{(T_{i,2j} - \mu_T(S_{time}))^2}{2 \times \sigma_T(S_{time})^2}\right) \tag{B.3b}$$

$$\mu_T(S_{time}) = a_{14} \times S_{time}^4 a_{13} \times S_{time}^3 + a_{12} \times S_{time}^2 + a_{11} \times S_{time} + a_{10} \tag{B.3c}$$

$$A_0(S_{time}) = \frac{b_0}{(1 + S_{time})^{b_1}} \tag{B.3d}$$

$$\sigma_T(S_{time}) = \frac{c_0}{(c_2 + S_{time})^{c_1}} \tag{B.3e}$$

B.2.4 Non-zero-weight generator

It consists in a truncated normal distribution described by Eq. 4.3b. The function σ depends on time-scale:

$$NonZeroGen_S(S_{time}) = a_{10} \times (S_{time})^{\frac{1}{a_{11}}} + a_{12} \tag{B.4}$$

B.2.5 SEP generator

The Stochastic Element Permutation follow a function generating the threshold to be compared to a uniformly generated random number depending on time-scale:

$$\begin{aligned} SEPGen_S(S_{time}) = a_{14} \times \log(S_{time})^4 a_{13} \times \log(S_{time})^3 + \\ a_{12} \times \log(S_{time})^2 + a_{11} \times \log(S_{time}) + a_{10} \end{aligned} \tag{B.5}$$

B.3 Data analysis

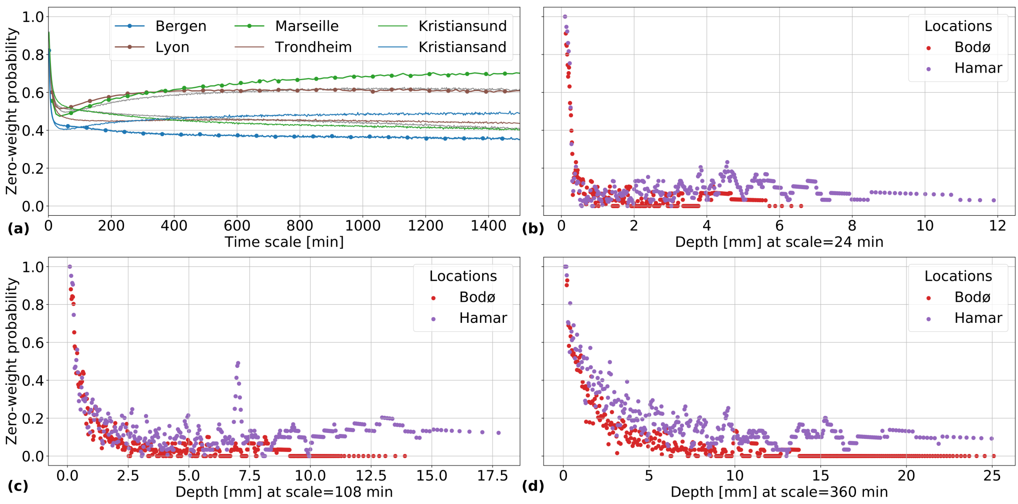

Figure B.1: Zero-weight probability depending on time-scale for Bergen Lyon Marseille, Trondheim, Kristiansund and Kristiansand (a). Zero-weight probability depending on the rainfall depth for different time-scale: 24 min (b), 108 min (c) and 360 min (d) for Bodø and Hamar. [Paper E - (Pons *et al.*, 2022a)]

B.4 Other locations performance

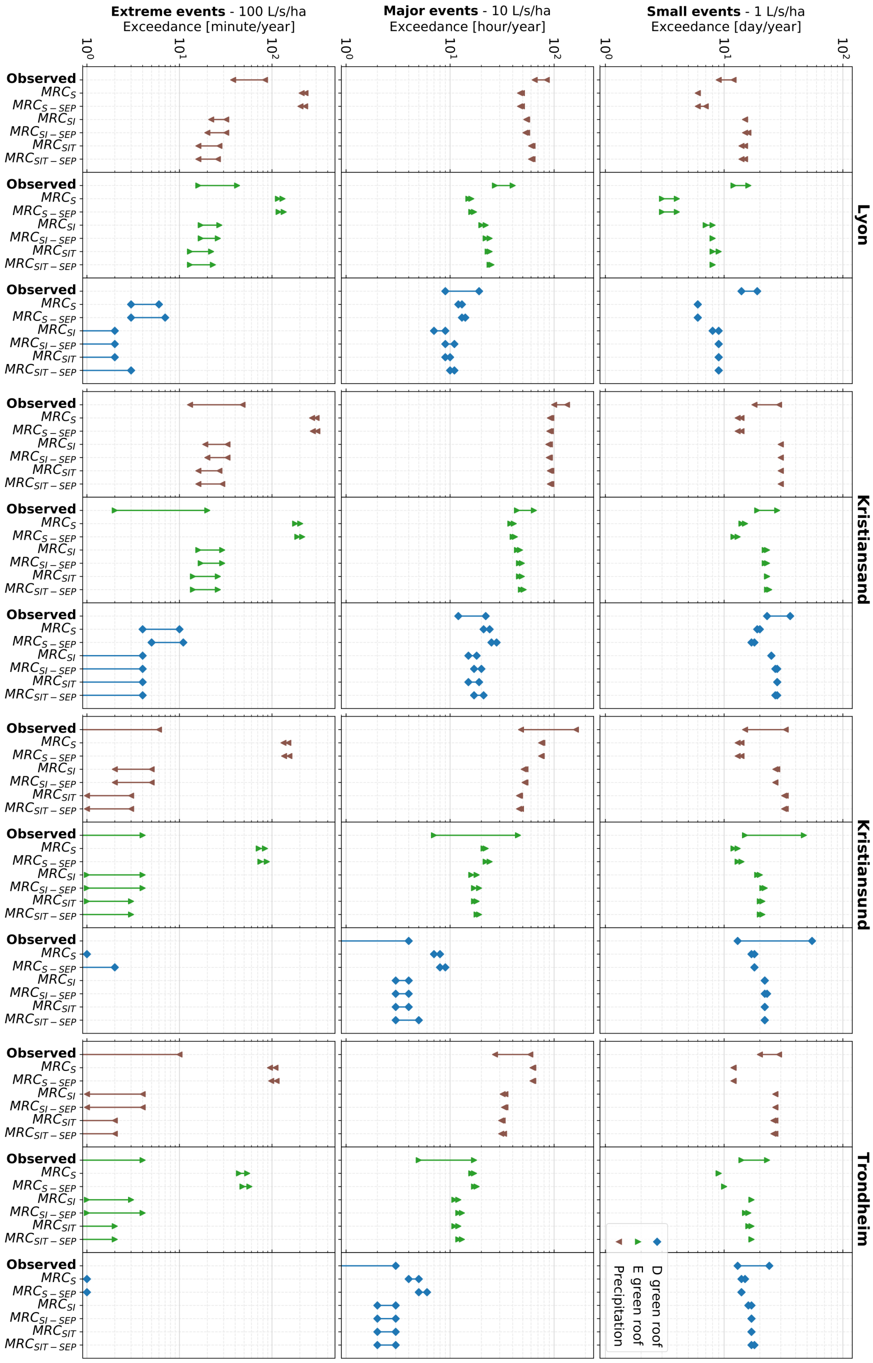

Figure B.2: Performance of the downscaled time-series in Lyon, Kristiansand, Kristiansund and Trondheim; exceedance frequency for small events, major events and extreme events. The stochastic variability linked to the downscaled time-series is evaluated with the 5^{th} to 95^{th} percentiles. $Observed$ represents the fine-resolution observed time-series or simulation using this time-series as input; The 5^{th} to 95^{th} percentiles was estimated with a 3-year moving window. Due to log axis, occurences lower than 10^0 are not visible. [Paper E - (Pons *et al.*, 2022a)]

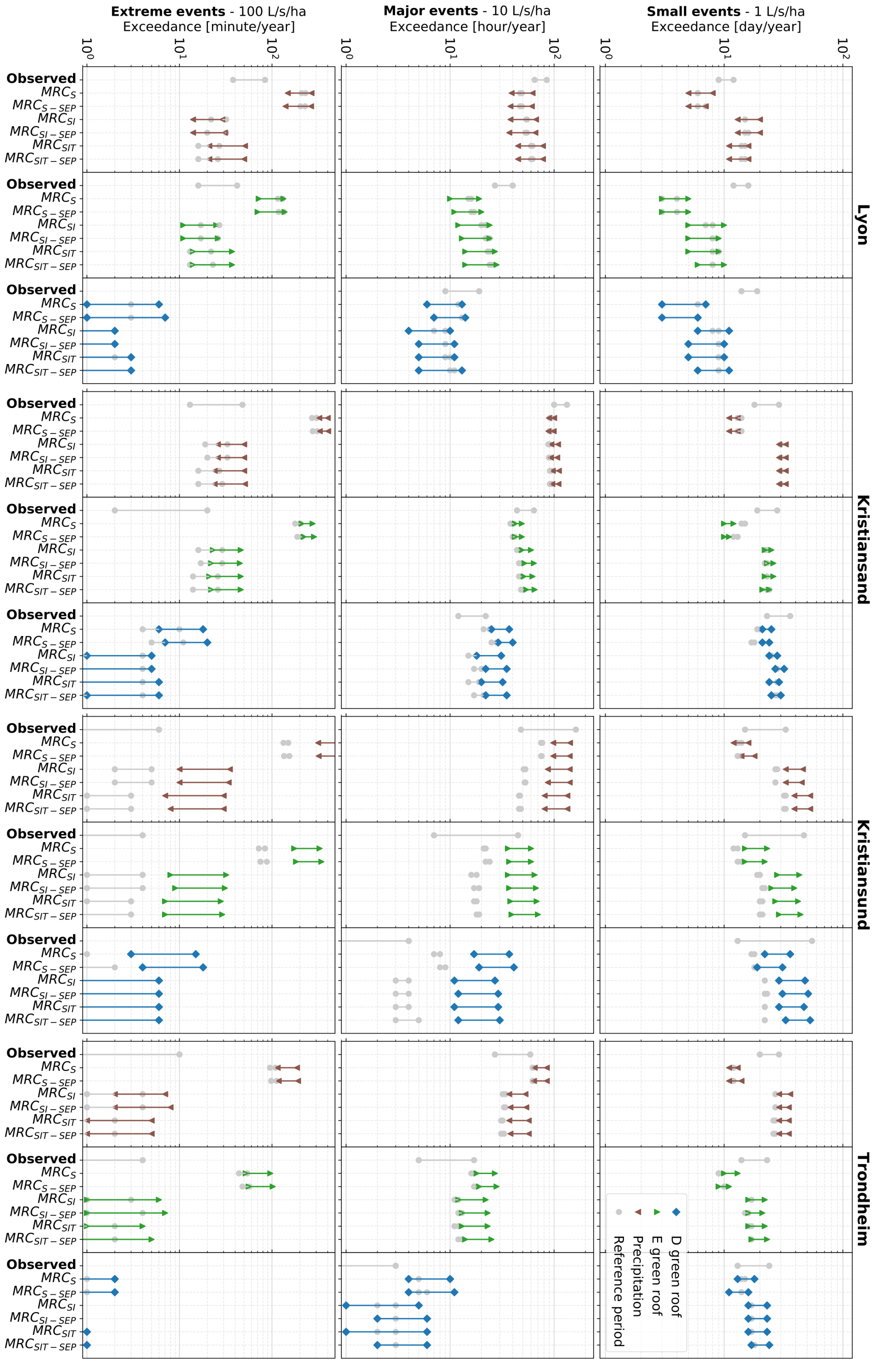

Figure B.3: Future performance of green roofs (D and E) in Lyon, Kristiansand, Kristiansund and Trondheim; exceedance frequency for small events, major events and extreme events. The stochastic variability linked to the downscaled time-series is evaluated with the 5^{th} to 95^{th} percentiles. $Observed$ represents the fine-resolution observed time-series or simulation using this time-series as input; The 5^{th} to 95^{th} percentiles was estimated with a 3-year moving window. Due to log axis, occurences lower than 10^0 are not visible. [Paper E - (Pons *et al.*, 2022a)]

C List of paper in the quantitative review

Table C.1: List of the papers included in the quantitative review

Title	DOI	Year
A case study of flow characteristics of permeable pavements by time and space model	10.1139/cjce-2013-0165	2014
A Comprehensive Analysis of the Variably Saturated Hydraulic Behavior of a Green Roof in a Mediterranean Climate	10.2136/vzj2016.04.0032	2016
A comprehensive numerical analysis of the hydraulic behavior of a permeable pavement	10.1016/j.jhydrol.2016.07.030	2016
A conceptual model for predicting hydraulic behaviour of a green roof	10.1016/j.proeng.2014.02.030	2014
A continuous simulation approach to quantify the climate condition effect on the hydrologic performance of green roofs	10.1080/1573062X.2019.1700287	2019
A Data Driven Approach to Bioretention Cell Performance: Prediction and Design	10.3390/w5010013	2013
A generic hydrological model for a green roof drainage layer	10.2166/wst.2013.294	2013
A HYDRUS model for irrigation management of green roofs with a water storage layer	10.1016/j.ecoleng.2016.06.077	2016
A long-term hydrological modelling of an extensive green roof by means of SWMM	10.1016/j.ecoleng.2016.07.009	2016
A modelling study of long term green roof retention performance	10.1016/j.jenvman.2013.09.026	2013
A modelling study of the event-based retention performance of green roof under the hot-humid tropical climate in Kuching	10.2166/wst.2017.472	2017
A modified FAO evapotranspiration model for refined water budget analysis for Green Roof systems	10.1016/j.ecoleng.2018.04.021	2018
A physics-based routing model for modular green roof systems	10.1680/jwama.18.00094	2020
A simplified approach for the design of infiltration trenches	10.2166/wst.2011.170	2011
A Simplified Model for Modular Green Roof Hydrologic Analyses and Design	10.3390/w8080343	2016
A test of porous pavement effectiveness on clay soils during natural storm events	10.1016/j.watres.2005.12.002	2006
A two-stage storage routing model for green roof runoff detention	10.2166/wst.2013.808	2014
A unified look at phosphorus treatment using bioretention	10.1016/j.watres.2015.12.015	2016
A USEPA SWMM Integrated Tool for Determining the Suspended Solids Reduction Performance of Bioretention Cells	10.14796/JWMM.C443	2018
An approach to analyze the hydrologic effects of rain gardens	10.1061/41009(333)1	2009
An assesment of green roof stormwater treatment systems for stormwater volume reduction	10.1061/40927(243)267	2007

An evaluation of applying existing bioretention sizing methods to cold climates with snow storage conditions	10.2166/wst.2007.745	2007
An evaluation of hydrologic modeling performance of EPA SWMM for bioretention	10.2166/wst.2017.464	2017
An event-based hydrologic simulation model for bioretention systems	10.2166/wst.2015.368	2015
An experimental and modeling study of evapotranspiration from integrated green roof photovoltaic systems	10.1016/j.ecoleng.2020.105767	2020
Analysing Bioretention Hydraulics and Runoff Retention through Numerical Modelling Using RECARGA: a Case Study in a Romanian Urban Area	10.15244/pjoes/79271	2018
Analysing Green Roof Effects in an Urban Environment: A Case of Bangbae-dong, Seoul	10.3130/jaabe.14.315	2015
Analysis of rainfall infiltration and its influence on groundwater in rain gardens	10.1007/s11356-019-05622-z	2019
Analytical Equation for Estimating the Stormwater Capture Efficiency of Permeable Pavement Systems	10.1061/(ASCE)IR.1943-4774.0000810	2015
Analytical Equations for Estimating the Total Runoff Reduction Efficiency of Infiltration Trenches	10.1061/JSWBAY.0000809	2016
Analytical Probabilistic Model for Evaluating the Hydrologic Performance of Green Roofs	10.1061/(ASCE)HE.1943-5584.0000593	2013
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Utilizing sensor networks to assess evapotranspiration by greenroofs	10.13031/2013.37771	2011
Variations of Roughness Coefficients with Flow Depth of Grassed Swale	10.1088/1757-899X/136/1/012082	2016
Vegetated Roof Water-Balance Model: Experimental and Model Results	10.1061/(ASCE)HE.1943-5584.0000531	2012
Vegetated roofs for stormwater management at multiple spatial scales	10.1016/j.landurbplan.2006.06.005	2007
Vegetation type alters water and nitrogen budgets in a controlled, replicated experiment on residential-sized rain gardens planted with prairie, shrub, and turfgrass	10.1007/s11252-016-0568-7	2016
Vertical and Lateral Extent of the Influence of a Rain Garden on the Water Table	10.1061/(ASCE)IR.1943-4774.0000799	2015
Viability of Green Roofs as a Flood Mitigation Element in the Central Region of Chile	10.3390/su10041130	2018
Water Balance of Soil Mixes for Rain Gardens	10.1061/9780784479889.006	2016
Water quality model for non point source pollutants incorporating bioretention with EPA SWMM	10.5004/dwt.2019.24684	2019
Water Resilience by Centipedegrass Green Roof: A Case Study	10.3390/buildings9060141	2019
Water retention and evapotranspiration of green roofs and possible natural vegetation types	10.1016/j.resconrec.2011.12.009	2012
Water retention performance of green roof technology: A comparison of canadian climates	10.1016/j.ecoleng.2018.10.006	2019
Water Runoff Characteristics in Porous Block Pavements Using an Accelerated Pavement Tester	10.1061/(ASCE)HE.1943-5584.0000949	2014
Water uptake in green roof microcosms: Effects of plant species and water availability	10.1016/j.ecoleng.2008.02.008	2008
Wet season hydrological performance of green roofs using native species under Mediterranean climate	10.1016/j.ecoleng.2017.02.025	2017

When Green Infrastructure Turns Grey: Plant Water Stress as a Consequence of Overdesign in a Tree Trench System	10.3390/w12020573	2020
WinSLAMM simulation of hydrologic performance of permeable pavements-a case study in the semi-arid lower Rio Grande Valley of South Texas, United States	10.3390/w11091865	2019

D Summary of PhD activities

D.1 Code development

During the duration of my PhD I have been involved in the development of the software URBIS developed in `Python`. This development involved mainly:

- Decoupling of the numerical engine and graphical user interface for facilitate the maintenance;
- Restructuration of the internal variable to homogenize the code
- Development of a vectorized solver to make sensitivity and uncertainty analysis more easily available.
- Implementation of the irrigation engine for green roofs

The results from the downscaling work and the development of HIDES were implemented in a `Python` package to make it possible to spread their use and make it available.

D.2 Teaching and supervision

During the first and second year of my PhD, I have been teaching assistant in 2 courses at NTNU in the VA group.

TVM4130 - Urban Water Systems coordinated by Tone Merete Muthanna. My contribution in this course involved:

- Exercise hour (2h per week during 2 semesters);
- Lecture on Uncertainty in models and mesurement;
- Lecturm on modelling;
- Development of a group project;
- Development of a MCQ with honesty incentive notation;
- Grading of exercises, group projects and term paper.

TVM4141 - Water and Wastewater Systems, Advanced Course coordinated by Tone Merete Muthanna. My contribution in this course involved:

- Exercise hour (2h per week during 2 semesters);
- Lecture on paradigm shift in urban water system;
- Lecture on introduction to `Python`;
- Grading of exercises.

The PhD involved the supervision, occasional or continuous, of several master students, both at INSA Lyon and NTNU.

E Extended summary in French - résumé étendu

The current extended summary constitute a requirement according to the cotutelle agreement between NTNU and INSA Lyon. Le présent résumé étendu est fourni conformément aux exigences de l'accord de cotutelle entre NTNU et l'INSA Lyon.

Les défis de la gestion des eaux pluviales au 21ème siècle sont nombreux et dans le contexte de cette thèse, on peut mentionner l'urbanisation, le changement climatique, les ressources limitées, la gestion des infrastructures existantes et vieillissantes, l'évolution des pratiques liée au changement de paradigme dans la philosophie de gestion des eaux pluviales. En effet, au cours des dernières décennies, un changement de paradigme a été opéré dans les villes européennes, passant d'un système d'infrastructures centralisé, résistant et invisible (i.e., sous terrain), visant invisibiliser la présence de l'eau et à l'évacuer des villes aussi vite que possible, à un système décentralisé dans lequel l'eau apparaît également en surface et qui vise à être plus résilient. L'objectif est de traiter la plus grande quantité d'eau possible le plus près possible de la source, de gérer la majeure partie volumes restant avec les infrastructures dites ≪ traditionnelles ≫ existantes et d'adopter une approche de priorisation et de gestion des risques pour gérer les événements les plus extrêmes. Alors que le sujet des techniques de gestion à la source des eaux pluviales devient de plus en plus central en raison de ses multiples avantages, il est important de se demander si elles peuvent réellement délivrer les services que nous leur prêtons. La présente thèse s'intéresse au développement de méthodes pour évaluer les performances futures des techniques de gestion à la source des eaux pluviales et à évaluer dans quelle mesure elles peuvent être pertinentes à des fins hydrologiques.

L'un des défis que les services de gestion des d'eau pluviale doivent relever est l'urbanisation croissante. La question de l'urbanisation croissante ne consiste pas seulement en un changement d'usage des sols, mais consistes aussi en prendre en compte ses conséquences sur les centres historiques, par exemple. En effet, dans de nombreuses villes européennes, les centres-villes sont organiques et très denses en l'état actuel d'urbanisation. C'est pourquoi l'urbanisation des bassins versants en amont peut avoir une influence sur les bassins versants déjà urbanisés où il est complexe et coûteux d'installer de nouvelles infrastructures.

Le changement climatique peut être interprété comme un changement dans les statistiques météorologiques. De ce point de vue, l'adaptation consiste à ajuster le service fourni par nos infrastructures à ce changement. Cependant, cette explication est trop simpliste puisque les pratiques actuelles de gestion des eaux pluviales ne sont pas adéquates. Un simple changement de niveau de service de nos infrastructures n'est pas suffisant pour résoudre le problème lié au changement climatique. De plus, la morphologie des villes influence nos habitudes qui, à plus grande échelle, peuvent être comprises comme une boucle de rétroaction entre la société humaine et le climat ou le climat local. Par exemple, l'effet de la bétonisation, artificialisation et imperméabilisation des sols dans les villes entraîne un effet d'îlot de chaleur, créant un problème majeur de confort urbain. De plus, cela peut également influencer microclimat, et en particulier l'occurrence de pluies convectives (Bornstein and Lin, 2000; Hettiarachchi *et al.*, 2018). Cela signifie que, dans une certaine mesure, il existe une relation bidirectionnelle entre le climat ou le climat local et la société humaine et ses infrastructures urbaines.

Les objets d'étude de la présente thèse sont les technique de gestion à la source des eaux pluviales, infrastructures généralement végétalisées (mentionnées comme ≪ *Green Infrastructure – GI* ≫ en anglais dans le corps principal de la thèse). Cette terminologie a de nombreux équivalents dans différentes régions du monde, et sa définition évolue avec les années (Fletcher *et al.*, 2015; Matsler *et al.*, 2021). Dans le cadre de la présente thèse, il s'agit d'infrastructures multifonctionnelles qui ont notamment une fonction hydrologique. Celle-ci consiste à : i) gérer localement les pluies quotidiennes au plus proche de la source, ii) atténuer dans une certaine mesure les pluies majeures, et iii) contribuer à la gestion des pluies extrêmes. Il s'agit par nature de solutions décentralisées, qui visent à imiter le cycle naturel de l'eau. Dans certains contextes, ≪ *Green Infrastructure* ≫ peuvent faire référence à de larges infrastructures, mais dans le cadre de cette thèse, elles font référence à des infrastructures plus petites telles que les toitures végétalisées, les jardins de pluie, des noues végétalisées, les tranchées d'infiltration, les chaussées perméables, etc. Afin de restaurer le cycle naturel de l'eau, elles s'appuient sur des processus dit "naturels", même dans une certaine mesure si ces processus utilisés via des méthodes ingénieures de dimensionnement pour satisfaire un niveau de service. Cela implique par exemple une conception de substrat ayant les propriétés recherchées d'infiltration, ou la sélection de végétation et d'engrais permettant d'atteindre des objectifs. En ce sens le terme de solution fondées sur la nature est à relativiser puisqu'il s'agit parfois plus d'un procédé rhétorique d'appel à la nature que d'une réelle renaturation des milieux. Ces processus ≪ naturels ≫ sur lesquels sont basés ces infrastructures sont principalement i) l'évapotranspiration qui permet de soustraire de façon permanente un volume d'eau à déverser dans le système de canalisations, ii) l'infiltration verticale qui consiste à infiltrer l'eau directement dans le sol natif et qui permet également de soustraire un volume d'eau de façon permanente du système de canalisation, et iii) l'infiltration horizontale et le ruissèlement qui consiste à atténuer en surface ou dans la couche de sol ou de substrat superficielle les événements pluvieux afin de réduire les débits de crête déversés dans le système.

Dans ce contexte, la présente thèse comporte plusieurs dimensions de réflexion afin de faire avancer le front de connaissances et d'étudier la contribution potentielle des techniques de gestion à la source des eaux pluviales à la philosophie de gestion intégrée des eaux pluviales. La première est la question des indicateurs de performance, en effet, il est nécessaire d'étudier quels indicateurs de performance transmettent le mieux l'information, et à partir des données de modélisation comment extraire les informations pertinentes. Cela amène également la question suivante : "Sur quel indicateur devrions-nous conseiller aux décideurs de baser leur décision ?". La deuxième dimension est liée aux incertitudes. En effet, le problème de la gestion des eaux pluviales et de l'adaptation au changement climatique implique des incertitudes à plusieurs niveaux. Elle est liée à plusieurs niveaux d'incertitudes profondes, qui peuvent être dues à des connaissances limitées (épistémiques) ou inhérentes aux processus étudiés (aléatoires). Dans le contexte de la modélisation, elle est notamment liée à un processus particulier de propagation d'incertitude en. En effet, les modèles climatiques globaux sont basés sur des données incertaines, et doivent encore être améliorés en termes de conceptualisation, leurs résultats sont utilisés dans des modèles climatiques régionaux qui ont eux-mêmes leurs propres incertitudes structurelles. Ces résultats sont ensuite utilisés avec un modèle de correction de biais et de descente d'échelle statistique (*statistical downscaling*) pour se rapprocher d'une échelle où les données peuvent être utilisées. Ces données, même si l'on parvient à quantifier les sources d'incertitudes précédemment mentionnées, sont basées sur des scénarios socio-économiques qui comporte plusieurs niveaux d'incertitudes dites qualitatives (i.e., non quantifiable). Ces données incertaines issues de la descente d'échelle constituent les données d'entrée utilisée dans cette thèse. Cette thèse de doctorat est elle-même constituée d'une chaîne de modèles qui accroît encore la propagation en cascade d'incertitudes. Elle précise donc les questions précédemment mentionnées : "Dans le contexte d'incertitude lié à cette thèse, comment transmettre l'information sur l'incertitude afin de guider au mieux la prise de décision". Enfin, la question de l'échelle est centrale dans la présente thèse. En effet, alors que la première partie de cette thèse est principalement dédiée aux techniques de gestion à la source des eaux pluviales à l'échelle du site, les décideurs doivent guider à un niveau stratégique à l'échelle de la ville. Par conséquent, les connaissances à l'échelle du site doivent être pertinentes lorsqu'elles sont intégrées dans une chronologie et mises à l'échelle du bassin versant ou de la ville.

L'objectif principal de la recherche est de fournir des connaissances et des méthodes pour évaluer le potentiel des techniques de gestion à la source des eaux pluviales pour l'adaptation au changement climatique. En particulier :

- Quelles sont les données disponibles, et quelles sont celles qui doivent être ciblées à des fins de modélisation ?

- Comment utiliser les données climatiques disponibles et comment les amener à la résolution nécessaire pour les modèles hydrologiques des infrastructures vertes ?

- Comment utiliser à la fois les données climatiques et les modèles hydrologiques de techniques de gestion à la source des eaux pluviales, et comment extraire les indicateurs de performance pertinents ?

- Comment transposer ces connaissances à d'autres échelles spatiales, notamment à l'échelle du quartier ou du petit bassin versant ?

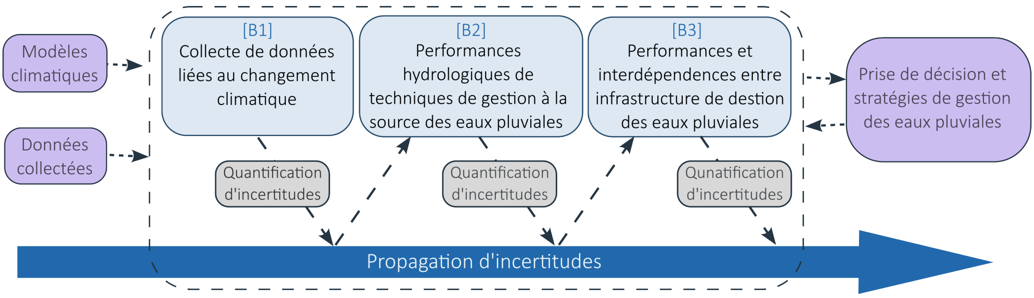

Figure E.1: Organisation de la présente thèse de doctorat, délimitées par la région pointillées. La thèse est présentées en trois subdivision interconnectées (B1, B2 et B3).

Le manuscrit est organisé en 6 chapitres. Tout d'abord, la plupart des concepts et notions pertinents à cette thèse sont introduits dans le CHAPITRE 1. Dans ce chapitre, les notions liées à l'utilisation des modèles numériques sont introduites. Cela comprend une section sur la calibration et les tests et une section sur la gestion des incertitudes. Ensuite, le concept d'échelle et l'articulation entre données et informations sont détaillées car elles occupent une place centrale dans la présente thèse. Après l'introduction de ces concepts, une section sur l'adaptation au changement climatique présente les concepts clés et l'état de l'art des modèles climatiques et comment ils sont utilisés pour aider à atténuer les effets changement climatique. Enfin, les techniques de gestion à la source des eaux pluviales, objet principal de cette thèse, sont analysées en termes de fonction, de pratique de modélisation et de performance. Il est montré que les pratique académiques de modélisation dans ce domaine manquent de transparence et en particulier de prise en compte des incertitude. De plus le choix des données lié au calade et test de modèles est rarement justifié. Cela constitue des limitations claire à la planification de stratégies d'adaptation au changement climatique alors même, comme il a été détaillé plus haut, que les données liées aux changement climatiques et leur choix sont en bout d'un chainage de modèles qui entraine une propagation en cascade d'incertitude. Ce diagnostic de l'état de l'art motive la structure de la thèse présentée sur la Figure E.1.

Suite à cette introduction, le CHAPITRE 2 se concentre sur la question des données pertinentes pour l'adaptation au changement climatique. Il consiste notamment à utiliser des pluies artificielles pour évaluer les performances futures des toits végétalisées. L'objectif sous-jacent est la collecte de données hors du domaine des données observables, ou plus exactement des données qu'il est probable de collecter lors d'une campagne courte : les événements extrêmes. La principale contribution de ce chapitre à la thèse est donc le développement d'un modèle, basé sur les données collectées, qui est utilisé comme modèle de référence dans la plupart des chapitres suivants. En effet, les données collectées permettent de calibrer un modèle en dehors de la gamme des données observable puisque le simulateur de pluie peut stimuler les toitures hors des conditions climatique. Il en résulte un modèle avec un simple conceptualisation et fiable à bas débits comme à haut débits. Il est aussi montré que les deux toitures de références ont un comportement hydrologique différent et sont sensibles à des événements pluvieux différents, notamment en terme de hyétographe. Cet aspect est clé pour la suite de la thèse puisqu'il permet fournit des solutions de références qui bornent une large variété de comportement ce qui aide afin de généraliser dans une certaine mesure les résultats suivants.

Le CHAPITRE 3 est consacré à la question des indicateurs de performance. Il s'interroge notamment sur l'influence des données d'entrées limitées et leur influence sur les performances. Comment prendre en compte la variabilité naturelle du climat et la chaîne d'incertitude liée à la modélisation climatique et comment la propager à la performance. Plus généralement, il aborde la question des informations à apporter aux décideurs à partir des données produites par la simulation. En particulier, il est montré que même en disposant d'une large base de données d'entrée, il y a un risque de communiquer des informations limitées voire prompte à induire en erreur. Ainsi il est suggéré de prendre en compte la variabilité climatique lors de la formulation d'indicateurs de performances. Il est aussi discuté de la pertinence de l'utilisation d'indicateur de nature probabiliste. Les indicateurs probabiliste sont parfois décriés comme incompréhensible pour un public non-sachant, mais comme montré par Pappenberger and Beven (2006) il s'agit d'un argument fallacieux. En effet, il peut s'agir simplement d'un problème de formulation ou de communication qui doit nécessairement être pris en compte en raison de la nature incertaine des performances liées aux mesures d'adaptation au changement climatique.

Le CHAPITRE 4 présentent une approche pour produire des séries synthétiques de précipitation futures à haute résolution temporelle. L'approche se base sur un couplage aux modèles hydrologiques toitures végétalisées afin d'évaluer si les séries synthétiques sont pertinentes en termes d'évaluation de performances hydrologiques. Elle consiste en particulier à développer un modèle de descente d'échelle (*downscaling*), à savoir les cascades multiplicatives aléatoires (MRC). Les modèles sont testés en utilisant les modèles de toitures végétalisées en supposant que la capacité à reproduire les performances des toitures végétalisées sur la base des séries temporelles haute résolution observées avec les séries temporelles haute résolution réduites signifie que les modèles de descente d'échelle d'échelle atteignent leur objectif. Un des modèles de MRC développés utilise un dépendance température-précipitation afin de générer les séries synthétiques ce qui permets une meilleure fiabilité en climat incertain futur. La structure des modèles de MRC est testée sur 8 villes (6 en Norvège, 2 en France) afin de montrer la pertinence des équations sur des climats européens variés.

Le CHAPITRE 5 se base sur la somme des résultats des chapitres précédents. Il présente un cadre visant à évaluer la performance hydrologique des techniques des gestion à la source des eaux pluviales pour plusieurs objectifs et la prise en compte du changement climatique en se basant sur les modèles de descente d'échelle développés dans le chapitre précédent. Du point de vue de la gestion des eaux pluviales, l'objectif de ce cadre est de réaligner les pratiques sur les principes d'une prise de décision robuste. Il s'agit plus formellement de proposer comment les objectifs formulés à une échelle stratégique (à l'échelle d'une ville et sur des échelles de temps longues de l'ordre de la dizaine d'année) peuvent être reformulés à une échelle plus opérationnelle (donc à l'échelle d'une infrastructure). Le cadre vise à quantifier un large spectre de performances hydrologiques pour chaque solution. En particulier : i) les performances d'infiltration et d'évapotranspiration pour gérer les pluies journalières, ii) les performances d'atténuation pour les pluies de l'ordre de grandeur de la pluie de dimensionnement, iii) le comportement de l'infrastructure sous événements plus extrêmes que la pluie de dimensionnement (le comportement en domaine de défaillance). En particulier cela permet de montrer que les méthodes actuelles de dimensionnement ne sont pas adaptées et entraine une mauvaise prise de décision, et que leur approche simpliste ne permet pas de discriminer des infrastructures en fonction de leur robustesse. La robustesse d'une solution (i.e., sa capacité à soutenir une large gamme de sollicitation) étant une qualité clé dans le cadre de l'adaptation au changement climatique, il est alors suggéré d'utiliser le cadre d'évaluation HIDES développé ici afin d'évaluer les performance hydrologiques (Figure E.2).

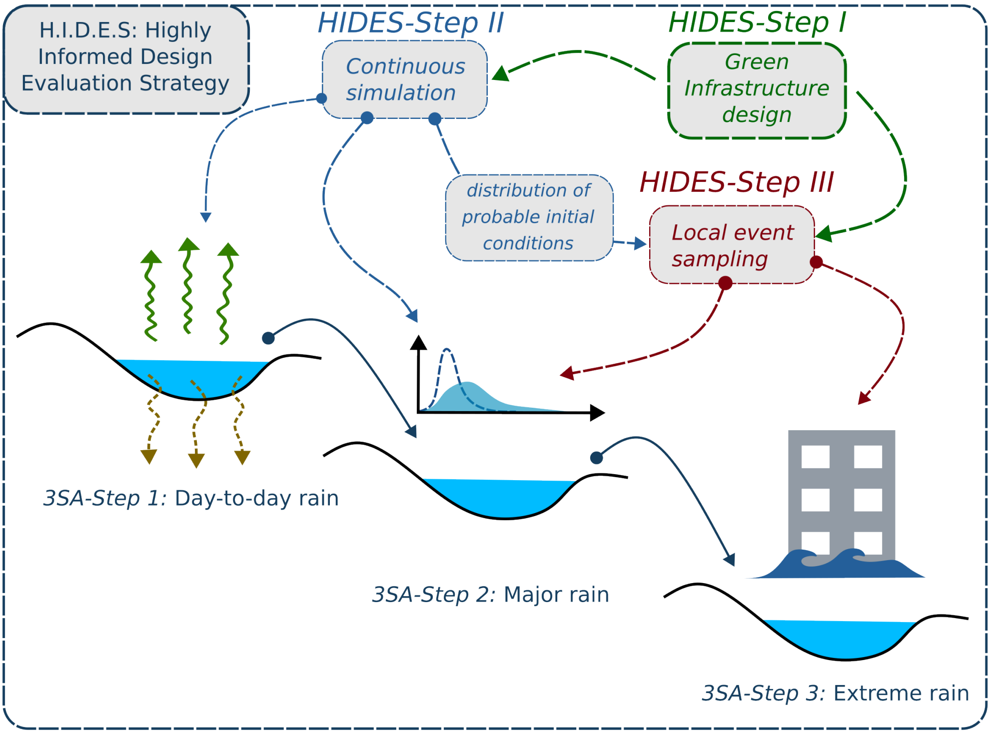

Figure E.2: Cadre d'évaluation des technique de gestion à la source des eaux pluviales HIDES (*Highly Informed Design Evaluation Strategy* - stratégie d'évaluation informée des méthodes de dimensionnement).

Le dernier chapitre, le CHAPITRE 6, vise à combler l'écart entre les modèles hydrologiques de techniques de gestion à la source des eaux pluviales à l'échelle de l'infrastructure et les modèles à l'échelle du bassin versant et de la ville. Plus précisément, il vise à utiliser le cadre d'évaluation HIDES précédemment développé pour identifier l'influence des interdépendances entre les infrastructures sur les performances à l'échelle d'un lotissement. Elle examine si, à une échelle intermédiaire entre l'unité et le bassin versant, la combinaison d'infrastructures a une influence. L'étude montre que dimensionner individuellement à l'échelle de l'infrastructure ne signifie pas qu'à l'échelle du lotissement les objectifs seront atteint. Cela implique que les dimensionnements individuels en plus de poser des questions de gouvernance ne sont pas fiable, et que dimensionner en prenant en compte le système est plus pertinent. Il est aussi montré qu'étant donné une configuration de solution dans le lotissement, les performances sont sensibles aux permutations. Cela signifie que même lorsque les délais entre les infrastructures sont très courts (en dessous de 2 minutes) le positionnement exact peut influencer les performances. Une analyse par scénario d'implémentation montre aussi que dans certain cas avoir des maisons sans infrastructure de gestion peut bénéficier à l'échelle du lotissement.

Pour conclure cette thèse présente des outils méthodologiques permettant de quantifier les performances hydrologiques futures de techniques de gestions à la source des eaux pluviales, en portant une attention particulière sur la prise en compte des incertitudes liées aux données d'entrée à la reformulation des données de sortie en information pertinente pour une prise de décision. Les résultats et le cadre formulés à l'échelle de l'infrastructure est reformulé à l'échelle du lotissement afin de questionner les pratiques actuelles de modélisation à l'échelle de la ville. En particulier il est montré que les interactions entre infrastructures, qui restent souvent négligées dans les approches à l'échelle de la ville en raison de couts de calculs, influencent les performances et devraient donc être étudiées plus en détails.

En raison des hypothèses des hydrologiques modèles actuels, certains modes de défaillances théoriques, notamment liés aux sècheresses et à la mortalité de végétation ne sont pas directement quantifiés dans le présent manuscrit. En revanche le cadre développé dans cette thèse permet l'utilisation de tels modèles. Il est donc suggéré d'améliorer les modèles actuels afin de prendre en compte l'influence de défaillances sur les performances. En effet, les modèles hydrologiques actuels reposent aujourd'hui sur des hypothèses fortes de stationnarité des paramètres et de non-défaillance qui manquent de réalisme puisqu'ils négligent l'évolution des infrastructures et leur maintenance. La présente thèse ouvre un champ de possibilité au travers de l'utilisation des outils développés et l'amélioration des modèles actuels afin de réaligner les objectifs de gestion intégrées des eaux pluviales dans le cadre de l'adaptation au changement climatique et au changement de morphologie des villes et les pratiques de modélisation.

F Co-authorship statements for the Publications used in the PhD thesis

Encl. to application for assessment of PhD thesis

Faculty of Engineering

NTNU

STATEMENT FROM CO-AUTHOR

(cf. section 10.1 in the PhD regulations)

Vincent Pons applies to have the following thesis assessed:

The future of Green Infrastructure: From climate data to informed hydrological performance

*) The statement is to describe the work process and the sharing of work and approve that the article may be used in the thesis.

*)

Statement from co-author on article: **Detention-based green roofs for stormwater management under extreme precipitation due to climate change,** Hamouz, V., Pons, V., Sivertsen, E., Raspati, G., Bertrand-Krajewski, J.-L., and Muthanna, T. M. (*Blue-Green Systems, 2020, Doi: 10.2166/bgs.2020.101*)

As a co-author, I have contributed with supervision of the work, discussion of results and methods and comments through the writing process.

Vincent Pons has made a major contribution in the conceptualization, methodology, experiments, data analysis, visualization, and writing of the original draft.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Vincent Pons

Trondheim, 2023-02-22

Place, date

Signature co-author, Edvard Sivertsen

*)

Statement from co-author on article: **Revising green roof design methods with downscaling model of rainfall time series,** Pons, V., Muthanna, T. M., Sivertsen, E., and Bertrand-Krajewski, J.-L. (*Water Science and Technology, 2021, Doi: 10.2166/wst.2022.023*)

As a co-author, I have contributed with supervision of the work, discussion of results and methods and comments through the writing process.

Vincent Pons has made a major contribution in conceptualization, methodology, simulations, visualization and writing of the original draft.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Vincent Pons

Trondheim, 2023-02-22

Place, date

Signature co-author, Edvard Sivertsen

*)
Statement from co-author on article: **Forecasting green roof detention performance by temporal downscaling of precipitation time-series projections,** Pons, V., Benestad, R., Sivertsen, E., Muthanna, T. M., and Bertrand-Krajewski, J.-L. (*Hydrology and Earth System Sciences, 2022. Doi: 10.5194/hess-26-2855-2022*)

As a co-author, I have contributed with supervision of the work, discussion of results and methods and comments through the writing process.

Vincent Pons has made a major contribution in conceptualization, methodology, simulations, visualization and writing of the original draft.

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Trondheim, 2023-02-22
Place, date

Signature co-author, Edvard Sivertsen

*)
Statement from co-author on article: **The practice makes the model: a critical review of green infrastructure hydrological modelling practice**, Pons, V., Abdalla, E. M. H., Tscheikner-Gratl, F., Alfredsen, K., Sivertsen E., Muthanna T. M. (*Under review in Water Research*)

As a co-author, I have contributed with supervision of the work, discussion of results and methods and comments through the writing process.

Vincent Pons has made a major contribution in conceptualization, methodology, data collection, data analysis, visualization and writing of the original draft.

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Oslo 2023-02-27 Rasmus Benestad

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G List of Figures

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