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Erle Kristvik

Climate-Informed Planning and Design of Urban Water Systems

Doctoral thesis

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Abstract

Global warming is expected to cause alterations of the climate with potential impacts on urban water systems. As the knowledge base on climate change expands, and regional climate projections become increasingly available to local water managers, the need for climate-informed tools and decision-support systems rises.

This thesis seeks to address local stakeholders needs for novel tools and frameworks for facilitating climate adaptation and to investigate how climate projections can inform the analyses. The work of this thesis has been conducted as part of the H2020 project BINGO - Bringing INnovation to onGOing water management - *a better future under climate change* (Grant Agreement number 641739), where the principal goal has been to provide end-users in the water sector with *practical* tools and knowledge on climate change.

The thesis specifically attends to three main applications of urban water systems: 1) drinking water availability planning, 2) storm water infrastructure design, and 3) urban drainage systems planning. To support the overall aims of the thesis, the following objectives were defined:

1. Investigate local climate projections and their potential to provide decision-support in local climate adaptation
2. Evaluate climate projections' applicability for design in current stormwater management practice in Norway
3. Develop climate-informed adaptation frameworks for Norwegian urban water systems

To pursue these objectives, a collection of regional climate projections for the city of Bergen, Norway, was produced, processed and assessed through various tools and techniques. This resulted in a rich ensemble of climate projections for the city, covering a range of emissions scenarios, parent global climate models, and downscaling methods. These projections have further been used as input to hydrologic and hydraulic models embraced by the three defined water sector applications. Through this, the application of climate projections in planning and design of urban water systems was demonstrated and assessed, and frameworks providing decision-support were proposed.

The assessment of the resulting climate projection ensemble emphasizes the general consensus in research that ensemble approaches are necessary to gain a holistic and reliable indication of future local climates, as choices of emissions scenario, parent GCM, predictor, and downscaling techniques all introduce their own range of uncertainty. This implies that climate projections should not be further applied in a traditional *predict-then-act* manner, but rather treated as what they are: possible scenarios of future climate, sooner than predictions, and ensembles rather than singular best-guess estimates.

To emerge at climate-informed design practices in Norway, the results of this thesis strongly suggest that existing tools and methods should be adjusted to handle a range of input scenarios rather than single event or time series inputs. This would allow a shift from prediction-based design, to a risk-oriented design of urban water systems and system components.

Finally, three main decision-support frameworks are proposed for climate adaptation in the water sector. The three frameworks incorporate a new dimension of climate change information into traditional tools known to the water sector. In addition to addressing the third, and last objective of this thesis, they also contribute to the principle goal of the BINGO project: to provide end-users in the water sector with *practical* tools and knowledge on climate change. Although the results are site specific, linking frameworks to existing tools ensures scalability and transferability of methodologies.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) in partial fulfillment of the requirements for the degree of Philosophiae Doctor (PhD).

The work is the result of a four-year PhD program conducted at the Department of Civil and Environmental Engineering. Associate Professor Tone Merete Muthanna has been the main supervisor and Professor Knut Alfredsen has been co-supervisor. The PhD position was allocated to 25% teaching and 75% research. Teaching activities included assisting in organization of the course TVM4141 - *Water and Wastewater Systems, Advanced Course*, co-supervising of master students, and participating in writing workshops with master students writing their thesis in a scientific paper format.

The PhD position was financed through the H2020 project BINGO - Bringing INnovation to onGOing water management - *a better future under climate change.* The BINGO project has received funding from the Europeans Union's Horizon 2020 Research and Innovation program, under the Grant Agreement number 641739.

In accordance with the guidelines of the Faculty of Engineering Science and Technology, the thesis comprises an introduction to the research and five scientific papers.

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Acknowledgements

First and foremost, I would like to thank my principal sponsors at NTNU's Department of Civil and Environmental Engineering: My supervisor, Tone Merete Muthanna, for her encouragement, inspiration, pragmatism, constructive feedback, and support in all work resulting in this thesis. My co-supervisor, Knut Alfredsen, for fruitful discussions and in-depth problem solving on research methods. And, finally, Sveinung Sægrov, who conceived in me the idea of pursuing a PhD – and has supported my pursuit through to the end. I could not have wished for better guidance than that provided by the three of you.

I would like to thank all my dear colleagues of the BINGO Project - the "BINGOlians". I am grateful for close collaborations with a broad set of stakeholders at Bergen Municipality, especially Marit Aase and Magnar Sekse who have provided all the material I needed and who have been invaluable discussion partners. You have helped me frame my research pursuits so that it could result in real-life application and practical value. A special thanks also goes to the Badalona team whom I have had the pleasure of working closely with during my 2-month stay in Barcelona. I am indebted to my talented co-authors: Ashenafi Seifu Gragne, Birgitte Gisvold Johannessen, Clemens Strehl, Guro Kleiven, and Jardar Lohne. Without you, this work would not have resulted in five scientific papers. I would also like to thank additional co-authors Birthe Riisnes, Byman Hamadudu, Aynalem Tasachew, and Marie Pontoppidan for rewarding research collaborations during this past four years, and the master students I have had the pleasure of working with – Guro, Guro, Thea, Malene, and Lise Berit. You have all been a true source of inspiration. I am so very grateful to all my dear colleagues at the department – and especially Noemi, Ana, Ragnhild, and Vladimir whom I now also consider dear friends.

A big thank you to my dear friends and family who have encouraged and believed in me while I have carried out this work. And a special thanks to Jennifer, Kyrre, Mats, and 'Pakken' for bringing joy to every day and for being the very best cheerleaders! Last but not least, I am forever grateful to my beloved husband, Pål, for his unlimited love, support and patience. Although these words are mine, this thesis is yours.

I am forever grateful but, nonetheless, all errors are my own.

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List of Abbreviations

AM	Annual Maxima
BINGO	Bringing INnovation to onGOing water management
BLRP	Bartlett-Lewis Rectangular Pulse
BMP	Best Management Practice
BRC	Bioretention Cell
CER	Cost-Effectiveness Ratio
CF	Change Factor
CI	Climate Index
CLM	CLimate Mode
CMIP	Coupled Model Intercomparison Project
CoP	Community of Practice
COSMO	Consortium for Small-scale Modeling
CSO	Combined Sewer Overflow
DB	Detention Basin
EOF	Empirical Orthogonal Function
ESD	Emperical-Statistical Downscaling
ESM	Earth System Model
FUB	Freie Universität Berlin
GCM	Global Climate Model
GEV	Generalized Extreme Value
GPD	General Pareto Distribution
GR	Green Roof
HBV	Hydrologiska Byråns Vattenavdelning
IDF	Intensity-Duration-Frequency
ISO	International Organization for Standardization
K_{sat}	Saturated hydraulic conductivity
KNN	K-Nearest Neighbor
LID	Low Impact Development
MET	Norwegian Meteorological Institute

MPI	Max Planck Institute
NBS	Nature-Based Solutions
NCAR	National Center for Atmospheric Research
NCCS	Norwegian Center for Climate Services
NCEP	National Centers for Environmental Prediction
NOK	Norwegian krone
PCA	Principal Component Analysis
PD	Peak Delay
PI	Performance Indicator
POT	Peak Over Threshold
RCP	Representative Concentration Pathway
REA	Reliability Ensemble Average
REF	Reference
RG	Raingarden
SD	Statistical Downscaling
SUDS	Sustainable Urban Drainage Systems
SWMM	Stormwater Management Model
UDS	Urban Drainage System
WAI	Water Availability Index
WP	Work Package

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Contributions

Original papers

This thesis is primarily based on the following five scientific papers:

Paper I: Assessment of future water availability under climate change, considering scenarios for population growth and ageing infrastructure

Kristvik E., Muthanna, T. M., and Alfredsen, K. (2018)

Journal of Water and Climate Change, **10**(1), 1-12. DOI:10.2166/wcc.2018.096

Paper II: Assessing the robustness of raingardens under climate change using SDSM and temporal downscaling

Kristvik, E., Kleiven, G. H., Lohne, J., and Muthanna, T. M. (2018)

Water Science and Technology, **77**(6), 1640-1650. DOI:10.2166/wst.2018.043

Paper III: Temporal downscaling of IDF curves applied to future performance of local stormwater measures

Kristvik, E., Johannessen, B. G., and Muthanna, T. M. (2019)

Sustainability, **11**(5), 1231. DOI:10.3390/su11051231

Paper IV: Long term simulations of combined sewer overflows for climate adaptation planning

Kristvik, E., Gragne, A. S., Muthanna, T. M., and Alfredsen, K. (2019)

Manuscript ready for submission

Paper V: Cost-effective solutions for climate adaptation of urban drainage systems

Strehl, C., Kristvik, E., Koti, J., and Muthanna, T. (2019)

Submitted for review in Urban Water Journal

Other Contributions

Supplementary peer-reviewed journal papers

Hydrological assessment of water resources in Bergen

Kristvik, E., Riisnes, B. K., and Hamududu, B. H. (2016)

VANN **51**(1)

Impacts of climate change on flood frequency and small rural catchments using parsimonious rainfall-runoff model

Tasachew, A., Pontoppidan, M., Kristvik, E., Alfredsen, K., and Muthanna, T. M. (2019)

Submitted for review in Natural Hazards and Earth System Sciences

Conference presentations

Seasonal variations in climate and the performance of stormwater collection systems (Oral presentation)
Kristvik, E.[1], and Muthanna, T. M.
14th IWA/IAHR International Conference on Urban Drainage (ICUD)
10-15 Sep 2017, Prague, Czech Republic

Comparison of two stochastic methods for disintegrating daily precipitation to a sub-hourly series (Poster presentation)
Kristvik, E.[1], Gragne, A. S., Muthanna, T. M., and Kpogo-Nuwoklo, K.
European Geoscience Union (EGU)
8-13 April 2018, Vienna, Austria

BINGO Project: Impacts of Climate Change on the Urban Water System - A case study from Bergen (Oral presentation)
Muthanna, T. M., Kristvik, E.[1], Sægrov, S., Sekse, M.
4th European Climate Change Adaptation conference (ECCA)
28–31 May 2019, Lisbon, Portugal

Digital Solutions for Early Phase Stormwater Planning (Poster presentation)
Stokseth, G., Kristvik, E.[1], Sandoval, S., Lohne., J., and Muthanna, T. M.
10th International conference on Urban water planning and technologies for sustainable management (NOVATECH)
1–5 July 2019, Lyon, France

[1]Presenting author

Contributions to the BINGO project

The candidate has co-authored a selection of BINGO reports (Table 1) and contributed to the planning and facilitation of BINGO organized workshops for the Community of Practice (CoP) at the Bergen Research site (Table 2). The BINGO reports are publicly available at: http://www.projectbingo.eu/content/deliverables (except those marked as *Confidential*).

Report	Title	Year
BINGO D3.1	Characterization of the catchments and the water systems	2016
BINGO D3.2	Future Land and Water Use Scenarios	2016
BINGO D3.3	Calibrated water resources models for past conditions	2016
BINGO D3.4	Model results for water and land use scenarios completed and analysed	2018
BINGO D3.5	Improved model applications/descriptions to the six research sites based on field data	2019
BINGO D3.6	Optimized water resources models to support management strategies at the six research sites	2019
BINGO D4.1	Context for risk assessment at the six research sites, including criteria to be used in risk assessment	2016
BINGO D4.2	Risk identification, relevant hazards, risk sources and factors (*Confidential*)	
BINGO D4.3	Likelihood and consequences of each extreme weather event at the six research sites (*Confidential*)	
BINGO D4.4	Estimated level of risk of each event and each scenario at the six research sites (*Confidential*)	
BINGO D4.5	List of the most significant risks for the six research sites	2019
BINGO D5.2	Compilation report on initial workshops at the six research sites	2017
BINGO D5.4	Report on the current governance situation and recommendations for improvement at the research sites using the three layer framework (part 1)	2016

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Report	Title	Year
BINGO D5.5	Complete report on the assessment of the current situation and recommendations for improvement at the research sites using the three layer framework	2019
BINGO D6.6	Interim portfolio of actionable research problems/challenges exploitation and development	2017

Table 1: Co-authored reports published by the BINGO project.

Workshop Number	Tag-Line Title	Timing
1	"Setting the Scene"	February 2016
2	"Are we prepared?"	September 2016
3	"Yes, we are!"	May 2017
4	"Solving the unsolvable"	November 2017
5	"Up the CoP"	March 2019

Table 2: Key Community of Practice workshops held within the scope of the BINGO project.

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We need a better understanding of the data we have, what they can give us, and what they can't.

Uwe Ulbrich

Final meeting of the BINGO project

Lisbon May 2019

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Chapter 1 Introduction

This chapter serves as an introduction to the work of this thesis. It includes its background related to global climate change (Section 1.1), the climate change knowledge base (Section 1.2), and paradigms of climate adaptation (Section 1.3). Then, current practice and adaptation-support needs in Norway are described (Section 1.4). Finally, the aims and objectives (Section 1.5), research context and boundaries (Section 1.6), and the structure of the thesis (Section 1.7) is outlined.

1.1 Background

The global climate is changing (IPCC, 2013). Global warming is expected to cause an intensification of extreme weather events, from high-intensity rainfalls to long-lasting dry-spells, both of which can have severe impacts on urban water systems. Drought and dry-spells cause an increased risk of water supply failure due to decreased water availability, while increased frequency and magnitude of extreme rainfall events, in combination with heavy urbanization and continued sealing of natural surfaces, may cause increased flooding and pollution from drainage systems. In a business-as-usual scenario, i.e., no adaptation, in Norway, the estimated damage costs due to stormwater the next 40 years are in the range 45 to 100 billion [NOK] (NOU, 2015). With the rising awareness of climate change, local water managers and stakeholders are increasingly seeking novel tools and decision-support systems to facilitate management of urban water systems under an uncertain future. The work of this thesis seeks to contribute to the development of climate-informed adaptation frameworks for urban water systems and has been conducted as part of the H2020 project BINGO - Bringing INnovation to onGOing water management - *a better future under climate change* (Grant Agreement number 641739).

1.2 Climate Change - the Knowlegde Base

The primary source of quantified information on future climates is output from Global Climate Models (GCMs). GCMs are comprehensive numerical models comprising the physical, chemical, and biological properties of the climate system (IPCC, 2014). GCMs are able to simulate the climate system's response to various forcings, including anthropogenic emissions of greenhouse gases. Thus, the future evolution in time of important meteorological variables for hydrological applications, such as temperature and precipitation, can be simulated by feeding GCMs input scenarios reflecting time-evolving emissions. The output of such simulations are referred to as climate projections.

The most recent generation of emissions scenarios are referred to as Representative Concentration Pathways (RCPs), where the use of 'representative' and 'pathway' emphasize, respectively: 1) that these are *scenarios* leading to a specific evolution of radiative forcing and 2) that also the trajectory taken to reach specific levels are important (Moss et al., 2010). The most recent group comprises four scenarios: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The numbering of each scenario indicates the level of net radiative flux [W/m^2] for which the scenario will stabilize by the end of the 21st century.

GCMs are becoming increasingly sophisticated and complex, but their ability to simulate local climate at a satisfactory spatial and temporal scale is limited. Thus, over the past decades, the concept of downscaling climate data to acceptable scales for hydrological and hydraulic applications and impact assessments have received growing and extensive attention within climate research (e.g. Fowler et al. (2007), Maraun et al. (2010), Arnbjerg-Nielsen et al. (2013) and Ekström et al. (2015)). There now exist numerous methods, where most falls into one of two classifications (or a combination of the two): 1) dynamical downscaling and 2) statistical downscaling. Dynamical downscaling can be explained as the process of nesting of a fine-gridded regional climate model within selected boundaries of a parent GCM. Benestad et al. (2008) defines statistical downscaling as *"The process of making the link between the state of some variable representing a large space and the state of some variable representing a much smaller space"*. Statistical downscaling techniques can further be categorized in methods aiming at resolving the spatial scale and those aiming at resolving the temporal scale, through IDF-curve projection (e.g. Nguyen et al. (2007) and Herath et al. (2016)) or by disintegrating times-series (e.g. Sharif and Burn (2007) and Kossieris et al. (2018)). In short, statistical methods are transferable and computationally inexpensive, but results are highly dependent on the realism of the parent GCM, choice of predictor and selected transfer schemes, while dynamical downscaling, requiring significant computing resources, respond in a physically consistent way to different external forcings (Wilby et al., 2002).

Climate projections are associated with significant uncertainties. Wilby and Dessai (2010) describe a cascading uncertainty, where the uncertainty of the future society is propagated through emissions scenarios, the climate model, the regional climate model, and so on, resulting in a wide envelope of uncertainty in the final output. Ekström et al. (2015) point to three types of uncertainty in estimating how the future will unfold. They define Type 1 uncertainty as the uncertainty due to future forcings of the climate, where forcings refers to external factors influencing the climate, such as greenhouse gas emissions and aerosols. Thus, Type 1 uncertainty in impact modeling can be captured by the using an ensemble of RCPs. Further, Ekström et al. (2015) define a second category of uncertainty, Type 2 uncertainty, as uncertainty related to how the climate system respond to external forcings. The climatic response to external forcing is, as described above, investigated through GCMs, and the uncertainty of the simulated response may be assessed by comparing the output of an ensemble of different models. The final type, Type III uncertainty, refers to the uncertainty due to natural variability in the climate system. According to Ekström et al. (2015), such uncertainty can be captured using ensembles of experiments from one climate model with differing starting conditions.

1.3 Paradigms of Climate Adaptation

There is a broad consensus that the ensemble approach is the most appropriate strategy for developing plausible future scenarios. However, such an approach, along with the recognition of the high degree of uncertainties, limits the applicability of climate scenarios in urban water management and reinforce the gap between climate research output and end-user needs. Nevertheless, this should not be used as an argument to delay actions for adaptation (Arnbjerg-Nielsen et al., 2013). Even without the support of comprehensive studies, it is clear that the consequences of no adaption will be negative (Refsgaard et al., 2013).

Research on climate change adaptation is lagging behind climate change impact studies in terms of scientific output (Wilby et al., 2009), although contributions are increasing (Preston et al., 2015). Climate change impact studies are often based on using projections of future climate as input to impact models to study the consequences of a certain climate scenario on urban water cycles. There exists numerous studies investigating climate change impacts on water resources (e.g., Brekke et al. (2004); Christensen and Lettenmaier (2006); Wilby et al. (2006); Buytaert et al. (2009); Schewe et al. (2014); Gosling and Arnell (2016); Shrestha et al. (2017)) and combined sewer systems and stormwater design (see for instance

Paradigm	Description
Predict-then-act	Paradigm fully dependent on climate change scenarios (scenario-based, top-down approaches)
Robust	Paradigm not based on climate change scenarios and for which the chosen adaptation strategies function acceptably well under all future scenarios and risks (vulnerability, bottom-up approaches)
Climate-informed	Paradigm linking bottom-up, vulnerability analysis with climate projections

Table 1.1: Paradigms of climate adaptation

Semadeni-Davies et al. (2008); Nguyen et al. (2010); Willems and Vrac (2011); Nilsen et al. (2011); Fortier and Mailhot (2014); Abdellatif et al. (2015)).

Using information from impact studies for adaptation-support falls under the *predict-then-act* paradigm of climate adaptation (Table 1.1. The main problem with the approach, is the accumulated uncertainty that arise from basing all the steps of modeling on uncertain input (as described by Wilby and Dessai (2010)), the lack of knowledge on how the climate actually responds to such input (Type 2 uncertainty according to Ekström et al. (2015)), and the limitations of simplifying the assumed response into theoretical models (Döll et al. (2015)). Decisions based on predictions with high degree of uncertainty might thus lead to mal-adaptation and solutions that fail, if the future turns out differently than predicted (e.g. Ekström et al. (2013) and Lempert et al. (2013)). Hence, in an attempt to avoid this deep uncertainty, other adaptation strategies that are independent of climate projections have been suggested.

Next to the *predict-then-act* approach, one of the most widely cited decision framework within climate adaptation is *robust adaptation*. This framework consist of systematic investigations to identify vulnerability indexes and acceptable thresholds using a wide range of *possible* futures. Beginning with vulnerability assessments, the starting point of this approach is the point at which the impact and probability studies end. Due to

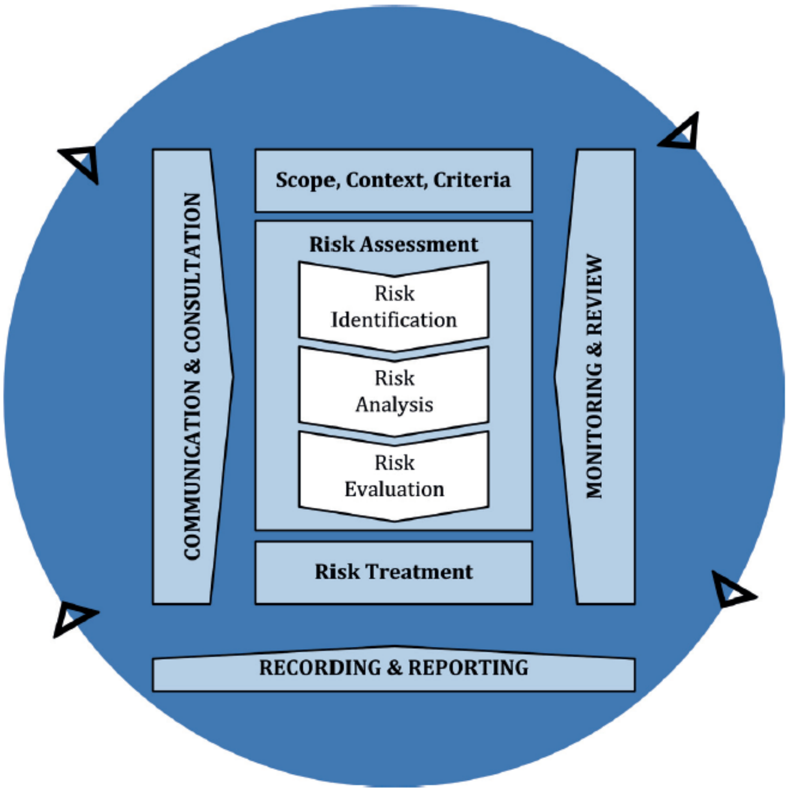

Figure 1.1: The Risk Management Process (ISO, 2018).

this, the two approaches are often referred to as top-down (scenario-based) and bottom-up (vulnerability-based) approaches (e.g. Wilby and Dessai (2010)). The term robust refers to decisions that covers adaptation to a wide range of future uncertainties and risks. Ideally, this will lead to no-regret solutions (i.e., resilient to all scenarios).

Focusing only on the robustness of the solutions also obstructs the search for optimality (Kunreuther et al., 2013). Thus, *climate-informed* approaches have emerged, linking top-down and bottom-up frameworks. These have many similarities with risk management frameworks. Risk is formally defined as the *effect of uncertainty on objectives*, usually expressed in terms of risk sources, potential events, their consequences, and their likelihood (ISO, 2018). The core of the risk management process (illustrated in Figure 1.1) comprise of 1) establishing scope, context, and criteria, 2) risk assessment (identification, analysis, and evaluation), and 3) risk treatment (ISO, 2018). Ekström et al. (2013) performed a study where an uncertainty matrix was applied to three risk assessments covering both top-down and bottom-up approaches. Their results indicated that a more robust adaptation can be obtained if climate information is incorporated in societal behavioural studies. Brown et al. (2012) proposed another framework where vulnerability analyses are linked to climate projections, referred to as decision-scaling. In this framework, hazard identification is obtained by stochastic methods and climate projections are used to estimate relative probabilities of these hazards. The idea is that the climate information should help prioritizing risk, rather than identifying risk. A similar mindset can be found in Weaver et al. (2013) where it is argued that climate projections are under-utilized as decision-supporting tools, and should be used in an exploratory rather than a consolidating way. Risk management frameworks lie somewhere in between *predict-then-act* and *robust adaptation* by including analyses of climate scenarios with respect to defined impact thresholds (Wilby et al., 2009).

1.4 Current Practice and Adaptation-Support Needs in Norway

It is the municipalities of Norway who bear the largest responsibility for climate adaptation. On the national level, the guidelines states that assessments of the consequences of climate change should be based on high emissions scenarios and a balance between climate change and other societal considerations must be made (Meld. St. 33, 2010). There is, however, not developed any national indicator-set for climate adaptation for which the municipalities can measure their performance. Thus, to date it is up to each municipality to determine what to do and how to do it.

The water sector manages infrastructure with long life cycles and with low tolerance of failure. Adapting to future climates is consequently of special importance. As for any urban site, the goals of adaptation are to maintain a safe and reliable drinking water supply, minimize flooding and consequences of such, and reduce pollution from combined sewer overflows, also in a future climate. Thus, the two main categories of adaptation-support needs are for 1) urban drinking water systems and 2) urban drainage systems. The planning of climate resilient urban drainage systems and stormwater infrastructure is without doubt the category receiving most attention, and for which most questions are unanswered.

In Norway, stormwater is commonly managed by a strategy comprised of three steps,

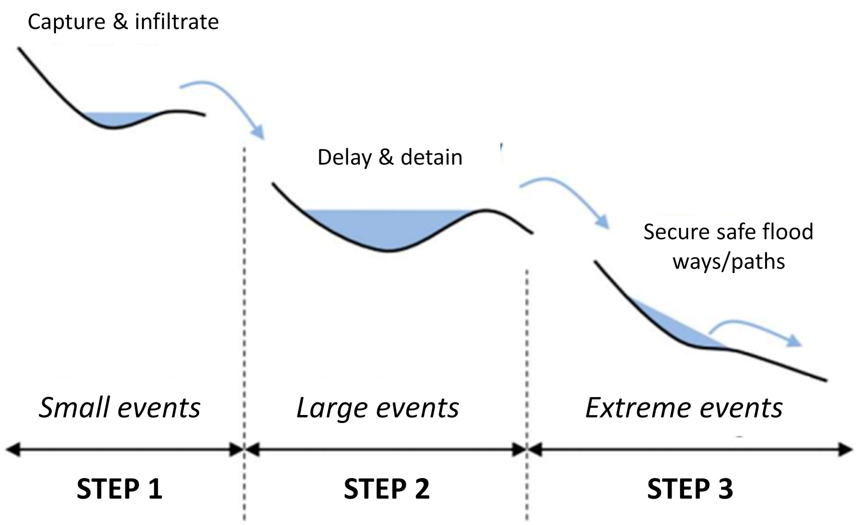

Figure 1.2: The three-step approach for stormwater management in Norway (Lindholm et al., 2008). As modified from Paus (2018).

corresponding to different intensity levels of rainfall events (Lindholm et al., 2008): 1) stormwater generated from smaller events should be retained and infiltrated locally, 2) larger events should be detained and delayed before conveyed further, and 3) extreme events should be secured safe flood ways (see Figure 1.2 for a visualization of this three-step approach). The limits between the steps are set locally. Lindholm et al. (2008) exemplifies with limits of rain amounts < 20 mm in step 1, 20-40 mm in step 2 and > 40 mm in step 3. For selected municipalities in Southeastern Norway, limits are set by return periods T=2 years in step 1, T=25 years in step 2, and T=200 years in step 3 (COWI, 2018).

Furthermore, there exist practice and guidelines for deriving design runoff values for each step. For larger areas a model-based approach for determining design runoff, Q, is advised. For smaller areas (< 50 Ha) Q is usually determined by the rational method, formally expressed as:

$$Q = CiA \tag{1.1}$$

where C is the runoff coefficient, i is the rainfall intensity, and A is the drainage area (Butler et al., 2018).

To account for climate change, a climate factor is added to the rainfall intensity, i. The magnitude of the climate factor has also traditionally been set locally, thus varying from region to region. In recent years, the Norwegian Center for Climate Services has provided local stakeholders with an increasing information base, including the publishing of the report "Climate in Norway 2100" (Hanssen-Bauer et al., 2015), county specific climate profiles (Hisdal et al., 2017), and recommended climate factors for short-duration rainfall in Norway (Dyrrdal and Førland, 2019). The recommended climate factor for rainfall durations < 3hr was originally 1.4 for all regions in Norway (Hanssen-Bauer et al., 2015; Hisdal et al., 2017). In the latter report, however, a finer differentiation is presented, where different recommendations are given for areas prone to high precipitation loads (lower climate factor) and more dry areas (higher climate factor), in addition to higher recommended climate factors for higher return periods. In their new guidelines, NCCS recommend factors between 1.3-1.5 for rainfall durations < 3hr (Dyrrdal and Førland, 2019).

The descriptions above highlight the need for an improved design-basis for stormwater, in order for municipalities and private developers to plan and build climate resilient infrastructure and systems. Linking climate adaptation to current design practices, thus involves a discussion on the design parameters described above, such as design intensity (including climate factor) and the limits in the three-step approach. Furthermore, there is a general trend in Norway, shifting from conventional, buried urban drainage systems, to blue-green, nature-based solutions (NBS), also referred to as LIDs[1], SUDS[2], and BMPs[3] (to mention a few) (Fletcher et al., 2015). Common NBS are green roofs, raingardens (also referred to as bioretention cells in this thesis), vegetated swales, and more. This is a relatively new practice, and there is no general practice established for the design of NBS in new developments. Investigations of the role of NBS in climate adaptation and climate resilient systems are therefor in high demand.

[1] Low Impact Development
[2] Sustainable Urban Drainage System
[3] Best Management Practice

1.5 Aims and Objectives

This thesis addresses local stakeholders need for novel tools and frameworks for facilitating climate adaptation of urban water systems. It specifically seeks to investigate *how* climate projections can be applied by the water sector in the following applications 1) drinking water availability planning, 2) stormwater infrastructure design, and 3) urban drainage system planning. To achieve this, available climate projections have been applied and statistically downscaled when necessary. To support the overall aim of this thesis, the following objectives are defined:

Objective 1. Investigate local climate projections and their potential to provide decision-support in local climate adaptation.

Objective 2. Evaluate climate projections' applicability for design in current stormwater management practice in Norway.

Objective 3. Develop climate-informed adaptation frameworks for Norwegian urban water systems.

1.6 Research Context and Boundaries

This thesis was funded by the H2020 project BINGO and the work conducted is accordingly closely related to the research activities of BINGO and the objectives of the Norwegian research site, Bergen as described in Chapter 2.

BINGO is short for Bringing INnovation to onGOing water management - *a better future under climate change*. It addresses the need for climate adaptation in the water sector and aims at providing practical knowledge, tools and adaptation strategies to local stakeholders. The project is a collaboration between 20 partners from six European countries. With the aim of producing actionable research, the 20 partners represents a broad range of research institutes and end-user project partners. From Norway, the Norwegian University of Science and Technology (NTNU) and the Municipality of Bergen (Bergen K) participated as research partner and end-user, respectively.

To accomplish the objectives of BINGO, the project was structured in seven workpackages (WPs). In addition to WP1 (Coordination) and WP7 (Dissemination), work was conducted in the following WPs: WP2) Climate predictions and downscaling to extreme weather, WP3) Integrated analysis of the water cycle, WP4) Assessment of the impacts of extreme weather events WP5) Developing risk treatment and adaptation strategies for extreme weather events, and WP6) Ensuring Excellence and Actionable research.

These WPs were all interlinked through feedback loops and input-output streams. Consequently, the candidate was involved in all WPs and provided contributions to chapters concerning the Norwegian research site Bergen in a selection of BINGO reports. The reports in which the candidate has contributed are listed in Table 1. The five research papers comprising this thesis are closely linked to certain deliverables of BINGO. All model development was performed in WP3 of the BINGO project. Thus, some papers of this builds directly on these works, which are documented in BINGO reports D3.1-D3.6. Specifically, this applies to the urban water systems assessed in papers I, IV and V. References to BINGO deliverables, in accordance with notation presented in Table 1, is therefor provided where necessary to make a clear distinction between a output of BINGO and the work conducted to produce the research articles. Furthermore, the scope and specific objectives of the BINGO project for the Norwegian research site, Bergen, was established in the workshops listed in Table 2. These objectives signify the main frames and context for this thesis work.

1.7 Thesis Structure

The remainder of this thesis is structured as follows: The research site, Bergen, that has served as a case study throughout the work is described in Chapter 2. Chapter 3 outlines the materials and methods used. Then, Chapter 4 accounts for the main results of the work. These are then discussed in Chapter 5 which also presents the main conclusions. In this chapter, venues for further work are also outlined.

This thesis primarily centers around 5 scientific papers, each of which are included in full in Appendix A. These have been aggregated in tabular form, structured in the three main water sector applications stated in Section 1.5, with descriptions of objectives, methods, and main findings. This has been done to help the reader with a view of the thesis at a glance and can be seen in Table 1.2.

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Theme	Paper	Objectives	Methods	Main Findings
Water supply	I	Provide water managers with an easy-to-use tool/framework for assessing water availability under high uncertainty.	ESD for the estimation of seasonal climate factors (O1). Hydrological assessment of impacts (O2). Scenarios of climate change and increased water demand assessed by Water Availability Index (WAI) (O3).	Demonstration of SD methodology suitable for long-term, slow hydrological processes, including uncertainty assessment. Introduction of a Water Availability Index (WAI) as performance indicator.
Stormwater infrastructure	II	Address end-users' need for practical tools for designing and assessing climate change adaptation measures in stormwater management .	SD of rainfall extremes and IDF curves by extreme value theory (AMS/GEV) and scaling laws. Assessment of a raingarden's performance and robustness in projected climate.	Demonstrated the practical value of climate forced IDFs. High infiltration rate of raingarden leads to less overflow and increased overflow lag time, while low infiltration rate is most efficient in reducing peak flow. Duality in performance indicate that robustness and flexibility may be increased by coupling LIDs of different infiltration rates in series.
	III	Investigate how different LIDs perform, both alone and in configurations, in present and future climate.	Temporal downscaling of IDFs by scaling laws and extreme value theory (POT/GPD) for three Norwegian sites. Assessment of long-term and event-based LID performance in future climate scenarios.	Development of scaling model from Paper II. Varying climate factors both across locations and return periods. Increased retention potential of LIDs based on infiltration and evapotranspiration processes in a future climate Detention basin volumes can be significantly reduced if applied in series (post green roofs / raingardens).

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Theme	Paper	Objectives	Methods	Main Findings
Urban drainage systems	IV	Explore the practical value of long-term, continuous simulations (LTS) of urban drainage systems under climate change.	Continuous simulations of CSOs response to long-term climate projections using a hydrodynamic urban drainage model built in SWMM, using an ensemble of regional climate projections as input. From the input climate series and output CSO series, a selection of CIs and PIs were extracted and analyzed individually and collectively.	Highlighted value of large-scale ensemble simulations of urban drianage systems for proper system diagnosis. Demonstrated how results can be input to different steps of a risk management process. Discussion on added value of LTS in light of resource demand and informational gain.
	V	Provide a framework for climate adaptation planning of urban drainage systems considering cost-effectiveness and efficiency of different measures.	Case study of Bergen: combined CSO projections, spatial, and cost data with CSO reduction simulation to infer cost effectiveness of different measures.	Results suggest proposed framework is robust wrt. uncertain input variables. For the Bergen case study, highest cost-efficiency is obtained for transport-based adaption measures designed to separate stormwater from sewage.

Table 1.2: Thesis at a glance: Brief outline and structure of 5 scientific papers composing this thesis.

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Chapter 2 Research Site

This chapter briefly describes the characteristics of the Bergen study site (Section 2.1) and the adaptive management framework used in this region (Section 2.2).

2.1 Study Site Characteristics

The city of Bergen is Norway's second largest city, housing approximately 280 000 inhabitants (Statistics Norway, 2019). The city is surrounded by mountains and is located in Western Norway (60°N, 5°E) where it is especially prone to the winds coming in from the southwest. In combination, the wind patterns and orographic lift due to the mountainous topography causes high loads of annual precipitation. Thus, the local climate is characterized as a mild and wet coastal climate, with a normal annual precipitation of 2250 mm and an average temperature of 7.6° (MET Norway, 2018). In addition to high annual loads, the city is prone to high-intensity rainfall events (Table 2.1), and several extreme events with severe consequences have occurred the past years. The most fatal event in recent years occurred in 2005, where the storm "Kristin" caused traffic jams, power outage, material damage and the death of three people due to a rainfall induced avalanche of mud and stones (Meyer et al., 2015).

Stormwater generated from rainfall and snow melt has historically been managed in combined sewer systems in Bergen. Today, however, most of the city's drainage system is separated from the sewage. One exception is the Damsgaard area located close to the city center at the foot of mount Lovstakken (see Figure 2.1 for map of Bergen study site and the Damsgaard area). This area is undergoing a large-scale transformation and rezoning from industrial activity along the city fjord, Puddefjorden, to housing and recreational activities in and around the water bodies. The combined system manages stormwater generated in the urbanized belt between the surrounding mountains and the fjord, in addition to stormwater draining from the mountainous areas. Intercepting collection pipes in the downstream part the systems secure transportation to treatment facilities. These pipes are further equipped with CSOs discharging to the fjord when the capacities of the intercepting pipes are reached (Kristvik et al., 2018b).

Although the city is facing challenges due to stormwater runoff and CSOs, the high pre-

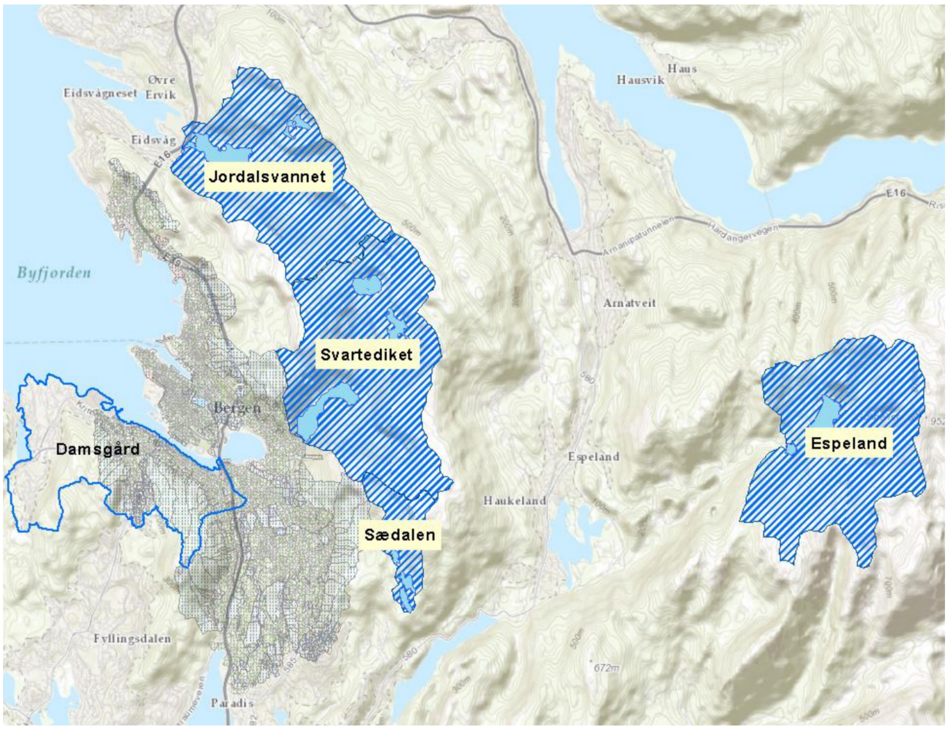

Figure 2.1: Map of Bergen study site visualizing catchments surrounding 4 main drinking water areas (blue shaded areas) as well the Damsgaard area (encircled in blue). Adopted from BINGO D3.1.

		Rainfall duration, minutes								
		5	**10**	**15**	**30**	**60**	**180**	**360**	**720**	**1440**
	2	67.2	46.7	38.4	25.7	17.2	10.0	7.3	5.3	3.7
	5	85.8	57.6	46.4	30.6	19.9	12.3	9.4	7.2	5.0
Return	**10**	98.0	64.8	51.7	33.9	21.8	13.8	10.9	8.4	5.8
period,	**20**	109.8	71.7	56.7	37.0	23.5	15.3	12.2	9.5	6.7
years	**25**	113.5	73.9	58.3	38.0	24.0	15.7	12.7	9.9	6.9
	50	125.1	80.6	63.3	41.1	25.8	17.2	14.0	11.1	7.7
	100	136.5	87.3	68.2	44.1	27.5	18.6	15.4	12.2	8.5

Table 2.1: IDF-table adopted from Norwegian Center of Climate Services (NCCS, 2019). Cells show rainfall intensities [mm/hr] for durations 5-1440 minutes and return periods 2-100 years.

cipitation loads are beneficial to the water supply. Inhabitants of Bergen are supplied with water from a network of drinking water reservoirs which are interlinked by transfer tunnels in order to secure supply if one of the reservoirs should be out of service. The catchments of the main reservoirs are depicted in Figure 2.1. The water levels in the reservoirs are usually close to the storage capacity due to continuous inflow due to high precipitation loads. However, the installed storage capacity is relatively low and have been upgraded the past years to secure water availability during dry spells. This upgrade happened after a winter drought in 2009/2010 which caused unusually low water levels in the reservoirs. Moreover, population growth and high degree of leakages in the drinking water distribution networks pose a risk with respect to the municipality's objective of providing a safe and steady drinking water service (Bergen Municipality, 2015).

2.2 Adaptive Management

A community of practice (CoP) comprised of the research partner NTNU, representatives from a variety of municipal agencies, and other stakeholders of the BINGO project, such as residents and residential interest groups, was established early on in the project for the purpose of co-production. Throughout the BINGO project, a series of workshops for the CoP have been conducted to define an adaptation strategy for the water sector in Bergen and to ensure that the research conducted resulted in actionable knowledge. The workshops are listed in Table 2.

Within this workshops series, the objectives and focus of the Bergen case study in BINGO was set. For both water supply and stormwater, future opportunities and possible risks were defined, resulting in two main research focuses determined by the CoP: 1) drinking water availability in a future prospective and 2) climate robust upgrading of the combined sewer system in the Damsgaard area. Of these two, the question of what the upgraded system in Damsgaard should be designed to handle was perceived the most urgent to address within the BINGO project by the CoP.

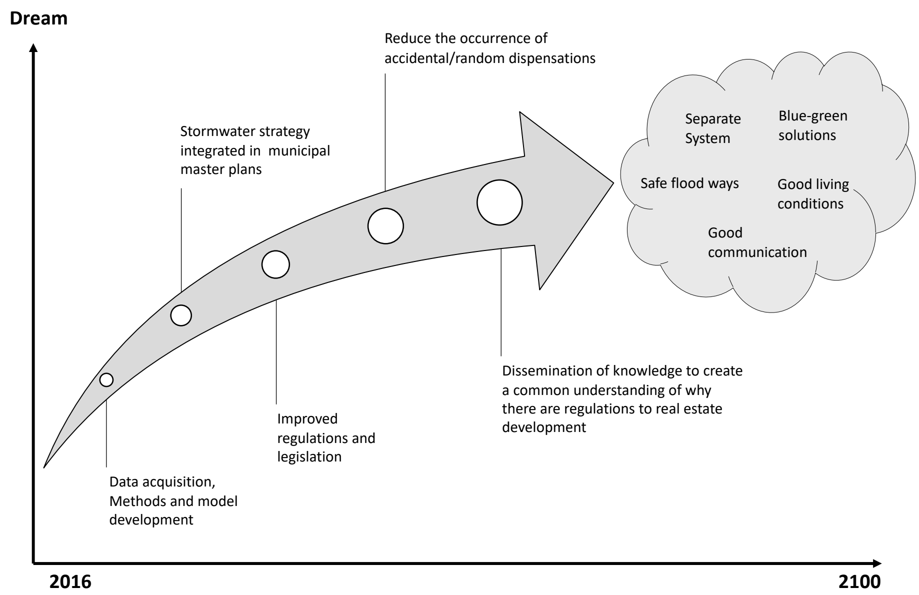

Figure 2.2: Roadmap to dream scenario: outcome of visioning exercise at the CoP workshop 2 of the BINGO project.

Further on, exercises were performed to identify goals, premises to achieve goals (e.g. governance needs and gaps), and relevant technical solutions for adaptation. Figure 2.2 shows the CoP's identified roadmap to a stormwater "dream scenario" in year 2100. From this figure, it is evident that this thesis work is closely linked to the first step of this roadmap. Furthermore, the figure gives an indication of adaptation measures considered by the Municipality of Bergen. The final measure selection is presented in Table 2.2. The

ID	Name	Description
MI	Safe floods ways	Safe surface transportation of ”clean” stormwater from mountains to fjord[1]
MII	SUDS	Implementation of nature-based, blue-green solutions
MIII	Separation	Separating stormwater and sewage by traditional methods and pipe systems

Table 2.2: Selected adaptation measures at the Bergen Research site.

selected measures MI-MIII were assessed both as part as BINGO and this thesis work (see Section 3.4).

[1]The safe flood ways measure specifically involved the use of streets as flood ways and was addressed in the thesis work by Skrede (2018).

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Chapter 3 Materials and Methods

This chapter briefly describes the data, tools, models, and frameworks applied in the five scientific papers comprising this thesis. These descriptions have been included as they are relevant for a holistic presentation of the thesis work. Most of the papers where written in collaboration with other researchers and project partners, and the work load shared accordingly. It should be clear from the co-author contribution statements in Appendix C which parts have been performed by the candidate.

3.1 Data

A variety of data was applied in this thesis. For downscaling of climate data (Papers I-III), observational data and output from global and regional climate models were gathered and processed. Data for the Bergen region was the key input in all papers. In Paper III, the assessments were extended to Oslo and Trondheim. With this, the analyses were performed for the three largest cities in Norway. In Paper IV and V the focus was on the application of climate data, and simulations of CSO time series (prepared within the scope of the BINGO project) and available spatial data were the main inputs to the analysis performed.

3.1.1 Observational Data

Observational data was gathered from the Norwegian Meteorological Institute's (MET) web-portal Eklima (www.eklima.no) which allows for downloading raw observations as well as prepared statistics, such as IDF curves for precipitation. This web-portal is currently being replaced by the NCCS data distribution platform (www.klimaservicesenter.no). For Bergen, the weather station Florida (ID 50540) was applied in all papers. In Paper III, minute records from Oslo Blindern (ID 18701) and Trondheim Risvollan (ID 68230) were used. Both stations have over 30 years of records.

3.1.2 Spatial Data

Physical layout of urban areas have a strong effect on stormwater generation processes and flow paths. Possible changes in the urban landscape are therefore important when assessing future trends and climate impacts. Land-use scenarios for the Damsgaard Area were generated as part of the BINGO project (BINGO D3.2) but not used in further assessment as they were less relevant for the planning period 2015-2024 (BINGO D3.3). This was driven by most new development in the Damsgaard area for the named period happening in the downstream, water-front areas - where interventions have little or no impact on flow directions. Furthermore, the transition from industrial areas to recreational spaces and housing purposes generally leads to de-pavement and improved conditions with respect to stormwater. Spatial data of the existing situation was, however, used in Paper V in the assessment of possible locations for climate adaptation measures. These data were provided by the project partner Bergen Municipality, and comprised of land-use layers, such as buildings, roads, and green spaces, in addition to site boundaries, public properties, and more.

3.1.3 Climate Projections

GCM Projections (Paper I)

The Coupled Model Intercomparison Project phase 5 (CMIP5) provide a coordinated framework for climate change model experiments (Taylor et al., 2012). These are assessed in the IPCC fifth assessment report (AR5) (IPCC, 2013). Outputs of monthly large-scale precipitation and temperature from these GCM runs were used in Paper I. In this paper, all four emissions scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) were assessed. GCMs that have been run under all the four emission scenarios were selected to be able to compare across all these. In addition, only output from simulations with realization ID r1i1p1 were used, for the same reason. A table of the selected GCMs is provided in Paper I. GCM output for the period 1975-2005 was used for validating ability to reproduce historical climate, while future projections covered the period 2005-2100.

NCCS Projections (Paper II and III)

The Norwegian Centre for Climate Services (NCCS) provides projections of meteorological variables for Norway 2071-2100, at a daily temporal scale and 1x1 km^2 spatial resolution (NCCS, 2017). These projections are derived from 10 EURO-CORDEX GCM/RCM simulations, using an empirical quantile mapping technique for bias correction and downscaling (Wong et al., 2016). Downscaled projections exist for RCP4.5 and RCP8.5. An overview of the GCMs/RCMs and ensemble members are provided by Wong et al. (2016). The RCP8.5 ensemble was subject to temporal downscaling in Paper II and Paper III. Statistical properties, mean, and variance, of the RCP8.5 ensemble was used in Paper II, while the full time series was downloaded and temporally downscaled in Paper III. In both papers, the data for the grid (1x1 km^2) covering the weather station of interest was applied.

FUB Projections (Paper IV and V)

Decadal climate predictions for Bergen were developed within the BINGO project by the project partner Freie Universität Berlin (FUB). In line with overall goals of BINGO, decadal predictions provide climate scenarios that are somewhere between long-term climate projections and short-term weather forecasts. In decadal prediction, both external anthropogenic forcings and internal climate variability are accounted for (Marotzke et al., 2016). In the BINGO project, such predictions were provided for the period 2015-2024 (i.e., one decade). Decadal predictions demand a high-quality initialization of the earth system model in use, in order to make reliable predictions based on internal climate variability (Rust et al., 2018). Thus, different initializations, originating from random perturbations of the best-estimate initial conditions, was applied in BINGO, forming an ensemble of 10 realizations. The parent GCM and RCM for these predictions were the Max Planck Institute's earth system model MPI-ESM-LR and the COSMO-CLM (Rockel et al., 2008), respectively. The data set was provided at the point scale for the Florida Weather station (ID 50540)

The FUB projections were provided for Bergen at the point scale (Florida weather station) and at a daily temporal resolution. For applications requiring a sub-daily time step, a disintegrated series was prepared within the BINGO project by the project partner NTNU. These series were derived with the K-Nearest Neighbor (KNN) approach (Lall and Sharma, 1996). Lall and Sharma (1996) describes the traditional KNN as a non-parametric re-sampling technique commonly used on hydrological data where the user needs not to make any assumptions about the distributional form or underlying stochastic processes. The KNN approach was compared with the parametric Bartlett-Lewis Rectangular Pulse model with adjusting procedures (BLRPRx), as described by Kossieris et al. (2018), and the former was found to outperform in reproducing sample mean, variance, skewness and empirical cumulative distribution for both the hourly and 5-minute time step (Kristvik et al., 2018a).

3.1.4 Hydraulic Data

The projected CSO series analyzed and assessed in Paper IV and V were part of the deliverables of the BINGO project (BINGO D3.3 and BINGO D3.4). These series originate from hydro-dynamic simulations of the combined sewer system at the study site using the full ensemble of disintegrated FUB precipitations as input. The data set constist of 8 CSO series for the Damsgaard area of Bergen discharging to the receiving fjord, Puddefjorden. It has temporal extent of 10(years)x10(realizations) at the 5-minute time-step, corresponding to the KNN disintegrated FUB projections.

3.2 Processing of Climate Data

Different applications of climate data require different format and temporal resolutions. Given the impacts of interest, application may require either continuous or event-based simulations and the required time-step of the meteorological input data depends on the characteristics of the hydrological or hydraulic process under investigation. Over the course of this thesis work, increasing amounts of processed and downscaled climate data have been made available. Hence, the climate data processing needs for the three applications described in Chapter 1 shifted accordingly. The following sections describes the statistical downscaling performed for Papers I-III and processing of the dynamically downscaled climate data in Paper IV.

3.2.1 Delta-Change Factors

Changes in local climate are often expressed as delta-change factors, also referred to as climate factors (CFs). These represent the absolute or relative change in a meteorological variable when comparing two different climate periods (typically of length 30 years). In this thesis the following definitions of delta-change factors for precipitation, P, and temperature, T, respectively, are used:

$$\Delta P = \frac{{}_{PRO} - \overline{P}_{REF}}{\overline{P}_{REF}} \tag{3.1}$$

and

$$\Delta T = \overline{T}_{PRO} - \overline{T}_{REF} \tag{3.2}$$

where *PRO* and *REF* refer to a projected period and reference period, typically of length 30 years, and $\overline{P}$ and $\overline{T}$ are means or medians of the respective variable over this period.

3.2.2 Empirical-Statistical Downscaling (Paper I)

An empirical-statistical downscaling (ESD) of GCM output was performed for the assessment of future water availability in Paper I. ESD was performed following the approach of the thesis work by Kristvik and Riisnes (2015) and by using functions from the R package 'esd' developed by the Meteorological Institute in Norway (MET) (Benestad et al., 2015). Empirical orthogonal functions (EOFs) were created from the gridded GCM output and gridded observations from the NCAR/NCEP reanalysis (Kalnay et al., 1996). Multivariate linear regression was then used to establish a statistical relationship between monthly station records and gridded observations. The obtained statistical relation was finally applied to the GCM output for the historical period (validation) and future period (projection). From this, monthly delta-change factors were calculated and added to the station observations to generate daily input series to the Hydrologiska Byråns Vattenavdeling (HBV) model (Bergström, 1976), as described in Section 3.5.2.

3.2.3 Temporal Downscaling (Papers II and III)

IDF curves relate rainfall intensity with durations and frequency of occurance. IDF curves are commonly applied for dimensioning of urban stormwater infrastructure designed to retain or detain short-duration, high-intensity rainfall events. In Papers II and III, projections of future IDF curves were generated by scaling the extreme value distributions of daily rainfall maxima to obtain sub-daily statistics for IDF construction. The approach for creating projected IDFs was based on the principle of scale invariant rainfall processes, where the statistical properties of rainfall at different scales are linked through scaling laws (Lovejoy and Schertzer, 1985; Gupta and Waymire, 1990; Burlando and Rosso, 1996; Arnbjerg-Nielsen et al., 2013). In this thesis, this principle was by investigating the link between the extreme value distribution (EVD) of daily rainfall extremes and the EVD of sub-daily and sub-hourly rainfall extremes. The scale-invariant property can formally be expressed as:

$$\alpha_{\lambda D} = \lambda^{\beta}\alpha_D \qquad (3.3)$$

where α is a parameter of the extreme rainfall distribution, D is the time scale, λ the scale factor, and β the scale exponent (Arnbjerg-Nielsen et al., 2013). Thus, by deriving the statistical properties for rainfall extremes at various time scales from observations, the scale exponent can be determined and used for projecting sub-daily statistics for future rainfall where only daily rainfall series exist.

A critical part of this analysis is the extraction of rainfall extremes for which an extreme value distribution can be fitted. This is commonly done in one of two ways. In the first approach, the annual maximum (AM) rainfall in each hydrological year represented in the time series is extracted. From this population of AMs a Genereral Extreme Value (GEV) distribution can be fitted. Due to its simplicity, this approach was used in Paper II. However, this strategy for identifying extreme events can possibly exclude relevant extremes if more than one extreme event occurs within a hydrological year. Moreover, the obtained population size is equal to the number of years present in the sampling pool, thus posing challenges for sites and stations of short record history. For this reason, a peak-over-threshold (POT) approach for extremes identification was performed in Paper III and The General Pareto Distribution (GPD) was fitted to the extracted extremes.

3.2.4 Climate Indices (Paper IV)

A climate index (CI) can be defined as a calculated value that can be used to describe the state and changes in the climate system, allowing for statistical studies of variations climatological aspects, such as analyses of time series, extremes, means, and trends (Safee and Ahmad, 2014).

A selection of CIs was used in the research resulting in Paper IV, and a complete summary of the selected indices can be seen in Table 2 of the paper. The selection was done to cover indices that explain both the overall rainfall patterns and are relevant to planning and design of urban water infrastructure. For the former, indices representing the statistical properties of the rainfall distributions where selected, including both annual rainfall frequencies and rainfall mean. This is a suited point of departure as the link to daily precipitation has been widely demonstrated for these two statistics (Benestad and Mezghani, 2015; Benestad et al., 2017).

Indices describing heavy precipitation events, such as annual maxima for various rainfall durations, are relevant to infrastructure design, depending on site-specific conditions and catchment concentration times. Thus, annual maxima were calculated across a set of eight durations, 5min, 15min, 30min, 1h, 3h, 6h, 12h, and 24h, in line with common design practices.

Bergen's precipitation is characterized by frontal precipitation, high annual loads, and relatively long periods of rain, as described in Chapter 2. Due to these particular climate conditions of the site in question, a few more indices, were included. These indices were selected from the Expert Team on Climate Change Detection and Indices' list of 27 core indices (Zhang et al., 2011). These selected indices included annual precipitation amount and annual counts of daily precipitation events exceeding 20mm and 50mm. See Paper IV for full details.

3.3 Implications of Climate Change on Urban Drainage Systems

Both prepared and provided climate projections were used to assess the implications of climate change on urban water systems. Climate projections were used as input to the three categories of application described in the introduction: 1) water supply, 2) stormwater infrastructure, and 3) urban drainage systems. For all applications, an indicator, or set of indicators, were defined in order to assess the added risk posed to system or component performance by the climate projections. The following sections briefly render the performance indicators used in the three applications.

3.3.1 Water Supply

For assessing future water supply reliability, a water availability index (WAI) was defined in Paper I. The criterion for the WAI was that the most important drivers for water availability were represented, such that both changes on the supply side, caused by climate change, and changes on the demand side, caused by changes in consumption patterns, were accounted for. In its simplest form, the WAI was defined as the instantaneous ratio between available water in the reservoirs and the total storage capacity at time t, formally expressed as:

$$WAI(t) = \frac{SW(t) - RR(t)}{SC} \tag{3.4}$$

where $SW(t)$ is the stored water at time t, SC the storage capacity and $RR(t)$ the required storage reserves at time t, defined by the municipality in Bergen as a threshold corresponding to 50 days of consumption. $SW(t)$ was determined by a storage reservoir balance comprising both projections of future inflow and water consumption patterns.

3.3.2 Stormwater Infrastructure

Paper II and III focused on components of the urban drainage systems, with special attention to blue-green infrastructures' performance in a future climate. Performance was assessed both for single units and units placed in series (SUDS-trains). The performance was measured by the components' ability to reduce and delay peak flow, as well as reducing overflow and need for additional detention capacity.

3.3.3 Urban Drainage System

In this work, assessment of the performance has been focused to the investigation of combined sewer overflows (CSOs) discharging to receiving water bodies. With this, flooding further upstream in the system has been left out of the scope.

Performance indicators (PIs) can be used to gain quantitative information on the performance of CSOs (Matos et al., 2003), and are key parameters for quantitative risk assessments. Frequency and volume of CSOs are among the most commonly used indicators, although some limitations in their predictive value with respect to receiving water pollution have been detected (Lau et al., 2002). Annual numbers of events, accumulated volume, and active hours of the CSO, in addition to event-based PIs were assessed. The selected PIs are summarized in Table 3 of Paper IV.

Assessment of CIs and PIs were performed in three steps to 1) detect changes and trends, 2) evaluate the scenarios, and 3) identify driving climate indicators for changes in CSO performance. In order to make a comparable basis of climate indices and performance indicators, change factors (CF) for all CIs and PIs were calculated using the following relation:

$$CF = \frac{X_{FUB} - X_{REF}}{X_{REF}} * 100\% \tag{3.5}$$

Where X refers to the median CI or PI of the periods 2004-2014 (REF) and 2015-2024 (FUB).

3.4 Cost-Effectiveness Assessments

A Cost-Effectiveness Ratio (CER) is a metric to enable a decision-maker to compare different measures by the relation of effectiveness to costs (Levin and McEwan, 2000). It can be expressed with the following:

$$CER_{ID} = \frac{COST_{ID}}{EFFICIENCY_{ID}} \tag{3.6}$$

where a specific measure is denoted by ID, CER_{ID} is the cost-effectiveness ratio of measure ID, the costs of the measure is $COST_{ID}$, and the efficiency is $EFFICIENCY_{ID}$. This metric was used in Paper V to assess a set of different measures for the Bergen study site.

To estimate the costs of each measure, previous studies assessing implementation costs associated with green roofs, raingardens, and other infiltration measures were leveraged (Strehl et al., 2017). The efficiency of each measure was estimated with an urban drainage model, as described in Section 3.5.3. To do so, spatial data, covering regulatory plans, area topography, land-use, buildings, sealed and unsealed surfaces, made available by Bergen Municipality, and land-use scenarios reflecting the adaption measures were used as input. See Paper V for further details.

3.5 Tools and Models

A selection of existing tools and models have been applied in this thesis. These are mainly developed within, or in connection to, the BINGO project in collaboration with others or by other team members. An overview of the tools are provided in the subsequent sections and references to original documentation provided for detailed reading.

3.5.1 R

The freely available language and environment R for statistical computations (R Core Team, 2013) was used for most climate data preparation, processing, and analyzes. This involves everything from downloading and downscaling of climate projections, to output assessment and visualization. Both internal functions and functions from R-packages have been used.

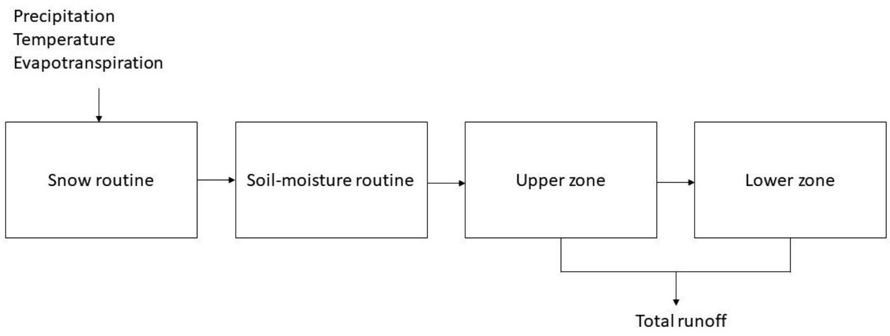


Figure 3.1: Simplified structure of the HBV-model, including routines and main input, output and flow directions.

3.5.2 HBV

The HBV-model (Hydrologiska Byråns Vattenavdelning) (Bergström, 1976) was developed in the 1970's and is a conceptually-based, deterministic rainfall-runoff model. Since its early development, the application of the model has been documented on over 30 countries (Bergström, 1992) and the model has developed such that both lumped and physically distributed versions of it exists. The structure of the HBV-model comprises of four routines for 1) snow melt and accumulation, 1) soil-moisture balance, 3) upper zone response (quick runoff), and 4) lower zone response (slow runoff) (Figure 3.1). The main advantages of the HBV-model is its balance between simple model structure and ability to replicate observed flows.

For assessment of future water availability in Bergen (Paper I), an existing model framework for simulating inflow to the drinking water reservoirs comprising the water supply in the city was used. The framework is based on a lumped version of the HBV-model for rainfall-runoff modelling and comprise of one, individually calibrated, HBV-model for each of the catchments draining to the respective reservoirs. The model was set-up in a pre-study phase of the BINGO project and is described in detail as part of a thesis work by Kristvik and Riisnes (2015) and relevant reports of the BINGO project (Table 1) as stated in Section 1.6.

3.5.3 SWMM

The Stormwater Management Model (SWMM) is an open source software for simulating stormwater quantity and quality (Rossman, 2015). SWMM is a dynamic rainfall-runoff model comprising of a runoff routine were stormwater is generated on the surface from rainfall and a hydraulic component for transporting this stormwater through the drainage network. SWMM version 5.1 was used in the research papers concerning the urban drainage system objectives, Paper IV and V.

Urban Drainage System Model

A model of the full drainage system in the Damsgaard area of Bergen was set up as part of the BINGO project by the research partner NTNU in collaboration with end-user partner Bergen K. The model comprises the full Damsgaard study area, as described in Chapter 2, using detailed system information obtained from the Norwegian Water and Wastewater system's database, Gemini, as input.

Measurements in the study area are scarce. Records of flow measurements from campaign measurement conducted in the period 2001-2008 were used for model calibration. These records consist of short measuring campaigns (35-173 days) of a selection of pipes in the system. These were used to calibrate the corresponding catchments and flows. The obtained parameters were transferred to ungauged catchments through a regionalization technique. The calibration and validation of the model is described in detail in the thesis work by Mittet (2017) and in BINGO reports D3.3 and D3.4.

The model was run with the FUB data to project future CSO discharge. Running the SWMM model with the full FUB data set was a computationally demanding task. In order to perform the simulations, model execution thus involved decomposing 1) the model into independent subsystems that could be run separately and 2) simulations of the flow generation and hydraulics run in a subsequent manner. The resulting time series (see Section 3.1.4) were assessed in Paper IV.

Adaptation Measure Potential Model

A sub-system of the full scale model was used in Paper V for the purpose of simulating a selection of CSOs' response to adaptation measure implementation. The sub-system comprised one of the independent groups as described above. This group involves 4 CSO nodes and 88 subcatchments with 88 corresponding system inlets. The model was used to investigate the potential effect of implementing adaptation measures in the different subcatchments of the system. This was evaluated in a subcatchment sensitity analysis, where the model was run event-based and by disconnecting one subcatchment at a time.

SUDS Performance Model

The SWMM version 5.1 includes a LID module for simulating the performance of a variety of LIDs, such as bio-retention cells, green roofs and swales. One advantage of using SWMM in such assessments is the option to place SUDS in series such that SUDS-trains can be created. The results of the aforementioned sensitivity analysis was used to identify high-potential subcatchments for SUDS implementation. For each of these catchments, a conceptual SUDS-train of green roofs and raingardens was set-up using the LID module in SWMM (Figure 3.2). The conceptual models were based on existing roof area and design values for raingarden area. Parameters of the green roofs and raingardens were reclaimed from previous studies as described in the paper and are given in Supplementary material.

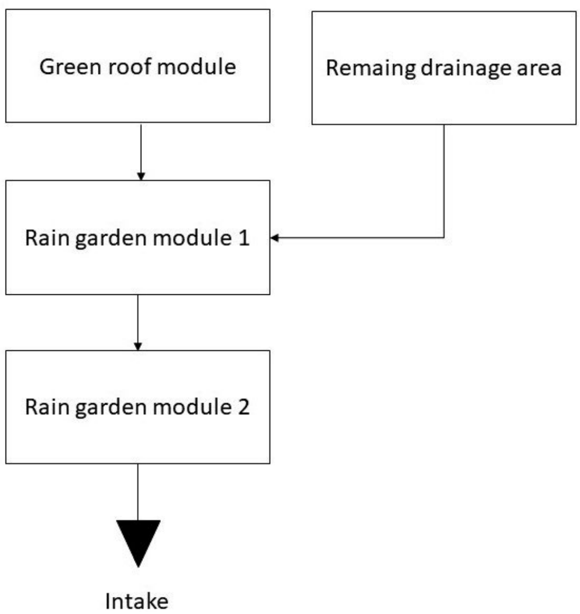


Figure 3.2: Conceptual scheme of SWMM SUDS-train, as simulated in Paper V.

Chapter 4 Results

This chapter describes the main results of the thesis work, primarily from the five main research papers. This is presented in two parts: projections of future climate in Section 4.1 and water sector applications in Section 4.2.

4.1 Projections of Future Climate

Two main works on statistical downscaling of climate projections have been performed: empirical-statistical downscaling (see Section 4.1.1) and temporal downscaling (Section 4.1.2). This has been done for two reasons: 1) to resolve spatial resolution of GCM output and 2) to address temporal resolution of regional climate projections. Finally, regional projections prepared in the BINGO project (Section 3.1.3) have been processed to develop and analyze climate indices (Section 4.1.3). A brief summary is presented in the following, with reference to Papers I-IV for further detailed reading.

4.1.1 Empirical-Statistical Downscaling

Empirical-statistical downscaling (ESD) of the ensemble of 19 GCMs was performed for the historical period 1975-2005 (Paper I). The results are presented in Figure 4.1. The figure shows observed and simulated climatology across an annual distribution with monthly resolution, for both mean temperature and precipitation, respectively. As can be seen, different GCMs yield different outputs and a wide range of mean monthly values can be observed. It can further be observed that the range is narrower for temperature, indicating that the calibrated ESD model for temperature has better fit.

Both ESD models were then used to project future values for monthly temperature and precipitation. As described in Paper I, an ensemble mean was calculated by the Reliability Ensemble Average (REA) methodology of Giorgi and Mearns (2002). The final REA-mean of delta-change factors are given in Figure 4.2. In the figure, this is depicted for temperature and precipitation, separately, for three 30-year periods, and four different RCP scenarios. Results of these projections indicate an overall increase in temperature for all months and seasons. Furthermore, annual precipitation is projected to increase overall, with the strongest increase in fall and winter months out-weighting the projected decrease in spring and summer months. For both meteorological variables, the described trends are increasing both with RCP scenario and with future time span.

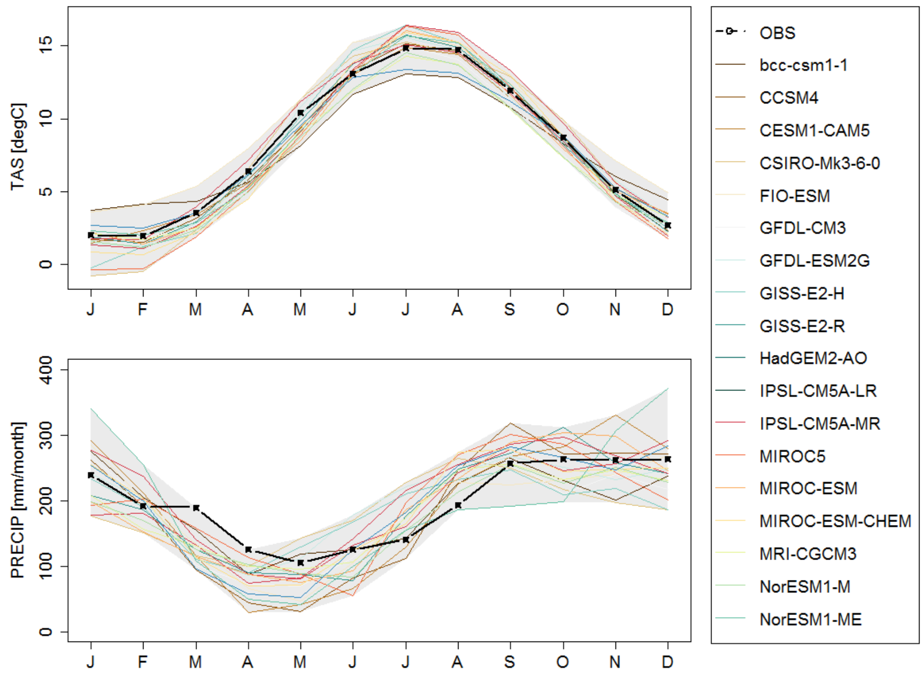


Figure 4.1: ESD of GCMs for the reference period (1975-2005). Observed and simulated climatology is visualized in colored lines corresponding to the list of applied GCMs (see legend on right hand side of chart). The shaded areas represent the range of ensemble climatology. Results adopted from Paper I (Kristvik et al., 2019b). See Table 1 in Paper I for description of GCMs.

4.1.2 Temporal Downscaling

Increased rainfall was also projected by performing temporal downscaling (see Paper II, Paper III, and Section 3.2.3). IDF curves were obtained by scaling daily precipitation observations (as described in section 3.1.1) and fitting two different distributions, General Extreme Value (GEV) distribution with Peak-Over-Threshold (POT) extreme values and General Pareto Distribution (GPD) with annual maxima, against the historical data. This is shown in Figure 4.3. The figure shows the performance of the calibrated scaling models used and it is evident that the scaling approach showed better performance when applied using GPD with POT-extracted extremes than GEV with annual maxima, spe-

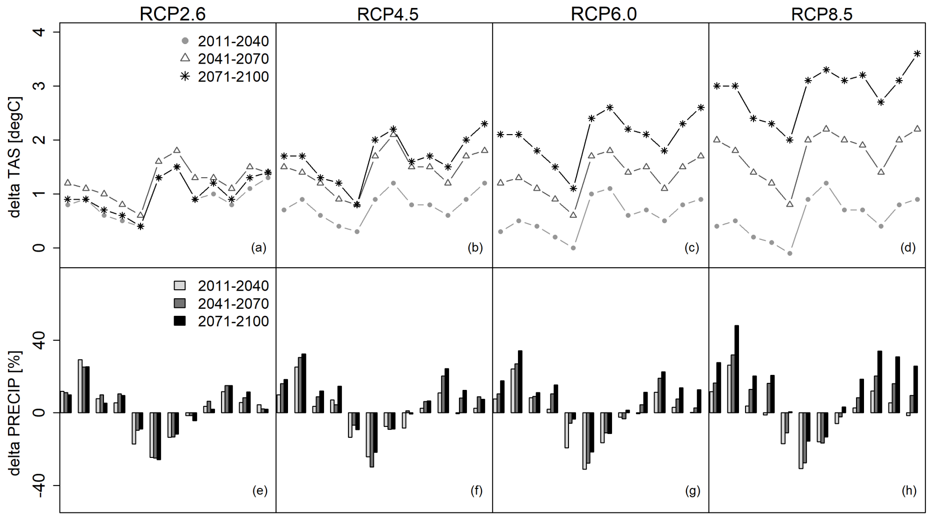
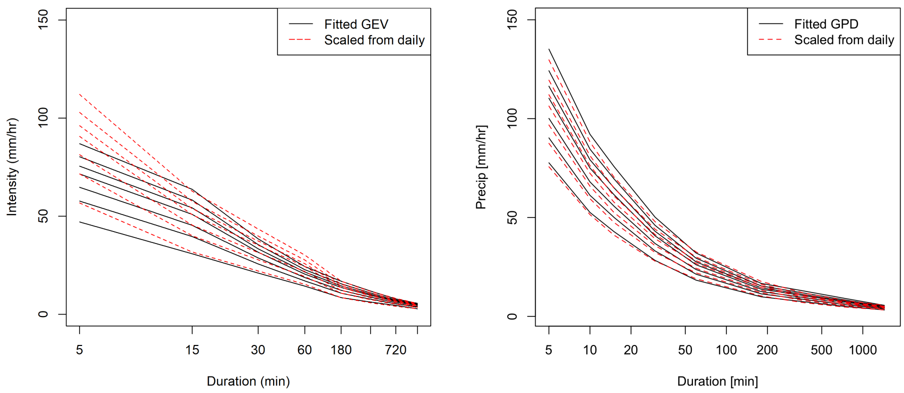


Figure 4.2: Computed change factors from downscaling of the GCM data set (Section 3.1.3). The figure show temperature (top row) and precipitation (bottom row) change factors originating from the reliability-based averaging procedure for three different 30-year periods and four different RCP scenarios. Results adopted from Paper I (Kristvik et al., 2019b).



(a) (b)

Figure 4.3: IDF curves obtained by scaling daily precipitation observations by (a) fitting the General Extreme Value (GEV) distribution with Peak-Over-Threshold (POT) extreme values and (b) the General Pareto Distribution (GPD) for durations 5 min to 24h and return periods 2, 5, 10, 30, 20, 50, and 100 years. Results of Paper II (a) (Kristvik et al., 2018b) and Paper III (b) (Kristvik et al., 2019a).

cially for short durations. The GEV-based results were therefor bias-corrected and values for duration below 15 minutes was excluded in further analyses in Paper II. Moreover, GEV-based assessment seems to underestimate rainfall frequencies when comparing with official value provided by NCCS (Table 2.1), while the GPD assessment show tendencies of overestimation. Overall, the GPD-obtained rainfall intensities are in better conformance with official values for short-duration, observed rainfall frequencies.

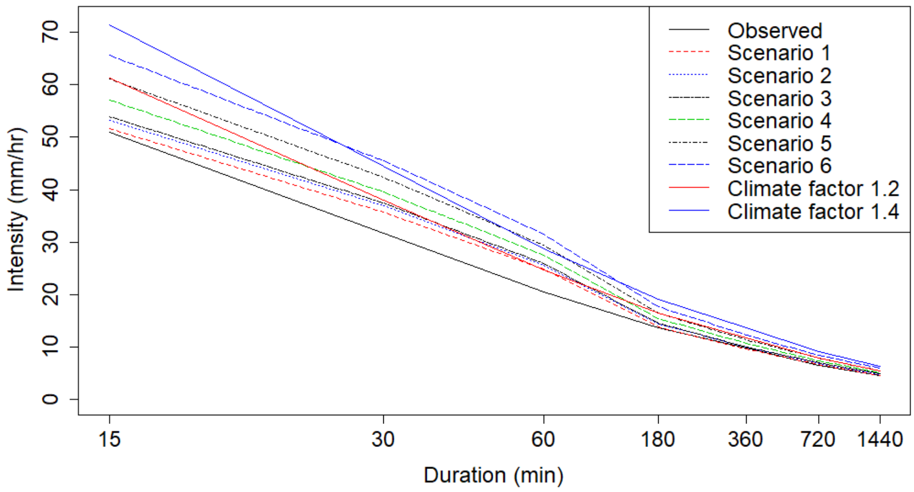
The obtained scaling models were then used to project future IDF curves for Bergen using NCCS data for the period 2071-2100. Resulting IDF curves are presented in Figure 4.3. This figure shows curves for the same two scaling models described previously in this section. Both these scaling models project an increase in future intensities, but there are noticeable differences between the magnitude of the increase in terms of change factors. The results of the temporal downscaling in Paper II concluded that the recommended climate factor of 1.4 (Dyrrdal and Førland, 2019) should be sufficient for most rainfall durations in Bergen. In Paper III, however, estimated change factors were higher and increasing with return period leaving some uncertainty.

4.1.3 Climate Indices

Change factors of the 5-minute resolution FUB projections (see Section 3.1.3) were assessed in Paper IV. The main result of this assessment is depicted in Figure 4.5. This figure shows delta-change factors for different climate indices (CIs) and FUB scenarios. In conformance with the statistically downscaled climate projections described previously, increased rainfall amounts are also projected in this scenario ensemble. The structured assessment of different indices, however, reveal that the increase is not necessarily caused by increased event rainfall amounts (Mu), but increased frequencies of events (Fw). In general, the average rainfall amounts show a slight decrease for almost all durations, while the annual maximum (Rx) increases for short durations and decreases for long durations (>6h).

4.2 Water Sector Applications

This section summarizes the results of the three outlined applications: water supply (Section 4.2.1), stormwater infrastructure design (Section 4.2.2), and urban drainage system performance (Section 4.2.3), each of which are contributions to adaptation support strategies. A brief summary is presented in the following, with reference to the appended papers



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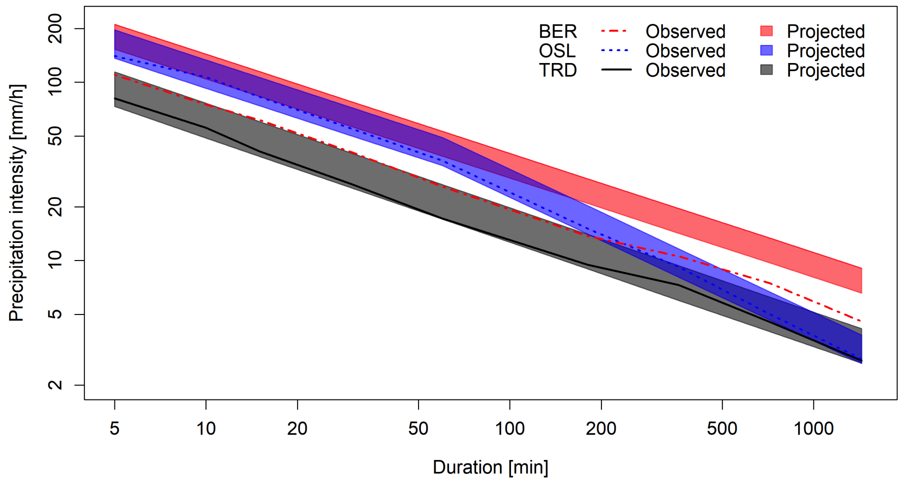
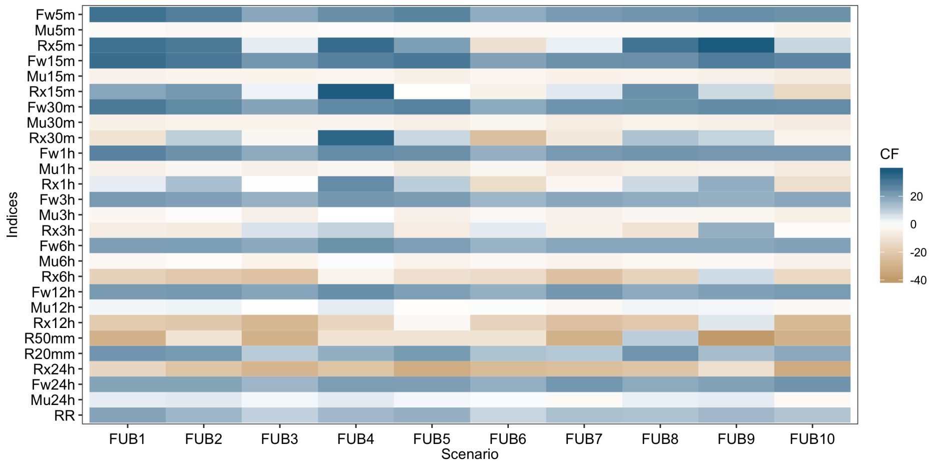
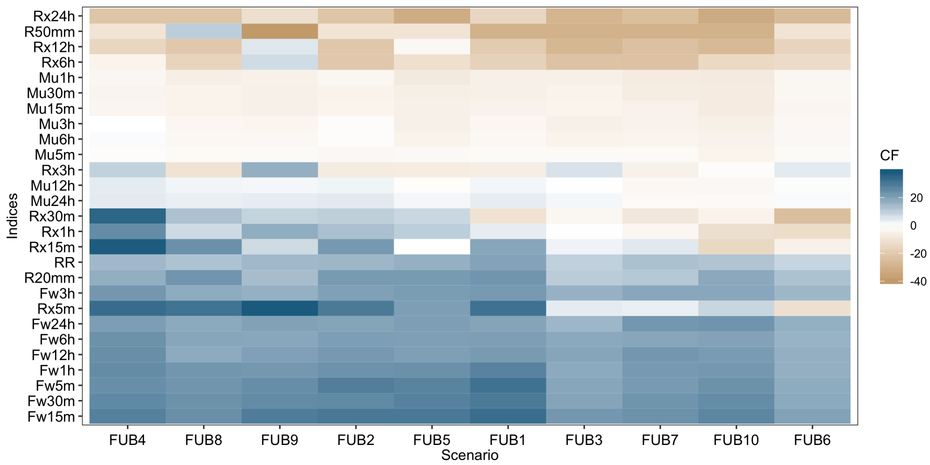


(b)

Figure 4.4: Projected IDF curves for 2071-2100 obtained by scaling of the NCCS projections (Section 3.1.3) based on (a) GEV with annual extremes and (b) GPD with POT-extracted extreme values. Curves and shaded areas represent different scenarios for the T=20 years return period. Note that the top graph has a linear scale whereas bottom graph has a logarithmic scale. This has been adopted from Paper II (a) (Kristvik et al., 2018b) and Paper (III) (b) (Kristvik et al., 2019a).



(a)



(b)

Figure 4.5: Color-graded delta-change factors for Climate Indices (CIs) of the FUB data set (Section 3.1.3), as assessed in Paper IV. The cells visualizes the delta-change factors with a color gradient according to the legends on the right-hand side of the charts. In (a) the CIs are ordered by duration on the vertical axis and by FUB realization order on the horizontal axis. In (b) PCA was performed on the basis of CF-value to group similar trends and thus rearranging the vertical and horizontal order of CIs and FUBs. This has been adopted from Paper IV which also includes a complete list and description of indices.

for further detailed reading.

4.2.1 Future Water Supply

Simulations of the Water Availability Index[1] (WAI), conducted in Paper I, revealed a decreasing trend under all emissions scenarios, with small differences between the RCPs (Kristvik et al., 2019b). Furthermore, the standard deviation of the WAI over the scenario period was increasing with higher emissions scenarios (see in particular Figure 4 of Paper I). These results imply both a decrease in future water supply security and larger variations in water availability in Bergen. It was further shown that the WAI was most sensitive to changes in population growth, when compared to other conditions such as leakage levels in the distribution network, and installed storage capacity. This sensitivity analysis is depicted in Figure 4.6. It shows the development of future water availability (denoted by the WAI) for different emissions scenarios, leakage level, population growth, and storage capacity assumptions. Moreover, this analysis suggests that increased storage capacity is the most effective measure to cope with seasonal variations and decreasing water availability, as can be seen from the impact the storage capacity high scenario has on the water availability.

4.2.2 Stormwater Infrastructure Design

Figure 4.7 gives the results of the scenario analysis of raingarden performance with varying rainfall intensities and K_{sat} values. From this it can be observed that the more conservative the rainfall scenario, the higher K_{sat} is needed to meet the criteria for overflow (left side of figure) and to obtain longer peak delays (lower right side of figure). However, higher K_{sat} values also lead to lower peak flow reductions (upper right side of figure). This duality in performance with respect to high versus low K_{sat} values implies 1) that special attention should be given to the principal objective of the measure (peak flow reduction or peak flow delay) and 2) that both objectives may be achieved if a combination of measures with different infiltration capacities are considered. This concept was further investigated and detailed in Papers III and V.

Figure 4.8 shows the results of raingarden simulations conducted in SWMM. These were done as preliminary studies for configuring the SUDS-train in Paper V (Section 3.5.3). The difference in performance between one and two raingardens with respect to obtained

[1] As defined in Section 3.3.1

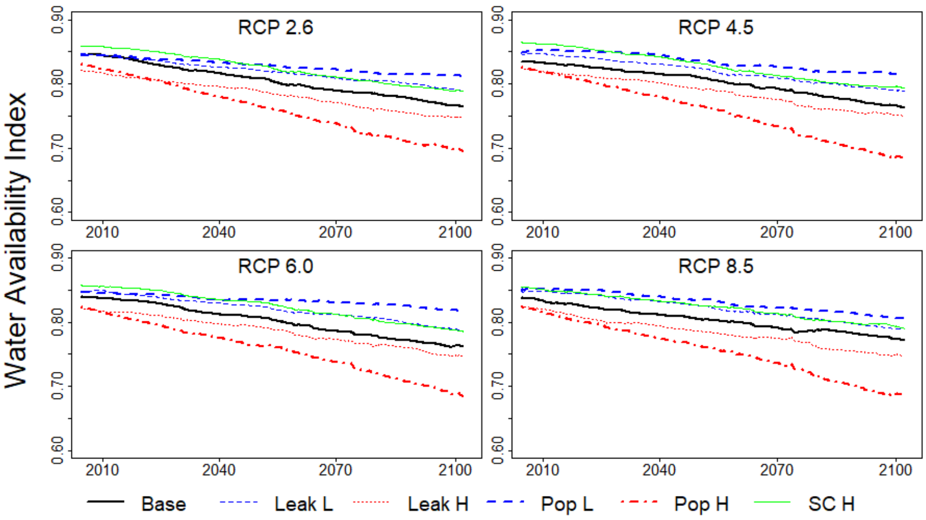


Figure 4.6: Results of the sensitivity analysis of the WAI performed in Paper I. The figure show the baseline scenario in the four investigated emissions scenarios (RCPs) along with the development of the WAI under various high (H) and low (L) assumptions for leakage level (Leak), population growth (Pop), and storage capacity (SC). Note storage capacity low has not been included since it is deemed unrealistic that the municipality would reduce it's capacity from current levels. This has been adopted from Paper I (Kristvik et al., 2019b).

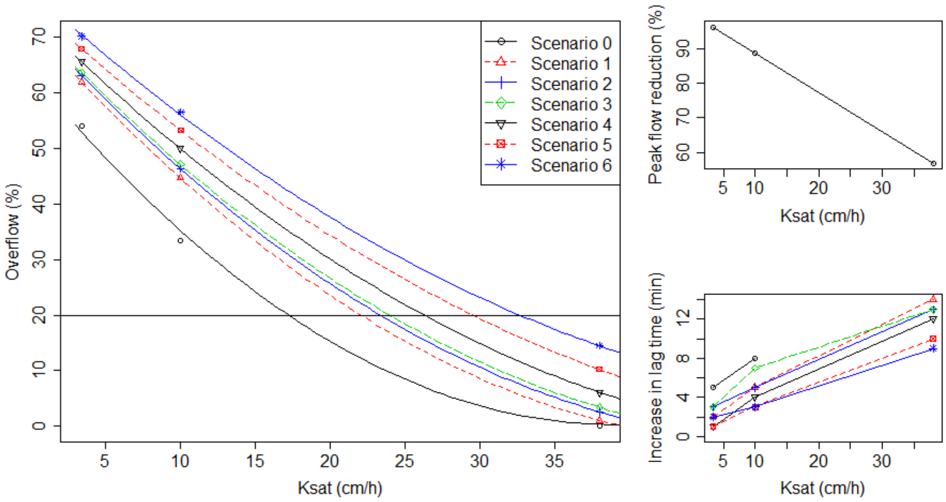


Figure 4.7: Simulated raingarden performance in Bergen under different projections of rainfall intensities and infiltration capacities of filter media. Performance is measured in terms of of overflow [%] (left side of figure), peak flow reduction [%] (upper right side), and increase in lag time [min] (lower right side). This has been adopted from Paper II (Kristvik et al., 2018b).

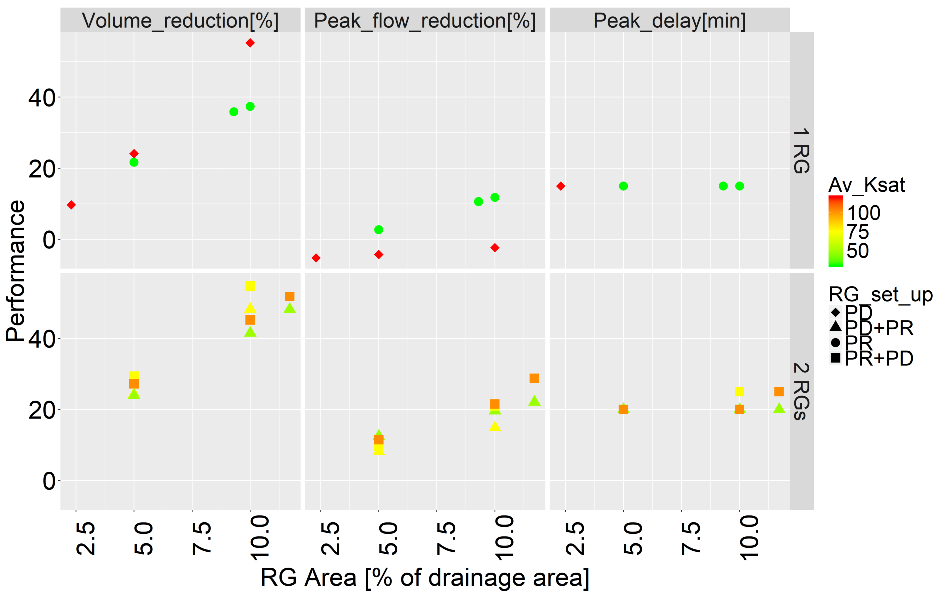


Figure 4.8: Raingarden (RG) configuration sensitivity analysis showing the SWMM-simulated performance of single (top row) and dual raingardens (bottom row) of different sizes and with different K_{sat} of the filter media. The figure shows the performance in terms of volume reduction [%] (left panel), peak flow reduction [%] (mid panel), and peak delay [min] (right panel) for different configurations. Configurations are noted PD or PR according to high K_{sat} for peak delay (PD) or low K_{sat} for peak reduction (PR). The average K_{sat} for the raingarden configuration is visualized with a gradient color, as per the legend on the right-hand side.

volume reduction is negligible. However, the use of multiple raingardens outperforms the single raingarden option with respect to peak flow reduction and peak flow delay. The results of the single raingarden simulations confirms those of Paper II, in terms of high K_{sat} leading to the highest volume reduction and low K_{sat} leading to the highest peak flow reduction. However, no difference in lag-time was obtained with varying K_{sat} in these simulations. By simulating two raingardens in series, a slightly better performance was obtained when high K_{sat} raingarden was placed before the low K_{sat} raingarden.

Finally, Figure 4.9 shows how raingardens can be used in combination with green roofs to fulfill design requirements in step 2 of the three-step approach to stormwater management in Norway (see Figure 1.2) and reduce the need for traditional, buried storage units. Simulations with both present and projected design values revealed that the required volume of such detention basins can be substantially reduced when combining SUDS. Figure 4.9 also show that required detention volumes will increase in line with the increase in rainfall intensity. Although varying, the required detention volumes with the combined configuration in Bergen under future scenarios are in similar magnitudes as the non-SUDS option (Only DB) under current conditions. Thus, these estimates imply that the proposed SUDS configuration can counteract the effects of projected climate change.

4.2.3 Urban Drainage System Performance

Urban drainage system performance was evaluated in terms of performance indicators (PIs) in Paper IV, as described in Section 3.3.3. In this paper, it was found that changes in PIs were substantially larger than the estimated changes in CIs (see in particular Figure 5 of Paper IV). This finding highlights the non-linear relationship between rainfall events and CSO events. It is the combination of smaller changes in different climate indices that cause the high changes in performance indicators. The correlations between CIs and PIs for different CSO nodes of the system were studied in detail, revealing insights to which CIs are driving for the system performance (Figure 4.10). Strongest positive correlations are found between annual PIs, such as total volume and active hours, and annual CIs, such as annual rainfall (RRyear) and number of days with precipitation > 20mm, in addition to rainfall frequencies (Fw) for various durations. Since a high increase of Fw was found for all FUB scenarios and strong correlation was found between Fw and certain PIs, this group of CIs was found to be of special interest for further adaptation planning. Higher Fw imply that there is less time after and between precipitation occurs. This indicate that

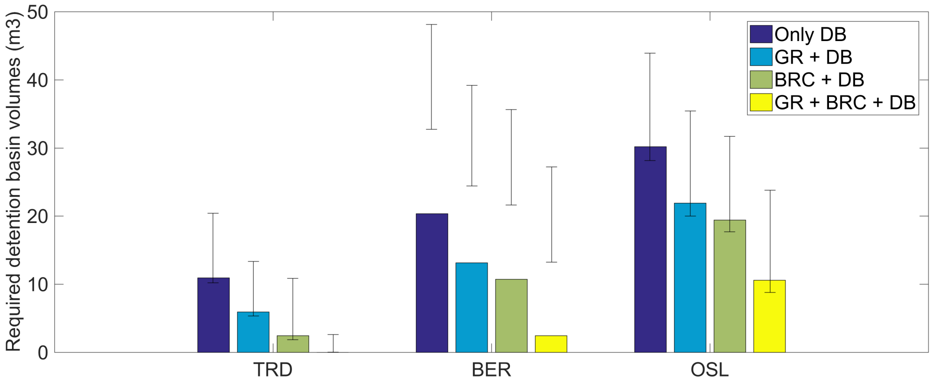


Figure 4.9: Required stormwater detention basin volumes for different combinations of green roofs (GR), bioretention cells (BRC), and detention basins (DB). Model results of design events for present (bar), future- max and min (error bars) for initial wet conditions, based on 1000 m2 impervious area and a runoff threshold of 20 l/s·ha. The analysis has been carried out for the three different cities Trondheim (TRD), Bergen (BER), and Oslo (OSL). This has been adopted from Paper III (Kristvik et al., 2019a).

adaptation planning should rely less on retention processes and, thus, more on detention capacities in the future. Although these results are site specific and limited to the FUB scenario ensemble, most results could not have been obtained if long-term continuous simulations were not performed, indicating an added value from event-based simulations. This added value should, however, be evaluated in light of the computational demand of such simulations.

Adaptation measures for CSO reduction for a subsystem at the Damsgard area was assessed (as described in Section 3.4) and the obtained cost-effectiveness for the the three selected adaptation measures, MI-MIII, outlined in Table 2.2 are presented in Figure 4.11. The highest overall effectiveness, in terms of volumetric CSO reduction, was obtained for the MIII measure, separation of the sewer system. The MI measure, safe flood ways, however, obtained the best score with respect to cost-effectiveness. MII, SUDS-train measure, was the most expensive, as expressed by costs per volume CSO reduction (m3). Furthermore, the obtained CER (NOK/m3) for the SUDS-train measure showed less resilience as it varied more over the FUB scenarios, than the remaining measures. It did, however, show better effectiveness relative to the areal disconnection, than the separation measure

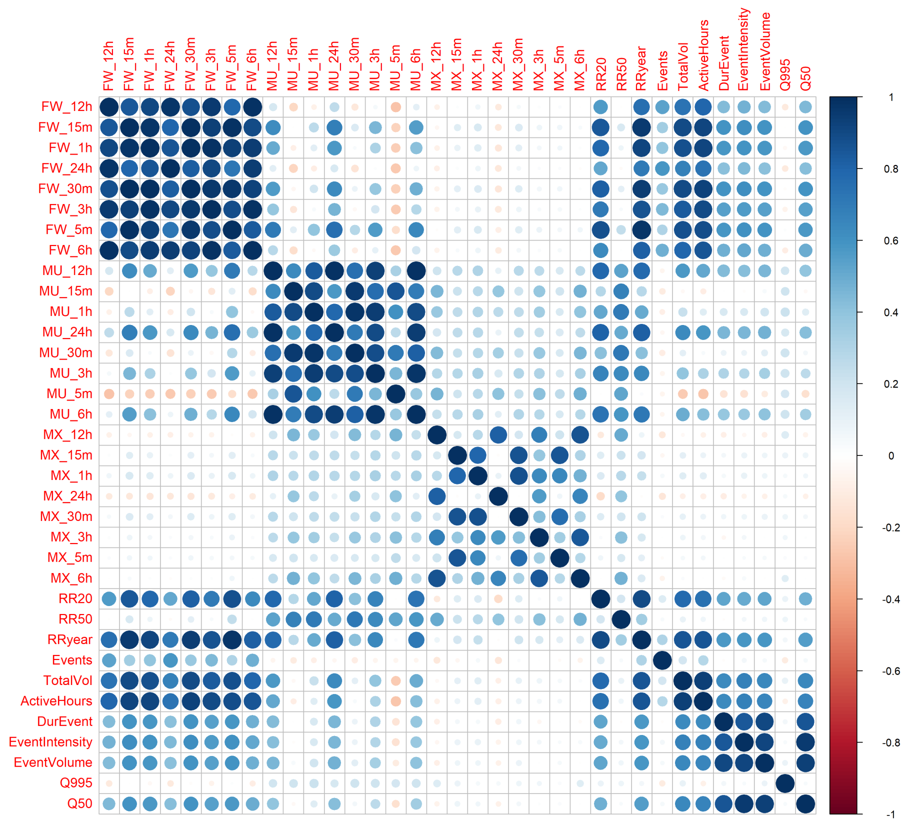


Figure 4.10: Correlation between climate indices (CIs) and urban drainage system performance indicators (PIs) for a selected CSO node of the Damsgaard area. Strongest positive correlations are indicated by darker blue colors and larger dot-sizes. This has been adopted from Paper IV.

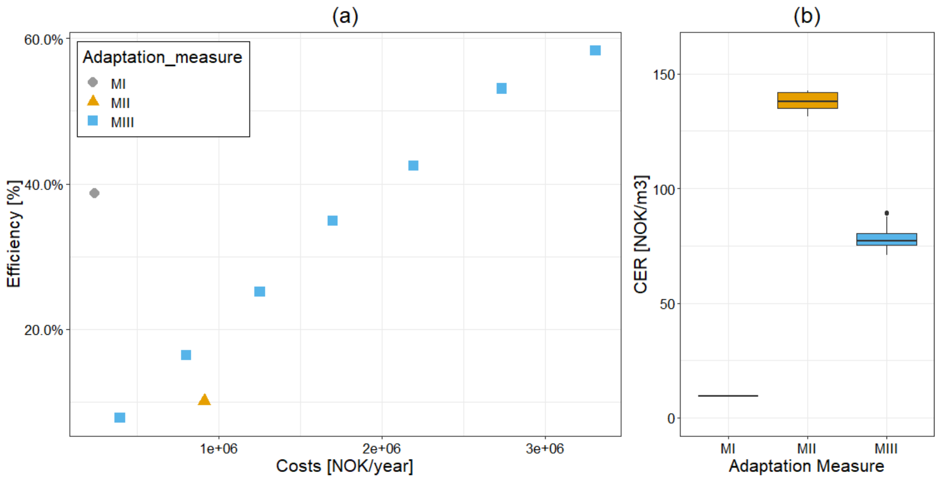


Figure 4.11: Cost-effectiveness ratio of adaption measures MI) Safe flood ways, MII) SUDS, and MIII) Separation, assessed in Paper V. In (a) the measures are plotted according to estimated effectiveness (%) (vertical axis) and cost (NOK/year) (horizontal axis). For the MIII measure, increasing levels of separation are assessed, hence multiple points. In (b), the calculated CER (cost per volume reduction) is given for each measures. All 10 FUB scenarios were assessed, and variance in obtained effectivenes, and thus CER, is represented by the box-plot. The boxes and whiskers show inter-quartile range and full range, respectively, while the median CER is represented by the horizontal line within a box. This has been adopted from Paper V.

(see Table 2 of Paper V for further details).

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Chapter 5 Discussion and Conclusions

This chapter provides a discussion of the main results of this thesis and conclusive remarks. It is structured in accordance with the research objectives defined in Section 1.5: 1) Investigate local climate projections and their potential to provide decision-support in local climate adaptation (Section 5.1), 2) Evaluate climate projections' applicability for design in current stormwater management practice in Norway (Section 5.2), and 3) Develop climate-informed adaptation frameworks for Norwegian urban water systems (Section 5.3). Finally, recommendations and venues for further work are provided (Section 5.4).

5.1 Decision-Support of Local Climate Projections

To address the first objective of this thesis, a range of local climate projections for Bergen have been assessed. The statistical downscaling and processing of regional climate projections for Bergen presented in Papers I-IV resulted in a broad ensemble of scenarios for future climate on a range of timescales and indices. The main meteorological variable of interest has been precipitation, although temperature was also considered in Paper I.

There is a general agreement in the presented ensemble of increased rainfall amounts. There were, however, also conflicting explanations of which changes in rainfall patterns are causing the increase. The main difference was found for extreme precipitation events. The temporal downscaling performed in Paper II and III both yielded substantial increase in rainfall intensity, causing a decrease in return period for heavy and extreme events. The contrary were found in the FUB projections, were the annual increase was mainly a product of increased rainfall frequencies, rather than magnitude of events. This differences between point- and gridded scale projections are to some degree expected, as regional climate models tends to smooth out extremes due to their spatial and temporal scale. Consequently, these findings emphasize the general consensus in research that ensemble approaches are necessary to gain a holistic and reliable indication of future local climate, as choices of emissions scenario, parent GCM, predictor, and downscaling techniques all introduce their own range of uncertainty. The ensemble of projections provided for Bergen shows only a limited range of uncertainty, as more projections exist or will be developed for the region.

In Paper III, the scaling model from Paper II was further developed in an attempt to improve projections. Although the scaling model adjustments were considered to give more reliable projections, the resulting change factors for rainfall intensities were much higher for Bergen than reported by other studies (e.g. Dyrrdal and Førland (2019)). This strengthens the emphasis on the uncertainties related to downscaling processes, as even similar approaches can yield very different results. It certaintly makes it difficult to make recommendations with regards to reasonable climate factors for design of stormwater infrastructure. It further highlights the drawback of purely statistical methods, where no considerations of physical processes are made.

In Paper IV, a PCA grouping of both change factors of climate indices and the urban drainage performance indicators for the FUB projections was performed in an attempt to identify the worst-case climate scenario, in terms of which scenarios are causing the most negative change, i.e. increased rainfall. As shown, CI grouping resulted in a different worst-case scenario than the PI grouping. This further strenghtens the argument for applying ensembles further in application, rather than continuing with an ensemble mean or perceived worst-case scenario.

Conclusively, the scenarios presented in this thesis should not be used individually, nor directly as decision-support for climate adaptation in a *predict-then-act* manner. Much rather, this ensemble assessment highlights the need to treat the projections as what they are: possible scenarios of future climate, sooner than predictions, and ensembles rather than singular best-guess estimates. Communicating the limitations of climate projections to local stakeholders is important, but it is also crucial that stakeholders accept the intrinsic uncertainty there is in scenario-generated projections of future climates in order for a climate-informed adaptation practice to emerge.

5.2 Adaptive Planning and Design of Stormwater Infrastructure

The second objective of this thesis was mainly addressed in Papers II and III, although certain results from the urban drainage system applications (Papers IV and V) are also relevant.

The results of Figures 4.7, 4.8 and 4.9 showed how configurations of SUDS with different retention and detention capacities had positive effects on performance, and how these effects could be used to counteract the negative effects of increased rainfall amounts (Figure

4.9). This result also indicated that the proposed SUDS configuration could counteract effects of climate change. It was shown, however, that the proposed configuration could not necessarily improve current conditions, as the same detention volume (for Bergen) is needed under future conditions and with prior SUDS detention as under current conditions without prior SUDS detention. As additional detention is still needed for large events, this places the proposed SUDS solution in step 1 of the three-step approach, as outlined in Section 1.4. The investigations of performance strongly suggest that the effects of SUDS measures placed prior to detention functions should be accounted for in design in order to obtain more optimal solutions.

The latter statement is supported by results of Paper V, where SUDS measures were found to be sub-optimal in terms of cost-effectiveness when compared to other adaptation measures. Although the goal of implementation in this paper was to reduce CSO volumes downstream, the SUDS were designed by a conservative criterion in order to simulate a step 2 measure. This led to extensive measures in terms of areal occupation and costs. Thus, although the measure performed well in terms of effectiveness, it gained a lower rank in the decision-support tool due to high cost-effectiveness. This further strengthens the conclusive statement of the previous paragraph that the role of SUDS in combination with other functions should be considered in order to obtain optimal solutions. As discussed in Paper V, the specific result for Bergen differ from other studies where SUDS are found to be more cost-effective than conventional, buried measures. The difference is explained by an 'economies of scale' effect occurring from the conservative design criteria of storm sewers in Norway, compared to less conservative design criteria in other studies causing the material costs to rise relative to the amount of stormwater the sewers can drain. This emphasizes the need to differentiate measures not only by their technical form and attributes, but also their hydraulic capacities according to the three-step approach. Furthermore, SUDS provide a panoply of positive side-effects that are unaccounted for in the proposed framework which was kept as simple as possible in order to balance the increased complexity due to the use of extensive data sets. Thus, the results highlights the difficulty there is in balancing method complexity and at the same time provide framweworks that gives a fair comparison.

Lastly, the results of Paper II and III show how greatly the performance of blue-green infrastructure varies under different climate scenarios (e.g. Figures 4.7 and 4.9). This complicates the decision-basis, but also emphasizes the value of evaluating scenarios in design practice. As no conclusion on which climate scenario or climate factor is the most likely can be made, other acceptance criteria should also be considered in design-decisions. In terms of climate-informed frameworks, this leads to a risk-oriented approach. To arrive at such, consequence assessment could be included in the design phase. This could involve investigation of the consequences in case of failure under different climate scenarios, and in each of the steps of the three-step approach. As extreme events are associated with the highest consequence, the third step of the approach is a natural point of departure - a concept that was also presented in the thesis work by Stokseth (2019) and subsequently in Stokseth et al. (2019). Stokseth (2019) propose to start analyses with flow path identification with the purpose of both securing safe flood ways but also for the purpose of identifying suitable locations for SUDS. This introduces a dependency between step 2 and 3, as indicated in red in Figure 5.1 where a revised three-step approach is presented. To include the conclusive statements of the preceding discussions, a dependency between step 1 and 2 is also introduced in the figure. This signals the recommendation of using SUDS-trains to obtain acceptable performance in both steps of the approach.

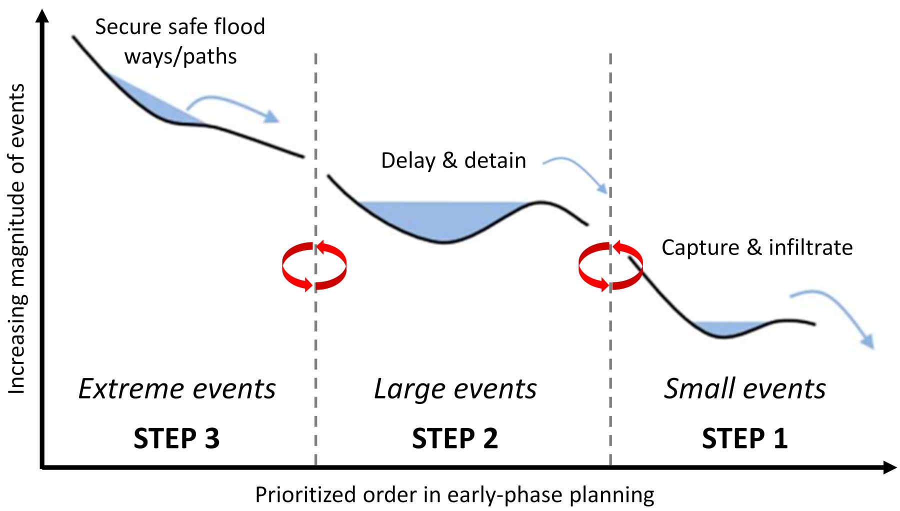

Figure 5.1: Revised Three-step Approach for Stormwater Management, as modified from Paus (2018) and Stokseth et al. (2019).

5.3 Climate-Informed Adaptation Frameworks for Urban Water Systems

To contribute to the third and final objective of this thesis, assessment frameworks for the two selected applications 1) water supply and 2) urban drainage systems, have been proposed and demonstrated.

Firstly, the WAI approach presented in Paper I was demonstrated for the assessment of water availability in Bergen. The approach allowed to investigate different measures and strategies for adaptation using both climate projections and consumption scenarios as input, thus providing a combined top-down and bottom-up, climate-informed, assessment. With sensitivity analysis of the WAI, different adaptation measures affecting either supply or demand side of available water resources could be evaluated.

For urban drainage systems, a long-term, continuous simulation of CSO under a climate scenario ensemble was presented in Paper IV. To analyze the extensive data set resulting from such simulations, an approach based on reducing the time series to indicator sets was conducted. Based on the analyzes and discussion of the results, a proposal for how the different results could be used in different steps of a risk management process was presented. It specifically showed how the analyzes revealed suitable risk indicators from the climate indices set and discussed how certain CIs showing high correlation to PIs could guide adaptation measure selection. It was also indicated that the resulting time series could be used in quantitative risk assessment - an effort that was not presented in the paper (due to results being confidential), but was performed as part of work-package 4 of BINGO. Most importantly, Paper IV highlighted the pros and cons of performing such demanding simulations by discussing the informational gain in light of the extensive resources necessary to conduct the simulations, defined as the net added value of the process. With the continuous development and increasing capacity of computational tools and models, it is also likely that the added value will grow.

Finally, climate adaptation decision-support was provided in Paper V, by including a range of climate information in a well-established framework for cost-effectiveness assessments. The same CSO scenarios that were used in Paper IV, were used in Paper V to identify CSO nodes for which risk reduction was necessary. The effectiveness of end-user selected adaptation measures (Section 2.2) was assessed using system knowledge and spatial data to construct adaptation measure land-use scenarios and estimating the effectiveness under the projections. This paper further linked more results together, by using recommendations from Paper II of a dual raingarden set-up with varying K_{sat}, the concept from Paper III of green roof and raingarden configuration of SUDS trains, in addition to applying projected rainfall intensities from Paper III for theoretical design of the different measures. Although limitations of the method are present, a point-of-departure for further development of climate-informed decision-support has been established.

The three frameworks summarized above, all add a new dimension of climate change information in traditional tools known to the water sector. In addition to addressing the third, and last objective of this thesis, it also aims to contribute to the principle goal of BINGO: to provide end-users in the water sector with *practical* tools and knowledge on climate change. Although the results are site specific, linking frameworks to existing tools ensure scalability and transferability of methodologies.

5.4 Recommendations and venues for further work

The aim of this thesis has been to contribute to the development of climate-informed frameworks for urban water systems, such that the increasing knowledge base on climate change can provide decision-support in water sector applications. The results strongly suggest to include climate scenario ensembles in both planning and design of urban water systems. However, as discussed in the preceding sections, there are still gaps to be filled in order to for such a practice to emerge.

The investigation of locale climate projections showed a wide span in projected local climate. The main challenge of this is the resulting low confidence in single model, RCP or downscaling method projections. It is also still difficult to obtain projections that are of sufficient spatial and temporal resolution. These data shortcomings needs to be further addressed through climate modeling and downscaling development.

As clearly stated, projection improvement alone is not enough to form a climate-informed practice, as the intrinsic uncertainty of the future course of society and emissions scenarios cannot be predicted. Thus, modifying existing tools and water application models for planning and design to handle input scenarios rather than single event or time series is key. Some developments for certain applications are proposed in this thesis, but further adjustments of existing tools and models are highlighted as a venue for further work. In order to be of practical value to local stakeholder such development should be focused on balancing the complexity of tools and models in relation to the added value the adjustments provide.

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Appendix A Selected Papers

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Paper I

Assessment of future water availability under climate change, considering scenarios for population growth and ageing infrastructure

Erle Kristvik, Tone Muthanna and Knut Alfredsen 2018

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Assessment of future water availability under climate change, considering scenarios for population growth and ageing infrastructure

Erle Kristvik, Tone M. Muthanna and Knut Alfredsen

ABSTRACT

Climate change is likely to cause higher temperatures and alterations in precipitation patterns, with potential impacts on water resources. One important issue in this respect is inflow to drinking water reservoirs. Moreover, deteriorating infrastructures cause leakage in water distribution systems and urbanization augments water demand in cities. In this paper, a framework for assessing the combined impacts of multiple trends on water availability is proposed. The approach is focused on treating uncertainty in local climate projections in order to be of practical use to water suppliers and decision makers. An index for water availability (WAI) is introduced to quantify impacts of climate change, population growth, and ageing infrastructure, as well as the effects of implementing counteractive measures, and has been applied to the city of Bergen, Norway. Results of the study emphasize the importance of considering a range of climate scenarios due to the wide spread in global projections. For the specific case of Bergen, substantial alterations in the hydrological cycle were projected, leading to stronger seasonal variations and a more unpredictable water availability. By sensitivity analysis of the WAI, it was demonstrated how two adaptive measures, increased storage capacity and leakage reduction, can help counteract the impacts of climate change.

Key words | adaptation, climate change, leakages, statistical downscaling, water availability, water supply

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INTRODUCTION

A safe and steady drinking water supply is one of the most important public goods there is. As awareness of climate change increases, there is rising concern for the future reliability of drinking water supplies. Climate change is likely to cause higher temperatures and alter precipitation patterns (IPCC 2013) and the understanding of the local impacts of this on the hydrological cycle is highly relevant for planning a provident water supply. At the same time, more and more people live in cities, yielding more strain on existing water supply systems as the water demand increases in pace with population growth. In addition, many cities experience high levels of water losses due to ageing infrastructure and deteriorating pipes. Responsible water suppliers need to assess both the potential negative effects of climate change to supply and the trends towards increased water demand if they wish to secure reliable water supply services in the future.

There exist numerous studies of the impacts of climate change on the hydrological cycle, water resources, and availability, see for instance Barnett *et al.* (2008) or Schewe *et al.* (2014). The impacts are estimated by hydrological models that are driven by the input of meteorological variables such as temperature, precipitation, and evapotranspiration. Thus, the hydrological impacts of climate change may be

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estimated by using projected values of the meteorological input variables required by the model. Global climate models (GCMs) are the primary source for projections of future climate, being comprehensive numerical models that simulate the past and future responses to external forces, such as greenhouse gases in the atmosphere (IPCC 2013). Representative concentration pathways (RCPs) are the state-of-the-art scenarios of future emissions in terms of the net radiative flux changes ($W\,m^{-2}$) in the year 2100 (Moss *et al.* 2010). The most recent group of scenarios consist of four scenarios: RCP2.6, RCP4.5, RCP6.0, and RCP8.5, where the number in each scenario name indicates the level at which the net radiative-flux change will stabilize by the end of the 21st century.

Over the last decades, GCMs have evolved and become more and more detailed. However, they are limited by coarse spatial and temporal resolutions and need further downscaling before they can be applied in local-scale studies (e.g. Fowler *et al.* 2007; Maraun *et al.* 2010). Several techniques for downscaling have been developed and they vary from dynamical to statistical approaches. Dynamical downscaling involves the nesting of a regional climate model within the boundaries of a GCM, such that sub-GCM grid scale features are simulated (Wilby *et al.* 2002). Statistical downscaling focuses on the statistical relationship between some large-scale variable and the local climate, defined by Benestad *et al.* (2008) as 'the process of making the link between the state of some variable representing a large space and the state of some variable representing a much smaller space'. Compared with the statistical approach, a strength of dynamical downscaling is that it is based on physics and resolving of atmospheric processes at the local level (Wilby *et al.* 2002). However, the application of dynamical downscaling requires significant computing resources compared with statistical models, which are also more flexible because they can be adapted to other regions other than the ones for which they are built. Some of the statistical downscaling techniques have resulted in practical tools, which contributes to making climate scenarios more available to impact assessors. Examples of such are the statistical downscaling software *SDSM* (Wilby *et al.* 2002) and the *R*-package '*esd*' by Benestad *et al.* (2015).

The availability of climate projections for impact studies are improving (CMIP5 2013), but there are still challenges related to handling the uncertainty of the projections. Ekström *et al.* (2015) categorized the uncertainty in climate projections into the uncertainty related to external forces (Type I), the uncertainty related to the climate system's response to these forces (Type II), and uncertainty due to natural variability (Type III). The paper argues that Type I uncertainty is handled using different emissions scenarios. Furthermore, using multi-model ensembles (ensembles of different GCMs) and perturbed physics ensembles (ensemble of one GCM with differing initial conditions and parameter schemes) should account for Type II and Type III uncertainty, respectively. Giorgi & Mearns (2003) proposed the 'Reliability Ensemble Averaging' method for assessing the reliability of simulated changes in multi-model GCM runs. The method involves quantifying the reliability of regional GCM simulations by combining two reliability criteria that accounts for: (1) the models' ability to reproduce historical and present day climate (the model performance criterion); and (2) the convergence of the models' simulated climate to the ensemble mean (the model convergence criterion). By following this framework it is possible to assess the probability of climate projections exceeding given thresholds and reduce predictive uncertainty in hydrological impacts studies (Giorgi & Mearns 2003).

GCM ensembles, downscaling, and reliability-weighted projections add valuable information that enables a better understanding of the future climate. However, the intrinsic uncertainty that accompanies the climate scenarios and projections makes it complicated to use them as a basis for decision making. Local water managers and stakeholders are still in need of easy-to-use tools that facilitate the assessment of water vulnerability (Sullivan 2011) and enable decision making and that are robust to the uncertainties of the future climate (Fowler *et al.* 2007). Thus, several studies have focused on the development of such tools, usually expressed as metrics or indexes that can quantify and measure the levels of impacts (see, for example, the robustness index defined by Whateley *et al.* (2014), or an overview of existing water vulnerability indices by Plummer *et al.* (2012)). Furthermore, Xia *et al.* (2012) defined water vulnerability as the ratio between the sensitivity of a water system to climate change and the adaptive capacity of the same system, and employed the framework to a case study in China. Their results led to the conclusion that water management in China needs to shift from supply-oriented to demand-oriented management.

Recent studies of water resources availability under climate change in the city of Bergen, Norway, suggests a potential conflict between water supply and demand unless water losses in the distribution network are reduced (Kristvik & Riisnes 2015). Accordingly, water supply security could improve by making changes at the demand side of water management (i.e. reduce leakages). However, the study also highlights the need for practical tools that both reveal a supply system's vulnerability to external factors, such as climate change and population growth, and shows the system response and sensitivity to changes in conditions that decision makers can control, such as leakage rates (demand side) and levels of installed storage capacity (supply side).

This paper suggests a framework for assessing future water availability in cities with the aim of resolving some of the issues described in this section. These are, specifically: (1) high levels of uncertainty in local climate projections; and (2) lack of easy-to-use tools to facilitate water availability assessments. To address the first issue, a large ensemble of climate data is statistically downscaled and the site-specific projections are prepared. Furthermore, an index for water availability (WAI) is introduced. This index accounts for climate change as well as other straining factors that cities may experience, such as population growth and deteriorating infrastructure for water supply. Finally, a demonstration of the WAI is presented through scenario and sensitivity analyses where the effects of counteractive measures that reduce negative impacts on water availability are investigated.

MATERIALS AND METHODS

Study area

Bergen is the second largest city in Norway and located on the west coast of the country. The climate is wet and mild with an annual normal precipitation of 2250 mm and mean annual temperature of 7.6 °C (monthly normal values for 50540 Florida Weather Station, http://www.eklima.no/). Bergen is a particularly rainy city due to its exposure to westerly winds and the pronounced topography characterizing the city. Statistically, the spring and summer months represent the driest period (see Figure 1 in Results and Discussion section). Usually, this does not conflict with water supply as snowmelt in this period makes up for lower precipitation amounts. However, the city has experienced substantial dry periods that have challenged water supply. The latest incident was in winter 2009–2010 when the climate was unusually dry and cold. At the turning point, water levels had dropped to half of their usual levels (Kristvik & Riisnes 2015).

The raw water serving the water supply system in the city is drawn from several reservoirs located close to the city centre and the water is treated at five major treatment plants: Svartediket, Jordalsvatnet, Espeland, Kismul, and Sædalen. Water from these plants is supplied to the inhabitants of Bergen through a distribution system comprising 900 km of pipe network. The network is complemented by transfer tunnels between treatment plants, securing a steady supply even if one plant is out of service (Bergen Municipality 2015).

Most (97%) of the total population of 278,000 inhabitants in Bergen are connected to the municipal water supply. In 2014 the estimated domestic consumption amounted to 45% of the produced drinking water, 21% was consumed by industry and 31% was ascribed to leakages in the distribution network (3% unspecified) (Bergen Municipality 2015; Statistics Norway 2016a). The municipality is continuously working on reducing the high level of leakages and the objective is to achieve a leakage level that equals 20% of produced water by 2024 (Bergen Municipality 2015). However, regional centres in Norway, such as Bergen, are expected to experience high population growth due to urbanization (Tønnessen & Leknes 2016). Thus, although the municipality is working on reducing water production by rehabilitating leaking pipes, the overall consumption is expected to increase as there are strong indications of continued population growth throughout the 21st century.

Projections of future climate

Output from GCMs is available through the Coupled Model Intercomparison Project phase 5 (CMIP5). The projections of temperature and large-scale precipitation for all available emissions scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5)

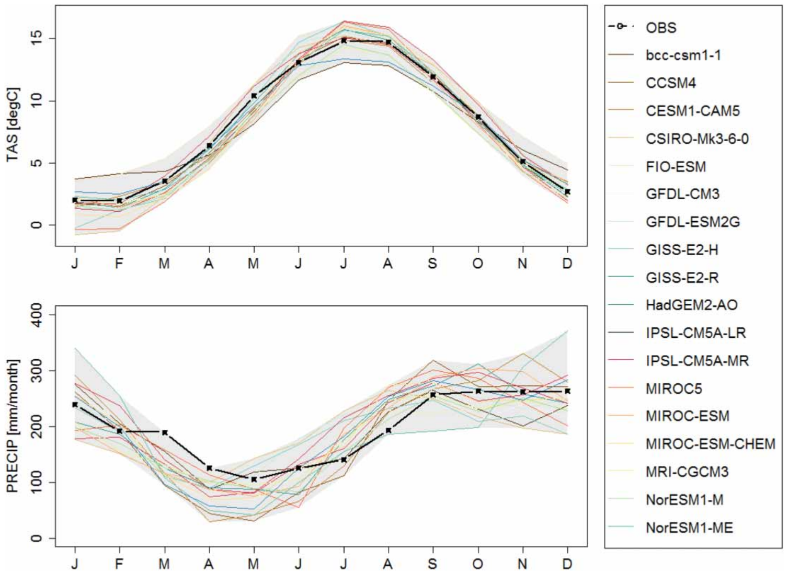

Figure 1 | Historical climatology (1975–2005) from downscaled GCMs. The lines express the observed and simulated climatology, while the shaded areas represent the range of climatology simulated by the downscaled GCMs.

and from a selection of GCMs (Table 1) were statistically downscaled. The GCMs were selected based on a criterion that the results had to be comparable across emissions scenarios. Thus, only models that were run with all RCPs were selected. In addition, only GCM output from simulations with the same realization ID were selected. Based on this, the total number of common GCMs was 19. The downscaling was performed following the statistical approach as described by Benestad *et al.* (2008) and using tools provided by Benestad *et al.* (2015). The gridded datasets of observed temperature and large-scale precipitation from the NCAR/NCEP reanalysis (Kalnay *et al.* 1996) were combined with gridded projections of the same variables from GCMs to create common empirical orthogonal functions (EOFs). The common EOFs were used to fit a linear regression between the principal components of the EOFs and station data of observed temperature and precipitation from 50540 Florida Weather Station in Bergen. The regression model was calibrated with station data from the period 1975–2005 and gridded NCEP/NCAR reanalysis with a monthly time resolution. The obtained statistical relation was then employed to the GCM outputs to project monthly precipitation and monthly temperature at the Florida Weather Station for the period 2006–2100.

The climate projections were further refined using a modified version of the Reliability Ensemble Average (REA) methodology described by Giorgi & Mearns (2003). Herein, an averaging of the projections from the different GCMs was performed. The averaging was based on two criteria: model performance and model resemblance. For each criterion, the projections from the different GCMs were given a rank. Firstly, the models were ranked based on their ability to reproduce the historical climate in Bergen. This was achieved by comparing the monthly precipitation and mean monthly temperature produced by the GCMs over the reference period 1975–2005 with observations from the research site. Secondly, the monthly temperature for the period 2071–2100 and for each GCM were compared to the ensemble mean of each variable and RCP for the same period. The closer the GCM simulations were to the ensemble mean, the higher the rank. The ranks were given equal weights and combined into one overall reliability rank for each GCM.

Table 1 | List of selected GCMs for downscaling to 50540 Florida Weather Station

Model name	Modelling centre / group	Institute ID
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	BCC
CCSM4	National Center of Atmospheric Research	NCAR
CESM1-CAM5	Community of Earth System Model Contributors	NSF-DOE-NCAR
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
FIO-ESM	The First Institute of Oceanography, SOA, China	FIO
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
GISS-E2-H	NASA Goddard Institute for Space Studies	NASA GISS
GISS-E2-R	NASA Goddard Institute for Space Studies	NASA GISS
HadGEM2-AO	Met Office Hadley Centre	MOHC
IPSL-CM5A-LR	Institute Pierre-Simon Laplace	IPSL
IPSL-CM5A-MR	Institute Pierre-Simon Laplace	IPSL
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC
MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC
MRI-CGCM3	Meteorological Research Institute	MRI
NorESM1-M	Norwegian Climate Centre	NCC
NorESM1-ME	Norwegian Climate Centre	NCC

Note: Overview and links to detailed model descriptions: http://cmip-pcmdi.llnl.gov/cmip5/availability.html.

Further, the reliability rank assigned to each GCM was used to calculate a weighted average of the temperature and precipitation projections, where a higher model rank gave the model higher weight in the averaging procedure. This was performed for three scenario intervals 2011–2040 (near term), 2041–2070 (medium term) and 2071–2100 (long term).

From this, change factors, i.e. the difference between historical climatology and downscaled climate projections, were calculated in accordance with the method outlined in Hamududu & Killingtveit (2016), where change factors for temperature are calculated as the absolute difference between observed and projected mean temperature and change factors for precipitation are calculated as the percentage difference between observed and projected precipitation. Change factors were calculated for each month of the year and for all scenario intervals.

Projections of future inflow

Inflow from the catchments surrounding the drinking water reservoirs in Bergen was projected using a hydrological model for the Bergen region (Kristvik & Riisnes 2015). The applied model is the lumped version of the conceptually based HBV model (Bergström 1976) for rainfall-runoff modelling. This model uses the change factors and historical records of daily temperature, precipitation and evapotranspiration as input to calculate the runoff in each catchment. In addition, the model takes in geographical parameters such as catchment area, hypsographic distribution, forest percentage, and lake percentage. The model structure consists of four storage elements: snow, soil moisture, upper zone, and lower zone. In each zone the inflow, storage level, and outflow to the next zone is calculated. Time series of daily temperature and precipitation to run the model were collected from the main weather station in Bergen (station ID: 50540 Florida) while evapotranspiration was calculated based on temperature observations and projections using the Thornthwaite method. The existing HBV model distributes the monthly change factors over the inherent days of one month such that the model can run at a daily time step. Evidently, the delta change approach has a drawback in assuming stationarity of the daily distribution over the year and for only adding changes in amounts. However, given this paper's emphasis on water resource availability, daily variations are not needed. Simulations were run for the historical period 1980–2009 and the three scenario intervals (near, medium, and long term) for all RCPs.

Water availability index (WAI)

An index for water availability was defined to facilitate the analyses on the effects of different drivers on water availability in the future. Herein, water availability is defined as the total amount of water that is available for water supply when requirements to minimum storage reserves are accounted for. Minimum storage reserves (RR) refer to the volume of water that is always required in the reservoirs. The municipality in Bergen has set this threshold to a volume that corresponds to 50 days of consumption. The water availability index (WAI) is defined as the ratio between the available water and the capacity of the system to store water (Equation (1)):

$$WAI(t) = \frac{SW(t) - RR(t)}{SC} \tag{1}$$

where WAI(t) is the WAI at time t, SW(t) is the stored water at time t, RR(t) is the required storage reserves at time t, and SC is the installed storage capacity. Stored water, SW, is a reservoir balance considering all the water that enters the reservoirs and all that is withdrawn, such that:

$$WAI(t) = \frac{SW(t-1) + (Q_{in}(t) - Q_{out}(t))dT - RR(t)}{SC} \tag{2}$$

where Q_{in} represents the inflow from surrounding catchments to the drinking water reservoirs. As there are transfer tunnels in the distribution network of Bergen that connect the treatment plants, the water balance is treated as a one-reservoir model where Q_{in} is the sum of all inflows to the various reservoirs. Q_{out} covers consumption, water lost to overflow when reservoirs are full, and a regulated flow of $12\ m^3\ s^{-1}$ that is released from the reservoir connected to the Espeland treatment plant during the period 1 April to 30 September. The consumption is defined as:

$$C_{tot} = (1 + a)C_{sp}P \tag{3}$$

where C_{tot} (m^3/timestep) is the total consumption, a is the leakage rate, C_{sp} (m^3/people/timestep) is the specific consumption related to the real consumption (e.g. domestic, industrial, and other), and P (people) is the total number of people supplied by the municipal water supply. C_{sp} was kept at a constant level of 241.3 liter/people/day (7.2 m^3/people/month) based on numbers provided by the municipality (Bergen Municipality 2015). The scenarios for population size, P, were based on population projections from Statistics Norway (2016b). Three scenarios from Statistics Norway's projections were selected: (1) the main alternative (MMMM); (2) low national growth (LLML); and (3) high national growth (HHMH). These scenarios provide projections until 2040 and were extrapolated until 2100 to match the length of the climate projections in this study. The extrapolated scenarios correspond to a monthly population growth of 177(MMMM), 88(LLML), and 301 (HHMH) people per month.

RESULTS AND DISCUSSION

The climatology for the reference period 1975–2005 simulated by the downscaled GCMs is presented in Figure 1 along with observed climatology for the same period. All GCMs are plotted, yielding a range of values for each month represented by the shaded areas. The bandwidth of this range varies for the two variables (temperature and precipitation) and for each month of the year. From visual inspection, it is observed that the offset is larger for precipitation amounts than average temperatures, i.e. the downscaling of temperature is more accurate. Furthermore, there is a general tendency of underestimation in precipitation amounts in spring months (March, April, and May) overestimation in summer months (June, July, and August).

Mehran *et al.* (2014) investigated the bias between CMIP5 continental precipitation simulations and satellite-based gauge-adjusted observations, and found that, in general, monthly precipitation is well captured by most GCMs. However, inaccuracies of downscaled GCMs to the city of Bergen have been demonstrated. Due to their coarse spatial resolution, large-scale precipitation is not able to capture effects of local conditions, such as pronounced topography. Jonassen *et al.* (2013) demonstrated how spillover effects from certain mountains in Bergen strongly influence precipitation patterns, which could indicate limitations in using large-scale precipitation as predictor for local precipitation in Bergen. Nevertheless, the downscaled GCMs capture the seasonal variations over the year, characterized by high precipitation amounts in the colder months (winter and fall) and lower precipitation during spring and summer, which is considered adequate for the purpose of assessing long-term water availability.

Furthermore, variations in simulated climate can also be found in the future projections, as illustrated by Figure 2, which renders the distributions of the long-term change factors estimated from all downscaled GCMs and RCPs before any weighting or averaging. The monthly projections span a wide range making the difference in projections across RCPs not easily detected visually. This span reflects the Type II uncertainty described by Ekström *et al.* (2015), discussed in the Introduction of this paper. Type II uncertainty comprises the uncertainty linked to the climate system's response to emissions. Using an ensemble of different GCMs, with different representations of the climate system and its processes, and gives a range of possible responses that capture this uncertainty. These results also illustrate the importance of using multi-model ensembles in climate impact studies, as the risk of a GCM being an outlier compared to the ensemble mean is high when using a single model.

The impacts of different emission scenarios are visualized in Figure 3, where the projections are reduced to change factors using the reliability ensemble averaging procedure. Temperature changes show a clear trend towards higher levels throughout the 21st century and increase in line with higher emission scenarios. Precipitation changes are less distinct, but also here, the highest emission scenarios result in the highest changes. The changes are in general positive (i.e. more precipitation) on an annual basis, however, they also imply increased variations between the dry spring and summer months and the rest of the year. The results are, to some degree, in agreement with other

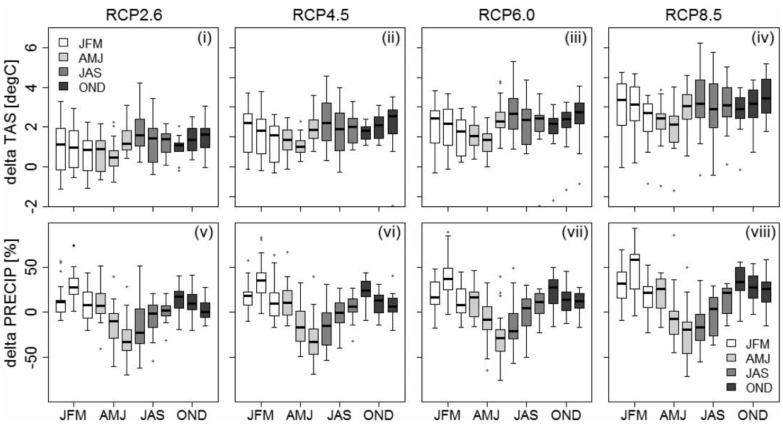

Figure 2 | Long-term (2071–2100) monthly change factors for (i)–(iv) temperature and (v)–(viii) precipitation from the model ensemble. The figure shows the spread in change factors simulated by the GCMs, expressed by boxes restrained by the 75th (upper box limit) and 25th (lower box limit) percentiles. The simulation results are grouped by months of the year starting in January and ending in December.

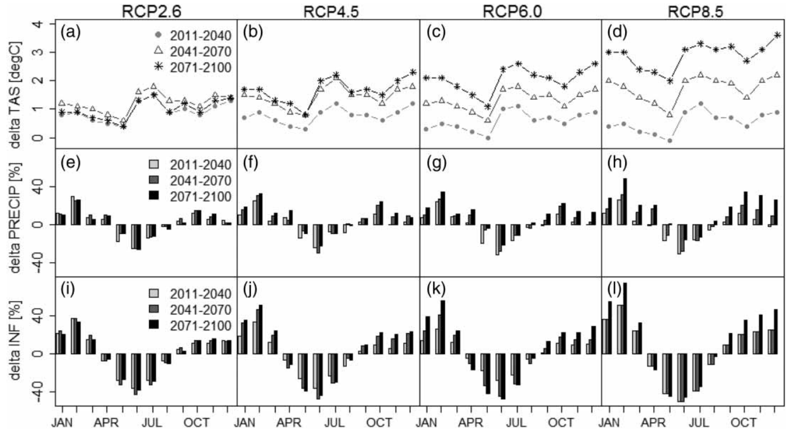

Figure 3 | Computed change factors for (a)–(d) temperature, (e)–(h) precipitation and (i)–(l) total inflow from the reliability-based averaging procedure and hydrological simulations with the HBV model.

studies covering the region of Bergen. Projections for the county of Hordaland, in which the city of Bergen is located, are provided by Norwegian Centre for Climate Services (2016) (NCCS). In this report, the annual temperature is projected to increase by 4 °C and precipitation is expected to increase on an annual basis. The projections for spring and summer months differ, as NSSC project an increase in these months, rather than a decrease as suggested by the downscaling performed in this study. However, the downscaling made by NCCS is performed with a different methodology than the one outlined here, which might explain some of the divergent projections.

Figure 3 also depicts scenarios, represented as change factors, for future inflow to the drinking water reservoirs. The projected changes in inflow mirror the increased seasonal variations in precipitation amounts. They also reflect the impacts of rising temperatures. These are particularly evident in the month of April where a decrease in inflow is projected despite estimations of increasing precipitation. The decreasing inflows in April are likely to be a result of higher temperatures, less snow accumulation, and finally less snow melt during spring. The results are consistent with findings by Arnell (1999), who demonstrated that effects of climate change on hydrological extremes is likely to be strongest in regions where snow regimes are weakened due to higher temperatures, leading to heavier winter runoff and decreased runoff during spring. Furthermore, due to higher temperatures and thus more evapotranspiration, the negative change factors in spring and summer are more severe for inflow than for precipitation.

Moreover, an increase of inflow during the remaining months of the year is projected. This increase indicates a potential for storage on both the near-, medium-, and long-term basis. To the projected scenarios, an increase of the storage capacity would allow for storing the increased inflow during winter such that the increased gap between dry and wet seasons is closed and a steady supply during summer months is secured.

The projected inflow scenarios are further used to calculate the WAI and the results are depicted in Figure 4. To assess the difference between the emission scenarios, all other variables (population growth, leakages, and storage capacity) are kept at a base level as rendered in Table 2. In this 'business-as-usual' scenario, leakages and storage capacity are kept at today's level, while the population projections follow the main alternative (MMMM) of Statistics Norway's population projections (Statistics Norway 2016b). The results show that the WAI is decreasing and the expected value is approximately the same for all emissions scenarios. However, the standard deviation increases with higher emissions scenario. The decreasing trend of the WAI implies a decrease in water supply security and

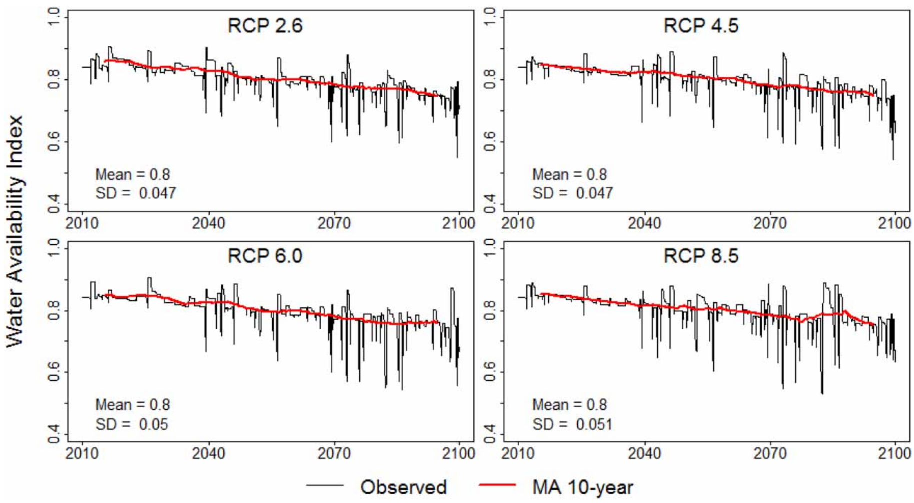

Figure 4 | Computed WAI for varying inflow corresponding to the four emissions scenarios and base levels for leakages, population growth, and storage capacity. The time series are plotted with the moving average using a 10-year window.

increased vulnerability. Moreover, the increased standard deviation to the higher emissions scenarios indicates that the higher emissions lead to more unpredictable water availability.

Furthermore, the level of leakages, population growth and storage capacity were changed one by one (while the others were kept at base level) as given in Table 2.

Changing the parameters one by one afforded five additional scenarios: (1) low leakage rate (Leak L); (2) high leakage rate (Leak H); (3) low population growth (Pop L); (4) high population growth (Pop H); and (5) increased storage capacity (SC H). The results are presented in Figure 5. In all emission scenarios, the WAI is most sensitive to, and negatively affected by, population growth. There are two main reasons for this: increased population causes increased water consumption putting more strain on stored water (SW); and the WAI is constrained by required storage reserves (RR), which are directly influenced by the population as the required volume equal to 50 days of consumption will increase with population growth. Moreover, the scenario for low population growth (Pop L) has the most positive impact on the WAI for each emission scenario. Furthermore, Figure 5 shows the effect of the counteractive measures (leakage reduction and increased storage capacity), as well as the effects of letting the leakage level exacerbate to higher levels (40%). Although it does not have as great an impact on the WAI as population growth, allowing leakages to reach a level of 40% will have a clear negative impact on the WAI. Reducing leakages to the desired level of 20% will have a positive impact. However, the effect of this level will have approximately the same effect on the WAI as increasing storage capacity by approximately 10% (illustrated by the coinciding plots of Leak L and SC H).

Table 2 | Selected scenarios for sensitivity analysis of the WAI

Scenario	Leakages (%)	Population growth (people/month)	Storage capacity (Mm^3)
Base	30	177	26.5
Low	20	88	26.5
High	40	301	30.0

Demand management does not appear to be the only viable option for addressing low water availability in Bergen, as concluded by Xia *et al.* (2012) in their Chinese case study. On the contrary, several studies argue that increased storage capacity will help in coping with increased seasonal variations and that the necessity for dams will

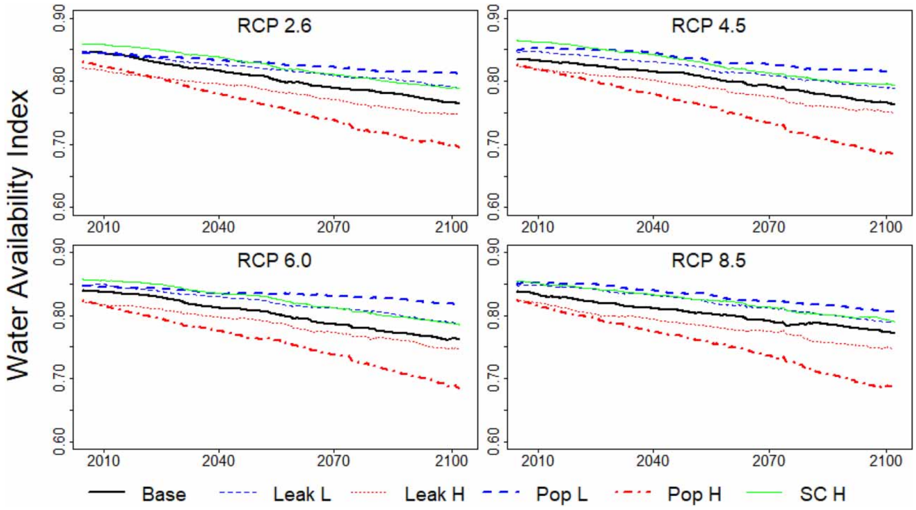

Figure 5 | Sensitivity of computed WAI (10-year MA) to changes in leakages, population growth, and storage capacity.

increase (e.g. Ehsani *et al.* 2017), while others have found that a combined solution is more appropriate (Lopez *et al.* 2009). Ultimately, comparing the cost and benefit of supply vs. demand side measures could enrich the analysis and help determine the optimal action to be taken for the specific case of Bergen.

CONCLUSIONS

This paper has presented a framework for assessing future water availability in cities. The suggested framework is tailored to account for not only climatic changes at the local level, but also other factors that might put strain on future water supply, such as population growth and leakages in the distribution network. These driving forces are summarized in an index for water availability which has been demonstrated for use in scenario and sensitivity analyses.

Special focus has been given to downscaling of GCMs and refining climate scenarios at the local level. The downscaled GCMs offer a wide range of possible future climates in the city of Bergen, Norway. This spread in downscaled results highlights the need for further processing of the projections as demonstrated here by the reliability averaging method. However, the large uncertainties linked to climate projections are still not fully excluded and need to be considered in further studies of water availability.

For this purpose, the WAI was introduced. This index allows for studying impacts on water availability under a range of various climate scenarios. Rather than predicting future water availability, this tool enables a climate-informed assessment. This flexibility makes it suitable for decision making under uncertainty. For transparency, other trends, such as population growth and deteriorating infrastructure are represented explicitly in the WAI. This makes the WAI a practical tool for water managers and decision makers in cities.

By applying the proposed framework, three main conclusions regarding future water availability in the city of Bergen, Norway, can be drawn. Firstly, the results of downscaling suggest higher seasonal variations in inflow and thus an increased potential for storage such that more water can be preserved for dryer seasons. Secondly, in a 'business-as-usual' scenario-analysis of the WAI indicated a more vulnerable water supply due to decreased and more unpredictable water availability. Finally, it was shown that the city's policy of reducing leakages to a level of 20% would have approximately the same effect on water availability as a 10%

increase in storage capacity. Along with socio-economic analyses of the costs of implementing such counteractive measures, this framework could form a solid basis for decision making.

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Paper II

Assessing the robustness of raingardens under climate change using SDSM and temporal downscaling

Erle Kristvik, Guro Heimstad Kleiven, Jardar Lohne and Tone Muthanna 2018

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Assessing the robustness of raingardens under climate change using SDSM and temporal downscaling

Erle Kristvik, Guro Heimstad Kleiven, Jardar Lohne and Tone Merete Muthanna

ABSTRACT

Climate change is expected to lead to higher precipitation amounts and intensities causing an increase of the risk for flooding and combined sewer overflows in urban areas. To cope with these changes, water managers are requesting practical tools that can facilitate adaptive planning. This study was carried out to investigate how recent developments in downscaling techniques can be used to assess the effects of adaptive measures. A combined spatial-temporal downscaling methodology using the Statistical DownScaling Model-Decision Centric (SDSM-DC) and the Generalized Extreme Value distribution was applied to project future precipitation in the city of Bergen, Norway. A raingarden was considered a potential adaptive measure, and its performance was assessed using the RECARGA simulation tool. The benefits and limitations of using the proposed method have been demonstrated and compared to current design practices in Norway. Large differences in the raingarden's performance with respect to percentage overflow and lag-time reduction were found for varying projections. This highlights the need for working with a range of possible futures. Further, it was found that K_{sat} was the determining factor for peak-flow reduction and that different values of K_{sat} had different benefits. Engineering flexible solutions by combining measures holding different characteristics will induce robust adaptation.

Key words | climate change adaptation, hydraulic conductivity, raingarden, SDSM-DC, temporal downscaling

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INTRODUCTION

The Damsgård area in the city of Bergen, Norway, is prone to high amounts of runoff, coming from the urbanized area itself and the hillsides upstream from the urban development. Damsgård drains to the small fjord Puddefjorden, resulting in combined sewer overflows (CSOs) to the fjord during heavy precipitation events. Bergen is renowned for its plentiful rainfall, with an annual mean of 2,250 mm (Jonassen *et al.* 2013). Climate change is expected to lead to higher precipitation amounts and more frequent storm events with higher intensities in the future (Hanssen-Bauer *et al.* 2015). This can lead to an increased number of CSOs (Nilsen *et al.* 2011). Solutions to reduce the stormwater runoff are therefore needed. Blue green stormwater infrastructure, like raingardens, have been highlighted as beneficial measures for climate change mitigation (e.g. Demuzere *et al.* 2014). This is amongst other factors due to their ability to significantly reduce peak flow runoff (e.g. Hunt *et al.* 2008).

In order to use raingardens as climate adaptation measures, they need to be designed for future rainfall intensities. A common practice for estimating future design storms in Norway today is simply to apply a percentage safety factor (climate factor) to present precipitation. To date, there is no common practice for determining the magnitude of the climate factor. The value applied by end-users across the country may range from 1.2 to 1.5, depending on municipal guidelines. Recently, the Norwegian Centre for Climate Services (NCCS) released a report with regional projections of future

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climate in Norway based on a combination of regional model output and statistical downscaling (Hanssen-Bauer *et al.* 2015) along with climate profiles for each county. They emphasize projections of short duration rainfall as work in progress and suggest a temporary climate factor of a minimum 40% for rainfall of duration <3 hours. Thus, frequently asked questions by the designers still concern the magnitude of the climate factor and whether simply multiplying today's design precipitation with a climate factor is sufficient. As the necessity of climate adaptation becomes more and more apparent, the demand for practical design tools is rising.

An alternative approach to the climate factor is applying General Circulation Models (GCMs), which simulate the future climatic response to a set of predefined emissions scenarios (referred to as Representative Concentration Pathways (RCPs)) that represent various levels of change in the energy balance of the atmosphere. The GCMs are, however, too coarse to reproduce detailed climate projections at the temporal and spatial scale necessary for hydrological assessments (Herath *et al.* 2016). To bridge the gap between the large-scale climate (predictor) and the local climate (predictand), downscaling techniques can be applied (Benestad *et al.* 2008). There exist numerous downscaling techniques, often categorized into dynamical and statistical approaches (e.g. Maraun *et al.* 2010), where the statistical approaches are the least costly computationally. Statistical downscaling could be aimed to solve the spatial gaps or temporal gaps between large and local scale, and are, in general, based on either empirical transfer functions, resampling methods (weather typing), or conditional probability (stochastic modeling) (Arnbjerg-Nielsen *et al.* 2013). Over the years, GCMs and downscaling techniques have developed and become more and more available to end-users interested in studying the impacts of climate change.

The motivation of the study presented in this paper is to address the end-users' need for practical design tools by demonstrating and assessing a method for evaluating the robustness of adaptation measures in a future climate. With a focus on common practices in Norway, this study seeks to investigate the added value of performing more comprehensive investigations of local rainfall projections compared to the climate factor approach. The Damsgård area in the city of Bergen is used as a case study, with the implementation of raingardens as a possible measure for climate adaptation. Based on the above, this paper addresses the following research questions:

1. To which extent can a combination of spatial downscaling, bias correction, and temporal downscaling be used to produce intensity–duration–frequency (IDF) curves for future climate in Bergen?
2. How does the applied downscaling method compare to the current practice of multiplying the design precipitation with a climate factor?
3. What is the robustness of raingardens as a stormwater peak flow reduction measure in Bergen for different future climate scenarios?

METHODS

The widely applied Statistical DownScaling Model-Decision Centric (SDSM-DC) (Wilby *et al.* 2014) was used to downscale local climate projections for Bergen. The output from SDSM-DC is limited to one day. However, for the results from the downscaling to be useful for evaluation of raingarden performance and other hydrological assessments in urban watersheds, a higher temporal resolution is necessary (Herath *et al.* 2016). In order to achieve this, SDSM-DC was combined with a temporal downscaling approach using the Generalized Extreme Value (GEV) distribution (Nguyen *et al.* 2002) to obtain IDF curves for future climate change scenarios for Bergen, following the procedure of Nguyen *et al.* (2007). Furthermore, peak flow reduction was assessed using the raingarden modeling tool, RECARGA (Atchison & Sverson 2004). The RECARGA model simulates raingarden performance using the green-ampt infiltration and the van Genuchten model for the shape of the water retention curves. It is an event-based or continuous simulations mode model using precipitation, temperature, and evaporation and input time-series. Software and tools were selected based on their applicability. Both SDSM-DC and RECARGA are open access software with user-friendly interfaces, while the temporal downscaling proposed by Nguyen *et al.* (2007) builds on statistical theory that should be manageable for engineers. Selecting methods that are easy to apply for practitioners ensures that the full procedure is a suitable alternative to the common climate factor approach.

Collection of precipitation data

Observed precipitation data were used for two purposes: (1) calibrating the SDSM-DC and statistically downscaling from global to local climate with SDSM-DC; and (2) developing IDF curves from (i) observed data and (ii) downscaled climate data using temporal downscaling.

The weather stations were chosen on the basis of proximity to the study site. The longest record of daily rainfall in the area was found at the Norwegian Meteorological

Institute's (MET) station at Florida, Bergen (50540). Thirty years of data (1985–2015) from this station was used for calibration and validation of the SDSM-DC model. However, this station has only 4 years of sub-daily rainfall data. A station 70 meters away, Florida UIB (50539), has minute data for 10 years. The two stations are located in a flat area and in equal distance to surrounding mountains influencing the precipitation regime (Figure 2). The latter station was therefore chosen for the sub-daily rainfall. The data have been quality controlled by MET and downloaded from eklima.no.

Downscaling of precipitation

The spatial temporal downscaling is a combination of separate spatial and temporal downscaling techniques (Figure 1). It uses SDSM-DC to link the large-scale climate to the local climate and make future climate estimates. The results are further bias corrected. The temporal downscaling approach uses the scaling concept and the GEV distribution to obtain a relationship between daily and sub-daily rainfall (Nguyen *et al.* 2002). The GEV distribution is also used to derive IDF curves. The SDSM-DC and the GEV have been applied successfully in combination to develop IDF curves (e.g. Nguyen *et al.* 2010; Herath *et al.* 2016).

The methodology for spatial, including bias correction, and temporal downscaling described by Nguyen *et al.* (2007) and Herath *et al.* (2016) formed the basis for the methodology applied below.

Scenario generation

Climate projections are linked to large uncertainties. These uncertainties are mainly related to natural variations of the climate system, level of future emissions, and the climatic response to emissions (see e.g. Ekström *et al.* (2015)'s classification of uncertainty). Thus, many have argued for an ensemble approach, where several RCPs, GCMs and downscaling techniques are considered to allow for uncertainty assessment (e.g. Arnbjerg-Nielsen *et al.* 2013). SDSM-DC does not include GCMs directly, but the user of the model can apply scenarios for the future climate by changing *occurrence*, *mean*, *variance* and *trend* of e.g. the precipitation (Wilby *et al.* 2014). To investigate the effects of higher amounts and intensity of rainfall, changes in the treatments mean and variance were investigated by adding expected (1) *change (%) in total precipitation amounts* and (2) *change (%) in rainfall amounts at days with heavy precipitation* to the SDSM-DC time series respectively (Table 1). In Table 1, (1) MEAN and (2) VARIANCE are projected changes from 1971–2000 to 2071–2100 retrieved from NCCS's regional climate projections for Sunnhordland (region covering Bergen) (Hanssen-Bauer *et al.* 2015).

The climate scenarios 1–5 were based on yearly values. Climate scenario 6 was based on the worst combination of seasonal values. Annual values for RCP4.5 High (12, 12) and RCP 8.5 Med (12, 14) were quite similar. Therefore, only a change corresponding to RCP 8.5 Med was investigated.

Temporal downscaling

There are several ways of estimating the GEV parameters, where non-central moments have been used with this approach before (e.g. Nguyen *et al.* 2010; Herath *et al.* 2016). However, due to the emphasis on applicability in the scope of this study, the commonly used maximum log-likelihood estimation method was used for parameter estimation in this study. The log-likelihood function is as follows:

$$l(\theta) = \sum_{i=1}^{N} \log g\,(x;\,\theta) \tag{1}$$

where g is the probability density function of the GEV distribution. $\theta = [\xi, \ \mu, \ \sigma]$. ξ, μ and σ are the shape, location, and scale parameter of the GEV distribution.

The scaling factors for the different parameters were found as described by Nguyen *et al.* (2007) and Herath *et al.* (2016). They were further plotted against precipitation duration with the aim of finding one common scaling factor. This was calculated by finding the mean of the derived scaling factors.

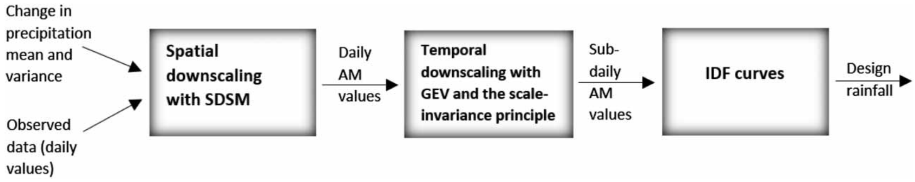

Figure 1 | Flow chart describing the downscaling step in the methodology. AM is an abbreviation for 'annual maximum'.

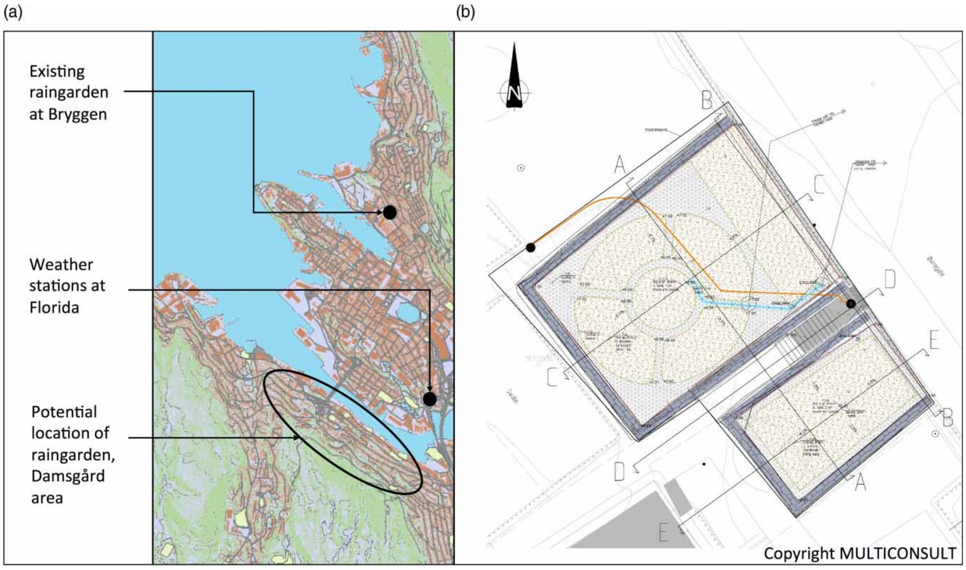

Figure 2 | Overview of the study site, showing the (a) location of existing raingarden at Bryggen, weather stations at Florida and study site Damsgård, and (b) layout of the existing raingarden at Bryggen.

Table 1 | Estimates on how the precipitation mean and variance might change

Climate scenario	0	1	2	3	4	5	6
Changes based on	Observed	RCP 4.5 low	RCP 8.5 low	RCP 4.5 med	RCP 8.5 med	RCP8.5 high	RCP8.5 high autumn/winter
MEAN: Change in total precipitation amounts (%)	0	0	2	6	12	20	30
VARIANCE: Change in precipitation amounts on days with heavy rainfall (%)	0	2	8	7	14	21	30

For constructing depth duration frequency curves, the quantiles (z_p) were calculated:

$$z_p = \mu - \frac{\sigma}{\xi}\left[1 - \{\ln(1-p)\}^{-\xi}\right] \tag{2}$$

where $G(z_p) = 1 - p$ and z_p are associated with the return period ($1/p$). To get IDF curves, the return periods were converted from mm to mm/hr. These intensities were plotted against the precipitation durations.

Construction of IDF curves for historical data

An IDF curve for observed historical precipitation was developed using the GEV distribution. The intensities were multiplied by the climate factors 1.2 (a commonly used climate factor) and 1.4 (Hanssen-Bauer *et al.* 2015). A second IDF curve for observed historical precipitation was constructed using the derived scaling factors for comparing purposes.

Raingarden assessments

Infiltration rate

It was assumed that a possible raingarden at Damsgård will have the same size relative to the watershed (6%) and the same watershed characteristics as an existing raingarden located at the close-by site Bryggen (the city center of Bergen). This raingarden has a facility area of $180.8\ m^2$ and depression zone of $d_{min} = 12$ cm. The robustness of the raingarden was assessed by investigating the performance with different infiltration rates, represented by the saturated hydraulic conductivity (K_{sat}). The raingarden was tested with three different K_{sat}: 38 cm/h, 10 cm/h and 3.4 cm/h. The high K_{sat} of 38 cm/h was the value from the existing raingarden at Bryggen, obtained by MPD infiltration tests, as described by Ahmed *et al.* (2014) and Paus *et al.* (2016), which found 10 cm/h to be the minimum recommended K_{sat} in cold climates. It was further found that K_{sat} during autumn/early winter (i.e. September to December) was 25–43% of summer infiltration, with a mean of (34%). Given the recommendation of $K_{sat} = 10$ cm/h, the range 2.5–4.3 cm/h represents the winter infiltration, which naturally will vary based on soil water content at the freezing point and soil and air temperature, and the non-frozen water content of the soil.

Evaluating performance

The performance was evaluated based on (1) overflow (% of runoff into the raingarden), (2) change in lag time (change in minutes from runoff without raingarden), and (3) flow peak reduction in underdrain compared to incoming runoff (%). Lag time is in this study was defined as the time from when the precipitation event starts until flow peak of runoff or flow peak in the underdrain.

Simulation in RECARGA

RECARGA models the performance of a raingarden in 1D vertical flow direction (Dussaillant *et al.* 2005). The model applies Green-Ampts (Mein & Larson 1973) and a surface water balance to model infiltration, runoff and evapotranspiration, and Genuchtens equations (Van Genuchten 1980) to model percolation between the model's three soil layers.

A modified version of RECARGA, allowing for minute resolution for input and output, was used for the simulations (Dalen 2012). Using RECARGA, the performance with the different K_{sat} values was tested for the obtained climate scenarios.

Preparation of RECARGA input

The obtained IDF curves were used to determine the magnitude of the design rainfall to be used in further analyses and to construct symmetrical hyetographs to simulate extreme events. The hyetographs were designed with a duration of 1 hour and varying peak intensities. In order to account for initial water in soil and for delays in runoff and infiltration, the hyetographs were constructed with a pre-wetting period that corresponded to average daily rainfall.

RESULTS AND DISCUSSION

The accuracy and applicability of the methodology was assessed by investigating the performance of each step separately and combined.

Spatial downscaling

The following predictors were chosen based on assessments of scatter plots, correlation matrices and p-values; Mean sea level pressure (Mslp), Geostrophic airflow velocity at 500 hPa (p5_f), Geostrophic airflow velocity at 850 hPa (p8_f), Zonal velocity component at 850 hPa (p8_u), and 850 hPa geopotential height (p850). The goodness of fit of the model was assessed by the explained variance (R^2). The model had an average $R^2 = 0.22$. This is comparable to previous studies (Mahmood & Babel 2013; Herath *et al.* 2016). Wilby *et al.* (2002) argue that an R^2 under 0.4 is likely for precipitation occurrence and amounts. Further, cross validating the model by a split sample test gave an average R^2 of 0.20. The two R^2 values being close indicates that the model is robust and resilient to data set partitioning. The model performs best in autumn/winter, with the highest R^2 in September (0.26). The poorest performance is found during summer ($R^2 = 0.11$ in July). The climate patterns might explain the difference. The precipitation in Bergen is in general governed by the topography and westerly winds from the North Sea (Jonassen *et al.* 2013). However, the precipitation during summer is typically influenced by convective processes, which are local phenomena.

Bias correction

Figure 3 shows that the SDSM-DC simulated daily annual maximum (AM) rainfall was overestimated for most years, and underestimated for the extreme years. This applies to some extent after bias correction too, though it is highly improved. Further, root-mean-square deviation improved from 8.14 mm to 4.19 mm, and the Nash-Sutcliffe efficiency coefficient (N-S) improved from 0.85 to 0.96 due to bias correction. The percentage bias (p-bias) improved from 7.20% to 0%. Overall, the improvement is most significant for the precipitation amounts with the lowest return period. The precipitation amounts with return periods of 5–20 years

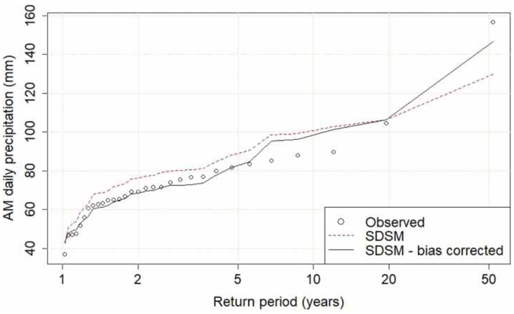

Figure 3 | Historical AM daily precipitation values based on observed data, SDSM results and bias corrected SDSM results.

are still notably overestimated. A likely reason for this is the lowered amount of data points in this region, caused by too few observational records of extreme daily precipitation.

Temporal downscaling

The scaling factor β was 0.472. When deriving the scaling factors, it was found that the scaling factors for all durations except for 12 hours were similar for all return periods. Therefore, the 12-hour duration was excluded in the calculation of a common scaling factor. The reason for the diverging scaling factor at 12-hour duration is that the daily data follows MET's definition of a day (7.00 am to 7.00 am). The sub-daily durations were derived from observed minute data. While aggregating these data, a day was considered midnight to midnight. This difference may have influenced the data for the 12-hour durations. However, when comparing the observed IDF curves found directly from the data and by using the scaling factor, it is seen that the longest durations are well represented by the scaling IDF curve (Figure 4(a)).

Figure 4(a) also shows that using the scaling procedure leads to high overestimation of the intensity for the shortest durations (<15 minutes). This implies that the scaling principle should not be used for these intensities. The finding corresponds to Herath *et al.* (2016), who downscaled to 30 minutes at the lowest. Nguyen *et al.* (2010), on the other hand, used a downscaled resolution of five minutes in further hydrological assessments. The temporal scaling procedure represents the durations over 180 minutes well (Figure 4(a)). For durations between 15 and 180 minutes, only the shortest return periods follow the pattern of the observed data. This is not surprising, as one could expect a closer statistical relationship between e.g. AM three-hour duration and AM daily rainfall than AM 15-minute duration and AM daily rainfall. Due to these results, the 15-minute duration was chosen as the lowest duration in the IDF curves in this study. In addition, only intensities over 15 minutes were further used in the RECARGA simulation in

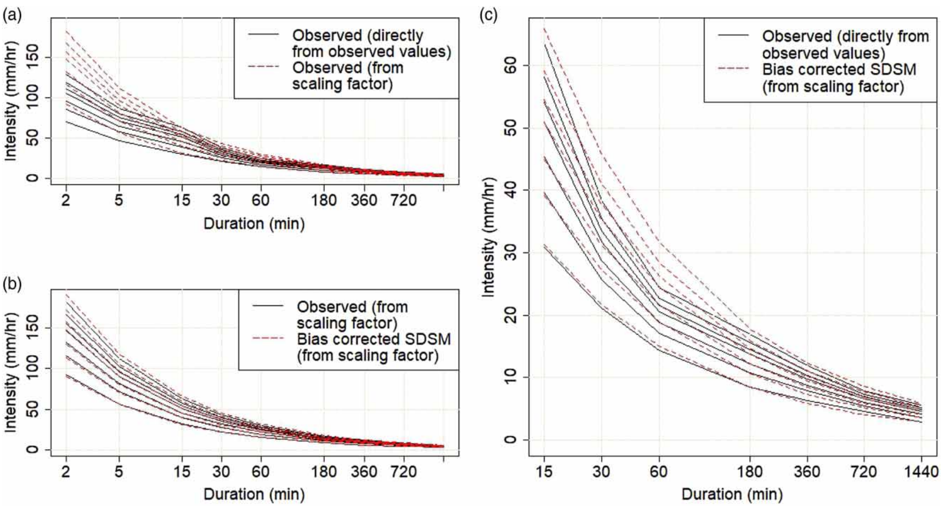

Figure 4 | IDF curves showing the ability of the applied methodology to represent historical precipitation intensities. (a) observed precipitation, derived directly from the observed values, and by using the scaling factor; (b) observed and bias corrected SDSM precipitation, both developed using the derived scaling factor; (c) observed precipitation found directly from observed values and bias corrected SDSM precipitation found by using the scaling factor. The return periods are 2, 5, 10, 20, 30, 50 and 100 years.

order to avoid propagating the inaccurate results of lower durations in further analyses.

Combination of spatial and temporal

Figure 4(b) shows that the accuracy of the spatial downscaling (after bias correction) applies for sub-daily intensities as well as for daily precipitation. The spatially downscaled IDF curve follows the same pattern as the IDF based on observed data when both curves are constructed using the derived scaling factor. However, the fit is best for the lower return periods.

Figure 4(c) shows that the same patterns as described in the temporal downscaling section apply for the spatially and temporally downscaled IDF curve. The overestimation for larger return periods in the spatial downscaling step (Figure 4(b)) carries over to the spatially and temporally downscaled IDF curves (Figure 4(c)), though the temporal downscaling is the main source of inaccuracy in the results.

In more detail, the model overestimates precipitation intensities for events of durations of 30–180 minutes and for the higher return periods. However, it is evident from Figure 4(c) that bias correction highly improves the performance for events of 15 minute durations for any return period.

Comparison between the downscaled scenarios and climate factors

The IDF curves for the chosen scenarios were compared to the climate factor 1.4, which is the recommended climate factor for durations of less than three hours for the Bergen area (Hanssen-Bauer *et al.* 2015), and to the commonly used climate factor of 1.2. The comparison is shown for the 20-year return period (Figure 5), which is the design criteria for stormwater pipes in the city of Bergen (Bergen kommune 2005). Applying the climate factor of 1.4 results in intensities higher than all the investigated climate scenarios for all durations, except for the durations from 30 to 120 minutes. Knowing that the spatially and temporally downscaled intensities are overestimated for these same durations, the 1.4 climate factor gives the highest safety margin amongst the investigated cases. The intensities given by the commonly applied climate factor of 1.2, on the other hand, are exceeded by several of the climate scenarios.

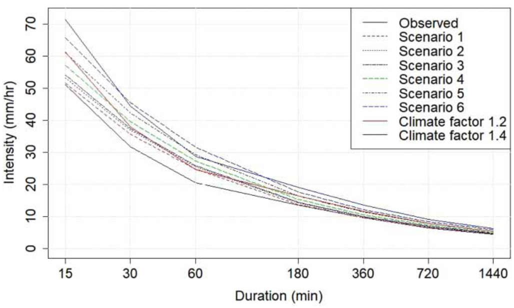

Figure 5 | IDF curve for all investigated cases for return period of 20 years.

It is, however, important to notice that this does not mean that applying a 1.4 climate factor is always sufficient. The investigated scenarios do not by any means constitute an upper limit for climate change. The uncertainties of future emission scenarios, the GCMs and the spatial and temporal downscaling procedure make it crucial to use the results cautiously. This is the motivation behind the SDSM-DC. The GCMs should be used to inform the analysis, but they are not driving them (Wilby *et al.* 2014). This is done by selecting treatments to apply to the current climate situation. In this study, the GCM output was used to inform the choice of treatments, as recommended by Brown & Wilby (2012). The annual and seasonal change estimates for the Sunnhordland region represented the climate changes and are, along with the 1.4 climate factor, from Hanssen-Bauer *et al.* (2015). Thus, the climate factor and the applied treatments are based on the same GCM output. One could therefore expect that multiplying with the 1.4 climate factor would give similar intensities as the worst climate scenario. This was indeed the case, which indicates that there is agreement between the downscaling approach used in this study and the downscaling methods used by Hanssen-Bauer *et al.* (2015).

The raingarden as peak flow reduction measure

The performance was assessed for precipitation events (expressed as symmetrical hyetographs of 1-hour duration) with peak intensity corresponding to 15 min duration and a return period of 20 years following municipal guidelines for stormwater pipes in Bergen (Bergen kommune 2005). However, it can be argued that it is not reasonable to design raingardens for capturing all the runoff from such a rather large event. Raingardens are recommended to be designed to capture the 'everyday' runoff, and to be combined with safe flood ways for larger events (Paus & Braskerud 2014). Therefore, infiltrating 80% of the incoming runoff is considered a successful performance. With concern to Puddefjorden, the risk of a CSO every 20th year caused by 20% of the runoff from Damsgård is well within acceptable risk levels.

$K_{sat} = 38$ cm/h was the only investigated infiltration rate that gave under 20% overflow for all climate scenarios (Figure 6(c)). It was further found that the K_{sat} should be above17 cm/h to infiltrate 80% of the runoff for today's condition. However, to meet the criteria for all the investigated climate scenarios, it should be at least 33 cm/h. In addition, winter conditions should also be accounted for. A reduction of K_{sat} 33 cm/h to e.g. 11.2 cm/h (34% reduction, see Paus *et al.* 2016), would neither today nor in the future give adequate infiltration all year round.

For all investigated K_{sat} values, the peak flow in the underdrain was reached before the peak runoff from the event. Hence the lag time was reduced for the flow in the underdrain compared to the lag time without a raingarden. However, an increase in lag time for overflow from the raingarden compared to the pre-raingarden conditions was observed. The largest increase was found for a $K_{sat} = 38$ cm/h, ranging from nine minutes for climate scenario 6 to 14 minutes for climate scenario 1 (Figure 6(c)). A $K_{sat} = 3.4$ cm/h gave the lowest increase in lag time, ranging from one to three minutes for the different climate scenarios and five minutes for today's situation.

The peak flow reduction was only dependent on K_{sat}, and was independent of the climate scenarios (Figure 6(b)). The highest peak flow reduction was found for $K_{sat} = 3.4$ cm/h (96.3%), while the lowest was found for $K_{sat} = 38$ cm/h (56.7%).

Thus, it is seen that a higher K_{sat} results in less overflow and an increase in overflow lag time, whereas a lower K_{sat} is the most efficient for reducing the peak flow. This shows that the choice of filter medium (and ultimately K_{sat}) should be based on whether peak flow reduction or detention is the most important objective. Alternatively, a combination of different solutions might be beneficial. One could for example have a series with a high-infiltration rate raingarden first, draining into another raingarden or infiltration-based solution with lower infiltration capacity. Or, the raingardens could be placed in opposite order, with a low-infiltration rate raingarden first, infiltrating the small events and overflowing to a second raingarden/infiltration-based solution with higher infiltration rate for the larger events. The above are two possible solutions,

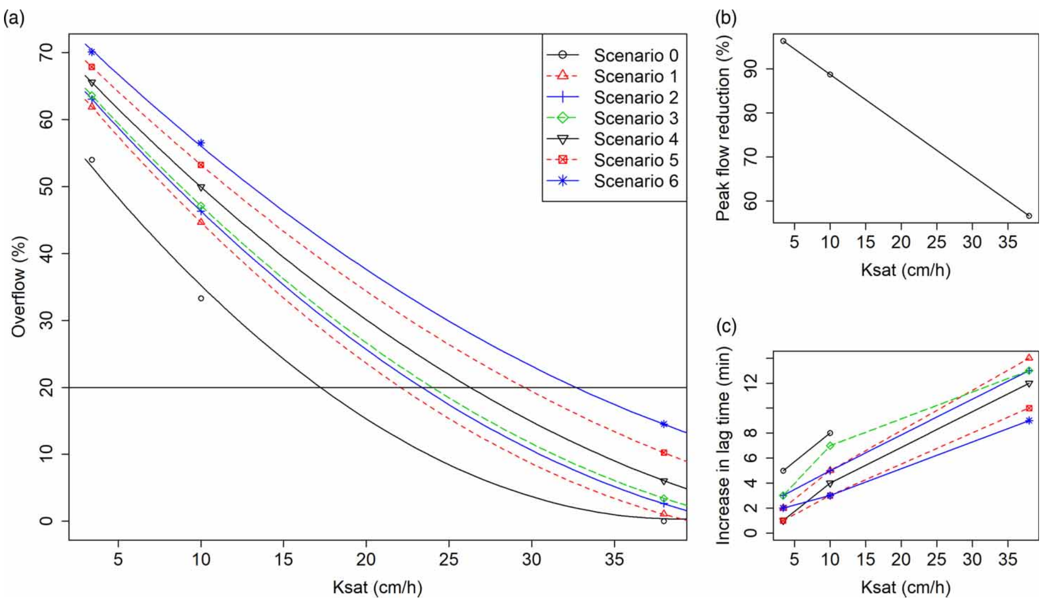

Figure 6 | Performance of the raingarden for different K_{sat} values for the investigated climate scenarios. (a) Percentage of incoming runoff becoming overflow from the raingarden (%); (b) peak flow reduction compared to peak flow without raingarden (%); (c) lag time reduction for peak overflow from the raingarden compared to peak runoff without raingarden (min).

illustrating that the key to increased robustness is a combination of solutions.

Practical implications of the study

The combination of spatial downscaling, bias correcting and temporal downscaling resulted in refined local climate projections for Bergen. The resulting IDF curves containing the climate signal of various scenarios has a high practical value to end-users, as they are easy to transfer to existing design practices. However, the projections are highly uncertain both due to model uncertainty introduced in climate modeling and downscaling, but also due to the fact that the future course of our society is unknown. This highlights the need for practitioners to assess a range of different scenarios when decisions about climate adaptation are to be reached.

IDFs resulting from the presented analyses were compared to the current design practice in Norway, referred to as the climate factor approach. The investigated scenarios were shown to be more conservative than applying a climate factor of 1.2 and less/or equally as extreme as applying a climate factor of 1.4, both factors commonly used in Norway. The practical implication of this is that implementing the full downscaling procedure as proposed in this study could help inform the choice of a suitable magnitude of the climate factor for different locations in Norway – a highly debated topic within the water sector. However, considering the varying model performance for different event durations and return periods (Figure 4), attention to model confidence at the different levels should be given in doing so.

The applied downscaling methodology is also a good tool for showing the range of possible outcomes of climate change. Generally, it can be used to stress test systems for possible climate change scenarios, and to evaluate the response of an investigated system, as suggested by Wilby *et al.* (2014). Specifically, it was shown, by assessing the performance of a raingarden (as an adaptive measure) to various scenarios, that the more conservative the scenario, the less satisfying the performance. In a design perspective, one should always consider the risk associated with failure of the system (Hanssen-Bauer *et al.* 2015). Thus, the analyses of raingarden performance could be combined with vulnerability analyses. In a highly vulnerable area, little risk might be accepted and the adaptive measure should be designed for a more conservative scenario. On the contrary, in a less vulnerable part of the urban area, one might be less risk aversive. As seen from Figure 6, the criterion of 80% infiltration is fulfilled at $K_{sat} \approx 17$ cm/h for the least conservative scenario and at 33 cm/h for the most conservative scenarios. Thus, choosing a scenario based on vulnerability analyses would highly influence the requirements to the raingarden and thus other aspects outside the scope of this study, such as costs.

Further, it was shown that different K_{sat} values had different benefits: high K_{sat} values resulted in increased lag time, and lower K_{sat} values improved peak flow reduction. It was further demonstrated that a possible solution to this could be to connect components with different characteristics (e.g. raingardens with different K_{sat} values) in order to add flexibility. This idea may be elaborated in studies investigating a coupling of raingardens with other measures that are less demanding in terms of costs and area. Considering seasonal variations and deterioration of K_{sat} value with time could help inform the selection of suitable co-measures. To exemplify, it was discussed how K_{sat} is reduced during winter in Norway. The implication for the raingarden performance is that lag time is reduced while peak flow reduction would be improved. Thus, a suitable co-measure should compensate for the reduced K_{sat} and lag time. Adding this flexibility ensures that the uncertainty in the scenarios are accounted for and that the measure performs well under a range of scenarios, not a specific one. This, ultimately, results in a robust adaptive measure.

CONCLUSIONS

This study demonstrates how recent developments in downscaling techniques can be used to support end-users and designers in assessing climate change impacts and effects of adaptation measures; specifically, the robustness of raingardens under climate change. A combination of spatial and temporal downscaling was applied to make IDF curves for Florida (Bergen, Norway), and assess the robustness of raingardens as peak flow reduction measures under climate change. The climate change scenarios were generated by manipulating the mean precipitation and precipitation variance. It was found that the largest inaccuracy in the downscaling procedure was in the temporal downscaling step. The IDF curves developed by using the methodology represent the lowest return periods well, but are inaccurate for the highest return periods and more research should be done on improving the temporal downscaling step. However, despite the large uncertainties, it has been demonstrated how the climate forced IDFs could be of practical value to end-users.

The robustness of raingardens as a peak flow reduction measure is highly dependent on the K_{sat} value. The higher the K_{sat} value, the more robust as a peak flow reduction measure the raingarden will be, both in terms of overflow and lag time. Based on overflow and lag time, the recommended minimum K_{sat} value for a cold climate of 10 cm/h is insufficient. However, the peak flow reduction is highest for the lower K_{sat} values. It is therefore concluded that the raingarden media (and ultimately the K_{sat}) must be decided based on which feature of the raingarden is most important. A solution combining different features, e.g. by having several raingardens/infiltration-based solutions with different infiltration rates in series will add robustness and flexibility.

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Paper III

Temporal downscaling of IDF curves applied to future performance of local stormwater measures

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Article

Temporal Downscaling of IDF Curves Applied to Future Performance of Local Stormwater Measures

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Abstract: Low-impact development (LID) structures are combined with traditional measures to manage stormwater and cope with increased runoff rates originating from heavy urbanization and climate change. As the use of LIDs for climate adaptation increases, practitioners need more knowledge on LID performance in future climates for successful planning and implementation. In this study, temporal downscaling of regional climate projections for three cities in Norway is performed, using the concept of scale invariance to downscale the distribution of extreme precipitation from daily to sub-daily timescales. From this, local-scale intensity-duration-frequency (IDF) curves for future precipitation were obtained. Using climate projections of daily temporal resolution as input to water balance models and the obtained IDF relationships as input to event-based models allowed for assessing the retention capacity, peak flow reduction potential and pollution control of three different types of LIDs: green roofs, bioretention cells, and detention basins. The downscaling resulted in large local variations in presumed increase of both precipitation amount and intensity, contradicting current design recommendations in Norway. Countrywide, a decrease in the overall LID performance was found, although some positive effects of temperature rises were detected. The study illustrated the importance of evapotranspiration- and infiltration-based processes in future stormwater management and how coupling of LID structures in series can significantly reduce required detention volumes.

Keywords: green roof; bioretention cell; detention basin; LID; climate adaptation; temporal downscaling; scale invariance; POT; GPD

1. Introduction

Modern stormwater management is aimed at reducing the disadvantages caused by urbanization by maintaining or restoring the predevelopment site hydrology [1]. Urbanization, with an increase of impervious areas, and the introduction of piped systems for stormwater have reduced the evapotranspiration rates, reduced the rate of infiltration to native soil and increased the surface runoffs both with respect to volumes and peak flows. It is expected that the impacts of increased runoff rates will be further induced as a consequence of more frequent and intense precipitation events caused by climate change [2,3]. A stormwater management that counteracts the effects of both urbanization and climate change is needed.

To cope with urbanization, stormwater at-site control was introduced in the 1980s resulting in a large development of distributed stormwater measures [4]. The management was first solely aimed at reducing flooding by peak flow control but has shifted over the past few decades to an approach with multiple objectives related to mitigating the changes in urban hydrology, improving the water quality of receiving waters and delivery of multiple benefits [5]. This approach has been given several different terms like low-impact development (LID), best management practices (BMP), and sustainable urban drainage systems (SUDS) and will in this paper be referred to as LIDs.

Peak flow control has commonly been solved by the use of distributed (site scale) or centralized (catchment scale) detention volumes. Peak flow control can contribute to reduced surface flooding, reduced erosion in natural waterways and reduced capacity problems in downstream piped systems associated with cellar flooding and combined sewer overflows. Challenges to the fixed-flow regulations alone are that they do not counteract the reduced infiltration and evapotranspiration rates, remove pollutants or restore the downstream low-flow regimes, and in some cases, unfortunate superposition of hydrographs might increase peak flows on a large scale and increase combined sewer overflows [1,4,6–8].

Volume control of stormwater runoff is important to restore predevelopment site hydrology and can also contribute to flood control, pollutant control and reduced sewer overflows [4,6,7,9]. The main processes involved in volume control are reduction of stormwater runoff volumes by evapotranspiration and infiltration, often achieved by introducing LID structures. Studies investigating implementation of LID structures on a catchment scale have found these to be efficient in restoring pre-development hydrological conditions and protecting the ecology in receiving waters for small and medium-size precipitation events, while for large design storms additional measures are needed to prevent flooding [8,10–12]. Performance of LID measures are found to vary with several factors, such as type and design of measure, initial saturation [13], precipitation characteristics [14,15] and location in the watershed [16].

Despite the increased knowledge on the disadvantages of applying solely peak flow control regulation on stormwater management, many cities, among those, large Norwegian cities, are focusing the design on large design events, while volume control and pollution control are requested but not quantified in the regulations [17–19]. This has resulted in comprehensive establishment of detention basins, while the introduction of other stormwater measures focusing on volume and pollution control has been limited [4,7]. This trend is currently changing and there is a growing interest in a wider variety of stormwater measures and their suitability for local climates and conditions [20–22].

However, city growth and climate change will increase the future challenges associated with stormwater management [23,24] and the extended focus to volume and pollution control alone is not enough to obtain a sustainable stormwater management. Regardless of the type of stormwater measure, it must be fit to meet future climates and there is a need for more knowledge on how the different stormwater measures perform both alone and together, in present and future climate, to assure resilient stormwater systems for a future climate. Changes in precipitation patterns and temperature might both affect future design values, as well as altering the hydrological processes that comprise stormwater management. This implies that optimal solutions in present climate are not necessarily optimal in a future climate. To investigate this, knowledge on future climate conditions is necessary. This knowledge is, however, very limited at the local and temporal scale needed for such assessments and there is a gap between available climate information provided by climate research and the information demanded by end-users [25].

To date, the primary source to projections of the future climate, is output of global climate models (GCMs), which are models that simulate the climatic response to scenarios of greenhouse gas emissions (referred to as Representative Concentration Pathways (RCPs)). On a political scale, much information can be drawn from the output of these models, but due to the models' complexity and substantial computational need, the spatial and temporal resolutions of the output are too coarse for the model output to be directly applied to stormwater purposes [25].

To resolve this, techniques for downscaling GCM output to an applicable temporal and spatial resolution have emerged. They are usually grouped into two main categories: (1) dynamical downscaling and (2) statistical downscaling [25,26], where (1) involves nesting of a fine-gridded regional climate models within selected boundaries of the GCM output and (2) refers to establishing a statistical relation between large-scale and local-scale climate [27]. The main advantage of dynamical downscaling is that it is based on physical relations, while the main advantage of statistical approaches is that it is more easily applied and does not require expert knowledge of the climate systems nor extensive computer capacity. Recent advances in climate research and downscaling techniques have made fine-gridded output from regional climate models (RCMs) accessible through projects such as the Coordinated Downscaling Experiment—European Domain (EURO-CORDEX) [28]. The improved resolution provided by such regional climate projections is valuable in order to assess slow hydrological processes, such as evapotranspiration and infiltration, over a long period of time, but the temporal resolution of the projections is, however, still an obstacle when dealing with the rapid runoff experienced in urban areas. Hence, further temporal downscaling of regional climate projections is needed in order to conduct a holistic investigation of stormwater measures' performance in a future climate.

Existing approaches for temporal downscaling can be categorized into stochastic rainfall generation by point process theory, multifractal and cascade processes, and rainfall disaggregation [3]. Common design practice in Norway is usually based on design events, where the design precipitation intensity is chosen from IDF curves following local guidelines. IDF curves are constructed based on frequency analyses of observed precipitation and shows the relationship between the intensity and duration of extreme precipitation events for a range of return periods. Thus, methods for projecting future IDF statistics are of high end-user demand in Norway in order to be able to merge current design practice with considerations for the future. Some studies on temporal downscaling have focused explicitly on such, by using fractal theory and the concept of scale invariance to find a scaling relation between the distribution of extreme precipitation of various durations to project extreme rainfall for the future [29–31].

In Norway, one of these approaches [30] has been tested for weather stations in the cities of Bergen and Trondheim. In these studies, daily and sub-daily extremes were extracted from observational series as annual maxima (AMs), fitted to the generalized extreme value (GEV) distribution, and a scaling relationship was found between the GEV statistics of the daily and the sub-daily scales. In Bergen, the results of the scaling were found satisfying for durations as low as 15 min, but the bias increased significantly for lower durations [32]. In Trondheim, the Gumbel distribution (GEV 1) had to be assumed for the AMs due to unsatisfying fittings of the shape parameter [33]. The results suggest that further research on defining rainfall extremes on fine temporal scales and proper parameter estimation is needed in Norway to provide reliable climate projections that can be accounted for in planning of stormwater management [32,33].

The motivation of this study was to address the need for knowledge on long-term LID performance and bridging the gap between available and required climate information. To accomplish this, the methodology for temporal downscaling from regional climate projections to future IDF curves is further developed and performed for three Norwegian cities. The regional projections and IDF curves obtained are further used to investigate the efficiency of different stormwater measures and their suitability in the present and a future climate. Relevant regulations like peak flow control, volume runoff control and pollution control are applied to evaluate the performance of three stormwater measures according to the state-of-the-art holistic approach for stormwater management. The stormwater measures assessed are: (1) green roof, (2) bioretention cell, (3) detention basin. Both water balance models and event-based models are used such that all hydrological processes, rapid and slow, under climate change are explored. Specifically, this study seeks answer the following research questions:

(1) What is the best suited method for constructing future IDF curves based on scaling laws;
(2) Investigating how geographical variations will influence the performance of local stormwater measures in a future climate.

The structure of the succeeding sections of this paper reflects the two-folded research questions. Section 2, Materials and Methods, includes a description of the study sites (Section 2.1) and the input data to the assessments (Section 2.2), namely meteorological observations and regional climate projections. Subsequently, the temporal downscaling approach for projecting future IDF curves and construction of future design-events (Section 2.3) and the LID models used for assessing future performance (Sections 2.4–2.6) are described. Furthermore, the climate projections and results of the downscaling are presented and discussed in Sections 3.1 and 3.2, and their implications for future LID performance in Sections 3.3–3.5. The work is concluded in Section 4, along with venues and recommendations for future work.

2. Materials and Methods

The defined research questions were addressed by coupling frameworks for temporal downscaling of climate projections with LID performance assessments (Figure 1). Observational data from three study sites in Norway was used for calculating extreme value statistics and establishing a scaling relationship between daily and sub-daily extreme precipitation (Step 1). The scaling relationship obtained was further applied to regional climate projections of daily precipitation for the same three sites (Step 2) to construct IDF curves of projected precipitation. Finally, the projected IDF curves and the projected daily precipitation series were used as input to design-event (DE) models and water balance (WB) models to assess the local stormwater measures' event-based and long-term performance in a future climate, respectively (Step 3).

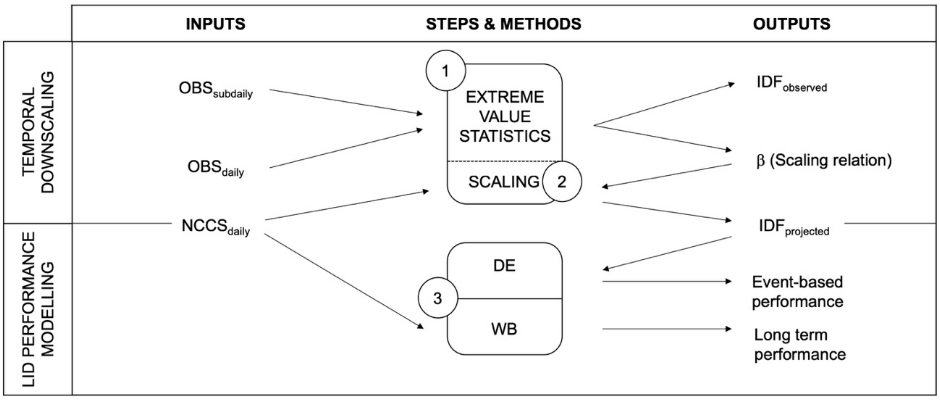


Figure 1. High-level description of the steps and data flow from temporal downscaling to performance assessment of local stormwater measures.

2.1. Study Sites

Norway is located in Scandinavia, Northern Europe, and characterized by its long and narrow shape, ranging from latitudes 57 to 71. This span of latitudes, along with an extensive coastline covering the western part of the country, contributes to large variations in local climate conditions, such as mild and wet coastal climates in the southwest and cold winters combined with hot summers, inland. Three cities have been selected for this study, in order to capture parts of the climate variability found in Norway. The selected cities, Bergen, Oslo, and Trondheim (Figure 2), are the three largest cities in the country. The climate in Bergen is characterized by mild temperatures and high amounts of annual rainfall, originating from a combination of frontal and orographic precipitation. In Trondheim and Oslo, the climates are more continental, with less precipitation and colder winters. For a more comprehensive description of the climates for the three selected cities, the reader is referred to Johannessen et al. (2017) [34].

Figure 2. Map showing the studied cities Bergen, Oslo, and Trondheim, and their location in Northern Europe [35].

2.2. Metrorological Input Data

Observations of precipitation were collected for the three study sites Bergen, Oslo, and Trondheim. The data was obtained from the Norwegian Meteorological Institute through the web portal www.eklima.no [36]. The currently operating stations with the longest records of minute data was selected (Table 1).

Table 1. Metadata for observed precipitation [36].

Location	Station ID	Latitude	Longitude	m.a.s.l.	Data Available From	%Missing Data
Bergen	50539	60.4	5.3	12	2003-06-18	13.2
Oslo	18701	59.9	10.7	94	1969-04-16	31.3
Trondheim	68230	63.4	10.4	127	1986-12-11	9.7

The climate projections used for temporal downscaling, were regional climate projections for Norway covering the time span 1971–2100 made available by the Norwegian Centre for Climate Services (NCCS). The data is from heron referred to as the NCCS data, and they originate from downscaling of 10 EURO-CORDEX GCM/RCM simulations by an empirical quantile mapping method [37]. The spatial resolution of the available data is 1 × 1 km and the temporal scale is daily, hence the need for temporal downscaling. All 10 simulations are available for RCP4.5 and RCP8.5, which refers to an intermediate level of emissions and high level of emissions, respectively. Since the future of human greenhouse gas emissions is unknown, the most conservative, worst case scenario was studied in this paper (RCP8.5). To capture some of the uncertainty associated with climate modelling, the full ensemble of the 10 simulations for RCP8.5 was used. The data used in this study included daily precipitation depth and daily average temperature.

2.3. Temporal Downscaling

The observations of fine time-scale rainfall were used to establish a scaling relation between the statistical properties of extreme daily and sub-daily precipitation. Assuming that the scaling relation found between observations also holds for the future, the obtained scaling relation was then applied to the projected daily precipitation (NCCS data) for the three study sites such that projections of the statistical properties of extreme sub-daily precipitation for the future period 1971–2100 was obtained.

The temporal downscaling of regional climate projections was based on fractal theory and the principle of scale invariance, which can be used to link the statistical properties of rainfall of different scales [38,39]. Fractal theory suggests that the statistical properties of the rainfall process are scale-invariant, and this scale-invariant property can be expressed by:

$$\alpha_{\lambda D} = \lambda^{\beta} \alpha_{D} \tag{1}$$

where α is the precipitation distribution parameter, D is the time scale, λ the scale factor, and β the scale exponent [3]. In a simple scaling case, the scaling exponent is constant and equal to the slope of the linear relation between β and D in a double logarithmic plot [39] and the scaling relation also holds for the distribution quantiles [38].

Equation (1) was used to scale the distribution of extreme rainfall. Rainfall extremes are commonly extracted from observed time series in one of two ways: (1) by extracting the most extreme event within a hydrological year (AM, or (2) by extracting all events above a predefined threshold (peak-over-threshold (POT)). In general, the AM approach helps selecting events that are independent and identically distributed and the simplicity of the method is an advantage. However, some extremes could be lost if other events than the maximum of a year exceeds the annual maxima of other years. Thus, the POT approach may give a more consistent definition of extremes [3] and might be preferred when the observed rainfall series are short. Extreme events extracted from observational time series by the POT approach follow a generalized Pareto distribution (GPD) [40]. The cumulative distribution function, $F(z)$, for the POT extremes (z) are given by:

$$\begin{array}{l} F(z) = 1 - \left(1 + \xi \frac{z-u}{\sigma}\right)^{-1/\xi} \ for\ \xi \neq 0 \\ F(z) = 1 - exp\left(-\frac{z-u}{\sigma}\right) \ for\ \xi = 0 \end{array} \tag{2}$$

where u is the defined threshold, σ the scale parameter, and ξ the shape parameter.

When applying models of threshold excesses, proper threshold selection is important in order to balance bias and variance. The threshold must be high enough to ensure that the observations do not belong to the central part of the distribution (without risking too few excesses above the threshold), but low enough to reduce variance [40]. Common approaches for threshold selection are to set the threshold based on a percentile (e.g., 99th or 99.5th percentile), by visual inspection of mean residual life (MRL) plots or dispersion index plots prior to model fitting, or by looking for stability of parameters after fitting the model over a range of thresholds. Manually inspecting many plots and series will be impractical, and some methods for optimizing this process have emerged, such as, the combined-peak-over-threshold (CPOT) approach by Anagnostopoulou and Tolika [41].

In addition to threshold selection, the GPD parameters will be affected by choice of method for parameter estimation. For practical reasons, all GPDs was fitted by maximum likelihood estimation (MLE) in this study [32]. Furthermore, the behavior of the GPD is greatly dependent on the shape parameter. A global study of the GEV shape parameter, including 71 data series from Norwegian stations found that the shape parameter in Norway lies in the interval 0.028–0.156, with an average of 0.044 [42].

In this study, precipitation extremes for time scales 5 min, 10 min, 15 min, 30 min, 1 h, 3 h, 6 h, 12 h and 24 h were extracted from aggregated time series of observations using various threshold selection techniques: (1) the combined POT (CPOT) approach [41], and (2) 95th, 99th and 99.5th percentiles. To secure independent events, an independence criterion of 48 h between daily and 12 h events and 24 h between the remaining sub-daily durations was set, following the recommendation that the independence criteria should exceed the durations of the events [3]. Since it has been argued that $\xi_{GEV} \cong \xi_{GPD}$ [42,43], the fitting of the GPD to daily rainfall extremes was tested with a fixed shape parameter of 0.044, corresponding to the Norwegian average [42] for all of the three locations. When fitting the sub-daily GPDs, the daily shape parameter for the respective locations was used, as previous studies has indicated that this gives a more stable downscaling model [44]. The goodness of the fit between the empirical and theoretical distribution was assessed by a traditional Chi-squared test, where the p-value was computed for a Monte Carlo test [45]. The analyses were performed in the open-source software R, using built-in functions and the R package 'POT' [46].

From the resulting extreme precipitation distribution parameters, return levels used for constructing the IDFs were estimated based on the formula:

$$Z_N = u + \frac{\sigma}{\xi}\left[\left(N n_y \zeta_u\right)^{\xi} - 1\right] \quad (3)$$

where N is the return period, Z_N is the N-year return level, n_y the number of observations per year, and ζ_u = Pr{X > u} [40]. In this study, the sample proportion of points exceeding u was used as an estimation for ζ_u [40]. From this, the scaling exponent, β, was found by studying the relationship between the observed Z_n and D in a double logarithmic plot. The scaling exponent obtained was then used to scale Z_N of the projected daily precipitation (NCCS data) to lower durations in order to construct IDF curves for the future period 1971–2100.

The projected IDF curves were used to create design events to be used as input to the event-based models of LID performance. Local stormwater measures for small catchments are, in Norway, commonly designed for peak flow control with storm durations corresponding to time of concentration, typically ranging from 5–10 min up to one hour [47]. Synthetic designed precipitation hyetographs based on local IDF-curves, incorporating intensities for several different durations, are recommended methods when designing based on IDF-data. This method requires knowledge on precipitation patterns [48]. Little work has been done on creating specific synthetic hyetographs for Norwegian short duration precipitation. For the purpose of this study, two synthetic design events were constructed representing the extremes, where the peak arrives on initial dry or wet conditions. Both were constructed based on local IDF-curves and a 20-year return period event with durations 10 and 60 min. The peak was constructed as a 10 min block rain starting after 5 min for the initial dry conditions and after 50 min for the initial wet conditions. Both alternatives were designed to include the 60 min precipitation depth. The design events were constructed from the present, future maximum and future minimum IDF-curves.

2.4. Low-Impact Development (LID) Performance Assessment

The effect of future climate scenarios on different stormwater measures have been investigated with respect to both long time series and short-term event performance under climate change. Three different measures, bioretention cells, extensive green roofs and detention basins, have been included in the study to represent important processes for stormwater management as infiltration, evapotranspiration and peak runoff reduction and delay (Table 2). The long-term performance depends mainly on the processes of evapotranspiration and infiltration to native soil reducing volume loads on the downstream system, while filtration processes reduce the runoff off pollutants and contribute to improved quality of receiving water bodies. The short-term design event performance, on the other hand, depend mainly on the processes of detention resulting in peak reductions and delay. The long-term performance was based on the 30-year time-series of daily precipitation and temperature projections (NCCS data). Short-term event-based performance was investigated by applying a 20-year return period design event based on locally derived IDF-curves for the future obtained by downscaling the NCCS data.

Table 2. Modelling framework for local stormwater measures' performance, with methods and type of results.

Measure	Long-Term Performance	Event-Based Performance
Bio retention cells	Water balance model [1] *Infiltration to native soil* *Filtration for pollutant removal* *Evapotranspiration*	RECARGA *Peak reduction* *Peak delay* *Infiltration to native soil* *Filtration for pollutant removal*
Extensive green roofs	Water balance model [1] *Evapotranspiration* *Runoff* *Drought considerations*	SWMM Green roof module *Peak reduction* *Peak delay*
Detention basins	No investigation relevant	Rain envelope method *Volumes needed* *Dimensional rain duration*
Combined measures	No investigation	Comparison of: (1) Detention basin alone (2) Green roof and detention basin (3) Bioretention cell and detention basin (4) Green roof and bioretention cell and detention basin. *Detention basin volumes needed*

[1] Water balance models were run in MATLAB.

The focus was on a site scale rather than on a catchment scale, based on an assumption, as suggested by Burns et al. [49], that urban stormwater management should emphasize the restoration or protection of natural hydrologic processes at small scales, with the aim of restoring natural flow regimes at larger scales downstream. For comparative reasons, all stormwater measures were tested on a site scale based on a catchment area of 1000 m^2 of roof or another impervious catchment area (e.g., parking lot). A detailed description of the methods follows.

The green roofs modelled in this study were based on a build-up used in field studies in four Norwegian sites; Trondheim, Bergen, Sandnes and Oslo [50]. The field studies had a build-up consisting of a 30 mm pre-grown, sedum-based vegetation mat over additional 50 mm of green roof substrate, a 25–75 mm plastic or polystyrene drainage layer and a 5 mm thick textile retention fabric as the bottommost layer. This build-up corresponded to a theoretical water storage capacity of 19–24 mm. The green roof water balance model was run with a maximum water storage capacity (S_{max}) of 25 mm. The denotation in parenthesis refer to the parameter abbreviations used in Equations (4)–(9). The roof made for the model exemplification was a typical commercial building with a 1000 m^2 flat roof. Slope was set according to minimum requirements in Norwegian building regulations of 1:40 (2.5%) [51] and the maximum distance to drainpipe was set to 10 m. The bioretention cell area (A_B) (50 m^2) was set to 5% of the catchment area (A_C) (1000 m^2) corresponding to common sizing recommendations [52]. The catchment was assumed to be 100% impervious illustrating a conventional roof or a parking lot. The maximum ponding depth was set to 15 cm, giving an above ground storage volume of 7.5 m^3 ($V1_{MAX}$) [53].

The bioretention media depth was set to 75 cm [53,54] with an infiltration rate of 10 cm/h (Inf1) which is a minimum recommended value for cold climates based on investigations carried out by Paus et al. [55]. A drainage pipe was placed in the upper part of a drainage layer. The drainage layer depth was set to 25 cm and with a high porosity of 50% this constituted a sub-surface storage layer of 6.25 m^3 ($V2_{MAX}$). Many costal Norwegian cities suffer from low infiltration capacities due to their costal location with a large extent of marine sediments. For this reason, a relatively low native soil infiltration rate of 0.5 cm/h (Inf2) was applied, corresponding to minimum values found from infiltration tests at 60 cm depth in loam, silt loam and silt clay loam soil in Oslo [56].

2.5. Daily Time-Step Models

Long-term behavior of green roofs was modelled to study future climates effects on volume flows of evapotranspiration and runoff, by the use of a continuous green roof water balance model as described in [34]. The model was based on daily time steps (t) and calculated green roof runoff (R) as a function of precipitation (P), actual storage (S), maximum storage capacity (S_{max}), crop coefficient (C_{crop}) and evapotranspiration (Equations (4) and (5)). Potential evapotranspiration (PET) estimates were based on the Oudin model (Equation (6)), which was found to be the simplified temperature (T) based model performing best for the Nordic climates [57]. PET estimates were coupled with a soil moisture extraction function and a crop coefficient to calculate actual evapotranspiration (AET) (Equation (7)).

The model applied in [34] was improved by calibrating the crop coefficient based on three years of continuous observations from field studies [50]. The model was calibrated was based on minimizing the objective function relative percentage difference (RPD) for three year of continuous data (2015–2017) and validated with the objective function Nash–Sutcliffe efficiency (NSE) for non-winter data [58].

$$R_t = 0 \qquad S_{t-1} + P_t - AET_t \le S_{max} \tag{4}$$
$$R_t = P_t - (S_{max} - S_{t-1}) - AET_t \qquad S_{t-1} + P_t - AET_t > S_{max}$$
$$S_t = S_{t-1} + P_t - AET_t \qquad S_{t-1} + P_t - AET_t \le S_{max} \tag{5}$$
$$S_t = S_{max} \qquad S_{t-1} + P_t - AET_t > S_{max}$$
$$PET_t = 0.408 * R_e * [0.01 * (T_t + 5)] \tag{6}$$
$$AET_t = PET_t * C_{crop} * S_{t-1}/S_{max} \tag{7}$$

t = Timestep (d)
R = Runoff (mm/d)
P = Precipitation (mm/d)
S_{max} = Maximum storage capacity (mm)
S = Used storage (mm)
PET = Potential evapotranspiration (mm/d)
AET Actual evapotranspiration (mm/d)
R_e = Extra-terrestrial radiation (MJ/m^2*d) derived from Julian day and latitude
T = Temperature (°C)
C_{crop} = Crop coefficient

Model results were calculated both annually and for the temperate season (defined as the period May through October) when most of the retention was expected to take place. The data was further divided into events divided by dry periods, defined as days with less than 1 mm precipitation. Maximum duration of dry periods was expressed by the 99.5% percentile of all observed dry periods and a drought incident was defined by less than 1 mm water stored in the end of a dry period. Available retention capacity at the beginning of a precipitation event was defined as the median observed retention from events with more than 5 mm precipitation, duration less than 3 days and where runoff occurred.

Long-term behavior of bioretention cells was modelled to study future climates effects on volume flows of infiltration, runoff and potential evapotranspiration. A bioretention cell water balance model (Equations (8) and (9)) with daily time-steps equivalent to the one used for green roofs were set up, with the same input time series of precipitation (P) and evapotranspiration (PET), as used in the green roof water balance model.

Calculations of overflow of the unit were based on an assumption that all precipitation arrived during a period of 1.7 h. The time period was found as the average time with precipitation on the days when the total precipitation amounts exceeded the above surface storage volume. Storage in the bioretention media was not included, and evapotranspiration estimates were set equal to the potential evapotranspiration only for time-steps with water available. This would probably lead to an underestimation of evapotranspiration, but due to the low catchment to bioretention surface area ratio, evapotranspiration would represent a small volume flow and the simplification was, therefore, considered to be sufficient for the purpose which was to evaluate changes in volume flow for future climates.

Initial values:

$Qinn_t = P_t * (A_B + A_C)/1000$

$AET_t = PET_t * A_B/1000$

$Q1_t = Inf1 * A_B * 1.7\,h/100$

$Q2_t = Inf2 * A_B * 24\,h/100$

$$S1_t = S1_{t-1} + Qinn_t - AET_t - Q1_t \quad (8)$$

If $S1_t > V1_{max}$ $\quad S1_t = V1_{max}$ and $Qov = S1_{t-1} + Qinn_t - AET_t - Q1_t - V1_{max}$

If $S1_t < 0$ $\quad S1_t = 0$ and $Q1_t = S1_{t-1} + Qinn_t - AET_t$

If $Q1_t < 0$ $\quad AET_t = S1_{t-1} + Qinn_t$

$$S2_t = S2_{t-1} + Q1_t - Q2_t \quad (9)$$

If $S2_t > V2_{max}$ $\quad S2_t = V2_{max}$ and $Qd_t = S2_{t-1} + Q1_t - Q2_t - V2_{max}$

If $S2_t < 0$ $\quad S2_t = 0$ and $Q2_t = S2_{t-1} + Q1_t$

t = Timestep (d)

Qinn = Inflow (m^3/d)

A_B = *Area bioretention* (m^2)

A_C = *Area catchment* (m^2)

AET = Actual evapotranspiration (m^3/d)

Q1 = Infiltration flow bioretention media (m^3/d)

Inf1 = Infiltration rate bioretention media (cm/h)

Q2 = Infiltration flow native soil (m^3/d)

Inf2 = Infiltration rate native soil (cm/h)

Qov = Overflow (m^3/d)

Qd = Flow through drain (m^3/d)

S1 = Used above surface storage S1 (m^3)

$V1_{max}$ = *Maximum above surface storage* (m^3)

S2 = Used sub surface storage (m^3)

$V2_{max}$ = *Maximum sub surface storage* (m^3)

2.6. Design Event Models

Green roof detention performance in present and future climate was investigated using the green roof specific LID module in the Storm Water Management Model (SWMM version 5.1.012) [59]. The green roof was modelled as a subcatchment totally covered by a green roof and compared to a reference roof modelled as a 100% impervious subcatchment covered with a black bitumen liner. The model was run on an event basis. The initial saturation in the green roof model is important as it defines the available retention capacity when precipitation starts, and was set to 5 mm. This is an approximate conservative value based on observations in Bergen, Sandnes, Trondheim and Oslo [50], as can also be seen when compared to the results from the green roof water balance model. The SWMM green roof module and a comparative black bitumen reference roof were based on parameters derived from a multi-site calibration of the model with field data [60]. The highest intensity events included in the calibration data was a 10 min intensity of 0.83 mm/min and 60 min intensity of 0.36 mm/min.

The RECARGA model developed by Wisconsin Department of Natural Resources was used to evaluate the performance of a bioretention facility [61]. The RECARGA is a 1D model including up to three soil layers and optional underdrains, simulating the water movement applying the Green-Ampt infiltration model, and the van Genuchten relationship for drainage between soil layers. Model output includes inflow, overflow, flow through underdrain and infiltration to native soil. Evapotranspiration is set to zero during this short-term event modelling.

Stormwater detention basins, commonly built as underground constructions in Norway, was investigated by the use of a simplified spreadsheet model using the rain envelope method commonly applied by stormwater engineers [17,19,62,63]. Required detention basin volumes were calculated based on a maximum rate of outflow for different durations of a box type design rain from local IDF curves, and the duration giving the largest volume was used for design. Outflow was set to a constant value of 20 l/s·ha corresponding to a maximum discharge limit to public piped systems applied by the City of Oslo [63]. Most orifice restrictors would give some variations in outflow rate depending on the water depth in the basin, but for the purpose of comparing required volumes for different future climate scenarios this simplified approach was considered to be sufficient.

The effect of installing green roof and/or bioretention cells prior to stormwater detention basins was investigated. The measures were put in series, e.g., the runoff profile from the green roof SWMM model was used as input to the RECARGA model of the bioretention-cell, and the runoff from REGARGA was used as input to the detention basin. Stormwater measures in series could have been modelled inside SWMM, which introduced the possibility to model LIDs in series between 2015 and 2016 [59,64]. Still, RECARGA was chosen for the bioretention cell modelling due to the authors' prior experiences, where this model showed acceptable performance compared to observed bioretention cell runoff in a similar climate [65].

3. Results and Discussion

3.1. Temporal Downscaling

In total, the GPD was fitted to 27 datasets of extreme events (3 locations × 9 durations), with four different threshold levels. The obtained parameters and results of the chi-squared test were stored for each fit. According to the statistics obtained for daily extremes (Table 3), the variation (σ) obtained could be characterized as stable, compared to the threshold level (μ) which varies greatly between percentiles 0.95 and 0.995. Using the CPOT approach for threshold selection results in threshold levels belonging to the lower range of the percentile-based thresholds.

Table 3. Results of the generalized Pareto distribution (GPD) fitting of daily extremes.

Location	Value	CPOT	0.950p	0.990p	0.995p
Bergen	Threshold, μ	42.904	35.680	54.136	64.140
	Scale, σ	13.338	13.117	15.227	12.427
	Shape, ξ	0.044	0.044	0.044	0.044
	Chi-sq. *p*-value	0.405	0.13	0.304	0.112
	% sub-daily GPD fits with $p > 0.05$	67	67	67	78
Oslo	Threshold, μ	21.413	18.400	31.400	35.400
	Scale, σ	8.469	8.370	6.811	8.738
	Shape, ξ	0.044	0.044	0.044	0.044
	Chi-sq. *p*-value	0.095	0.044	0.192	0.183
	% sub-daily GPD fits with $p > 0.05$	33	11	33	44
Trondheim	Threshold, μ	19.422	15.600	27.600	36.686
	Scale, σ	9.672	8.636	10.636	8.056
	Shape, ξ	0.044	0.044	0.044	0.044
	Chi-sq. *p*-value	0.120	0.035	0.163	0.570
	% sub-daily GPD fits with $p > 0.05$	44	11	44	56

The results of the fitting of the sub-daily extremes by the same approach is summarized by the % sub-daily GPD fits that resulted in the p-value exceeding a significance level of $\alpha = 0.05$. Based on the chi-squared test p-value, a threshold selection corresponding to the 99.5th percentile is superior to other threshold levels for all locations and sub-daily durations. However, the chi-squared test also shows that some unsatisfactory results were obtained, especially for sub-daily extremes in Oslo and Trondheim. This is likely to be explained by the presumed shape parameter, which was fixed at 0.044. Letting ξ vary in the range 0.028–0.156, as suggested by Ragulina and Reitan [42], and testing other methods for parameter estimation, could result in better parameter fits and should be further investigated. However, fixing the shape parameter ($\xi = 0.044$) and limiting the parameter estimation techniques to one (MLE), allowed us to study the sensitivity of the GPD fit to threshold selection. In further steps, the fixed shape parameter and the 99.5th percentile threshold level was kept.

Return levels for return periods T = (2, 5,10, 20, 30, 50, 100) years were estimated (Equation (3)) and plotted against duration in a double logarithmic plot (Figure 3). The scaling exponent, β, is calculated for each return period, and the average of these is used for further calculations. By inspecting the plots, a clear linear relation in the double logarithmic plot is found for Bergen and Trondheim (Figure 3a,c), indicating a simple scaling case with a constant scaling exponent for all durations. The return levels for Oslo, however, show a concave behavior (Figure 3b). The shift occurs at ~60 min, suggesting a difference in scaling behavior for sub-hourly extreme precipitation. This is similar to results reported by e.g., Nguyen et al. [30] who also found a simple scaling behavior within the same two different time intervals when performing a similar study for Quebec, Canada.

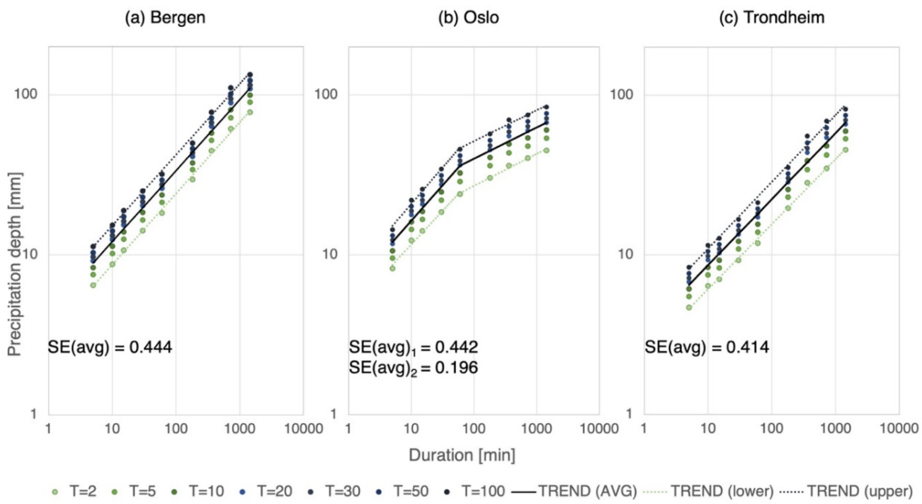


Figure 3. Estimated return levels of observed precipitation depth and observed trend with increasing duration for the three locations: (**a**) Bergen, (**b**) Oslo, and (**c**) Trondheim.

The results of scaling the observed daily return levels are compared to the return levels estimated based on the GPD parameters (Figure 4). Common for all locations is that the scaling models underestimate the return levels for the highest and the lowest durations. For Oslo and Trondheim, the scaling models are found to behave very well from a duration of 3 h and down to ~30 min and ~15 min, respectively (Figure 4b,c). The scaling model for Bergen is seen to always overestimate or underestimate the return levels and the offset is worst for higher durations and higher return periods. However, there is a higher agreement between scaled return levels and return levels estimated by GPD parameters than what has been found in earlier studies for Bergen [32] and Trondheim [33] based on AM and GEV distribution selection.

3.2. Projected Future Climate

Both average daily temperatures and precipitation increased for all (10) tested future scenarios. Temperature increase from present to the median off all future models were found to be quite similar, with an increase of 4.6 °C in Bergen (BER), 5.1 °C in Trondheim (TRD) and 5.6 °C in Oslo (OSL), while daily precipitation increased more in Bergen (2 mm) compared to Trondheim (0.6 mm) and Oslo (0.3 mm) (Figure 5). The 10 projected models also produce a range of scenarios. For daily precipitation in Bergen, this range is especially high. Furthermore, it is found that the models that produce the max and min scenarios are not the same across locations. This highlights the need for and usefulness of an ensemble approach.

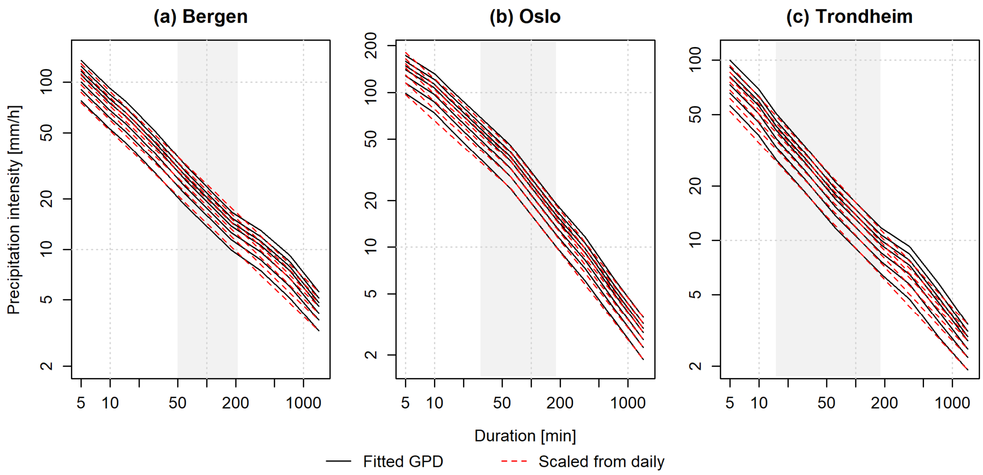


Figure 4. Estimated observed and scaled intensity-duration-frequency (IDF) curves for return periods T = (2, 5, 10, 20, 30, 50, 100) years for the three locations Bergen (**a**), Oslo (**b**) and Trondheim (**c**).

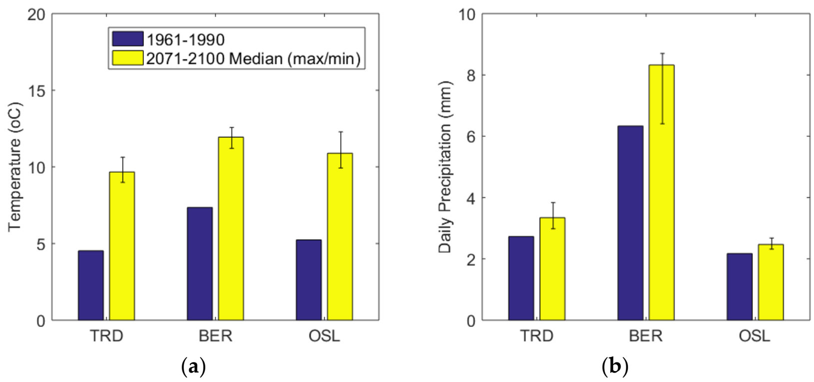


Figure 5. Average climate for preset (year 1961–1990) and future (year 2071–2100, median, maximum and minimum of 10 projections) normal periods: (**a**) average annual temperature, (**b**) average daily precipitation.

Scaling the projected daily return levels, using the obtained scaling relations was performed to construct IDF curves also for future precipitation. The scaling was performed for all 10 future scenarios, such that an ensemble of return levels was obtained for each return period. Similar to the daily projections, the projected T = 20 year sub-daily precipitation intensities for Bergen result in the largest increase compared to observations (Figure 6). For Bergen, an increase of return levels is projected to all scenarios, while some scenarios result in a decrease of return levels for Oslo and Trondheim. For the observed return levels, it was estimated that Oslo experiences the highest intensity of short duration rainfall and a shift between Oslo and Bergen occurs approximately around duration 3 h. In the projections, the intensity of short duration rainfall in Bergen is expected to exceed the corresponding intensities for Oslo for all durations, and no such shift occurs. Comparing Oslo to Trondheim, the relative difference between intensities stay roughly the same from observations to projections.

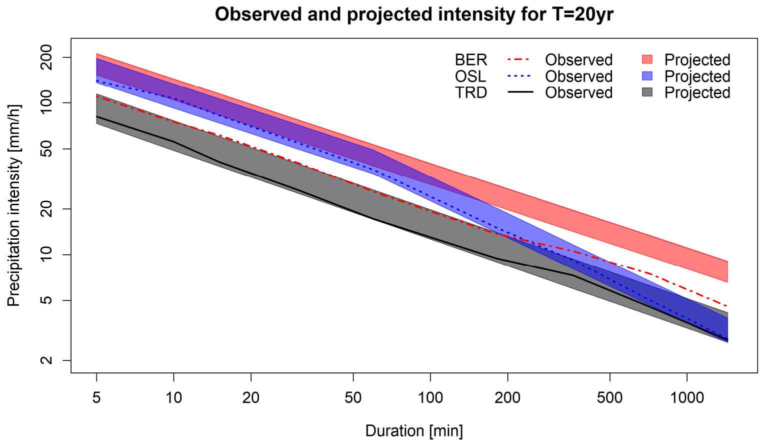


Figure 6. Comparison of T = 20 year return levels for locations Bergen, Oslo and Trondheim. Observed curves are shown as lines, while projections are visualized as bans representing the max/min-range of the scenarios.

The relative difference between projected and observed return levels, addressed climate factor (CF), is of practical interest for stakeholders planning sustainable systems in Norway as it is often included in design guidelines. In Norwegian municipalities, it is common to operate with a climate factor in the range 1.2–1.5 that is added to the design precipitation intensity (collected from IDF curve). Usually, vulnerable infrastructure is designed for higher return periods, but the climate factor is kept constant. The results of this study contradict this practice (Figure 7). For estimated hourly climate factors, there is a large variation in estimated climate factors both across locations and return periods. For return periods, T, in the range 2–100 years, the climate factor is increasing, indicating that vulnerable infrastructure also should be design with a higher climate factor. According to the investigated projections, Bergen is expected to experience the largest increase in extreme hourly precipitation, while the climate factors for Oslo and Trondheim are significantly lower but showing the same increase with return periods as Bergen.

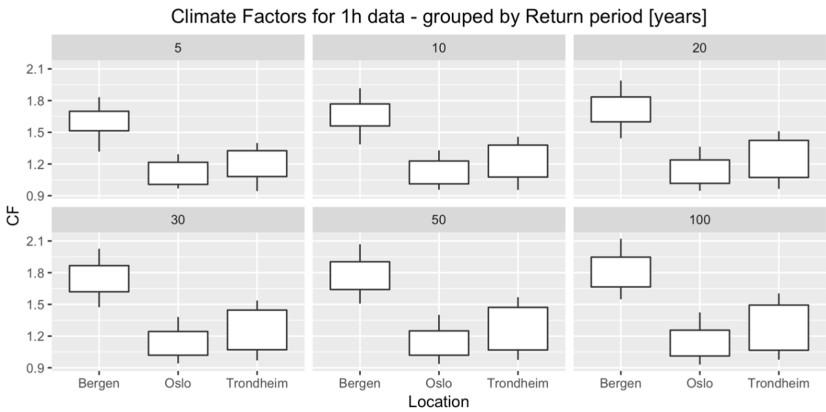


Figure 7. Climate factors (CF) of hourly precipitation intensity, calculated as the relative difference between observed and projected return levels for locations Bergen, Oslo and Trondheim.

3.3. LID Performance: Volume and Pollution Control

Evapotranspiration is in this study represented by green roofs and bioretention cells, while other stormwater measures like rooftop disconnections, the use of vegetation and pervious surfaces also benefit from this process. The green roof water balance model was run with a crop coefficient of 0.9, based on the calibration results from all sites with |RPD| < 10% and NSE > 0.6. Green roofs contribute to a considerable reduction in annual runoff volumes by retention and subsequent evapotranspiration in present climate with 15% in Bergen, 26% in Trondheim and 35% in Oslo (Figure 8a). The fractions increase slightly for most future scenarios in spite of the increased precipitation volumes, due to the increased temperatures' effect on evapotranspiration. The performance improved most for Oslo, due to the combined effect of temperatures and precipitation, which is most favorable for Oslo with the highest temperature increase and the lowest precipitation increase. This makes green roofs and other stormwater measures relying on evapotranspiration for stormwater removal, favorable solutions for present and future stormwater management with respect to volume reduction. These results are based on relatively cold and wet Norwegian climates and the findings are expected to be even more advantageous for warmer and drier climates. Median available retention capacity in the temperate season increases for all future scenarios at all locations (Figure 8b). This measure is especially of interest during the temperate season where small precipitation events can be retained totally or where larger precipitation events experiences an enhanced detention effect in the first part of larger precipitation events due to the initial retention taking place before runoff is initiated. Analysis of short-term extreme precipitation events (5–15 min duration) show that these events occur in the temperate season, where advantage can be taken of the available retention capacity of the green roofs.

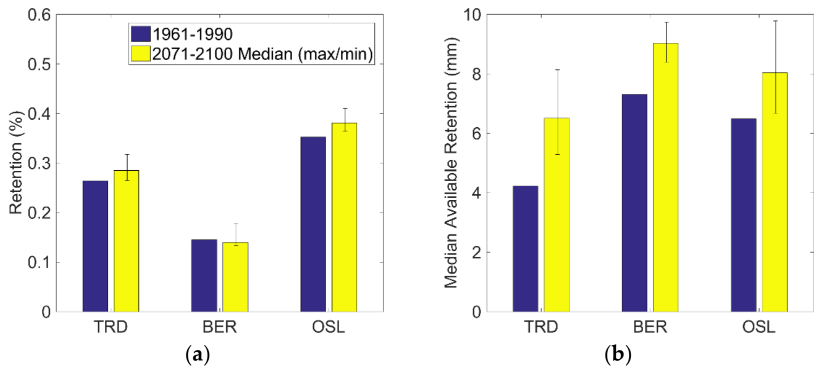


Figure 8. Green roof retention performance for present (year 1961–1990) and future (year 2071–2100, median, maximum and minimum of 10 projections) normal periods: (**a**) average annual retention; (**b**) median available retention capacity in temperate season (May through October).

Dry periods involve risk of vegetation drought. There is no clear trend in changes in duration of the extreme dry periods from present situation to future scenarios, but the increased evapotranspiration rates give an increased number of drought incidents for most future scenarios (Figure 9). This can be coped with by increasing the water storage capacities of the applied systems. The risk of increased future green roof drought was found to be largest for Oslo, increasing from 4 to as much as 19 incidents in 30 years for the highest future scenario, indicating that higher storage capacities than the chosen 25 mm should be considered when building extensive green roofs for a future climate in Oslo.

Infiltration to native soil is in this study represented by a bioretention cell in a soil with relatively low infiltration capacity, to illustrate the potential for this process even at less favorable conditions. Infiltration is also important for other stormwater measures like rooftop disconnections, infiltration trenches and all types of pervious surfaces. Bioretention cells contribute to a considerable reduction in annual runoff volumes by infiltration to native soil in present climate with 54% in Bergen, 83%

in Trondheim and 85% in Oslo (Figure 10b). The fractions decrease slightly for all future scenarios due to increased precipitation amounts but can also in a future climate give a large contribution to runoff volume reductions. Bioretention cells are the only stormwater measure in this study that can remove pollutants from stormwater by filtration treatment, while this effect will not be present for volumes that overflow the unit's capacity. Volumes treated for pollution control was found to be 63% in Bergen and 88% in Trondheim and Oslo for the present climate, decreasing slightly for all future scenarios tested (Figure 10a). The Bergen site experiences more than twice the precipitation amounts compared to the two other sites and a higher bioretention cell-to-catchment-area ratio, than the 5% used in this study, should be applied to improve the general performance. Bioretention cell above ground storage area could also be increased to improve performance with respect to fraction of runoff treated and/or infiltrated [8]. Evapotranspiration was only found to represent a small fraction of the volume reduction in bioretention cells (0.6–1.4%) due to the small surface to catchment area ratio.

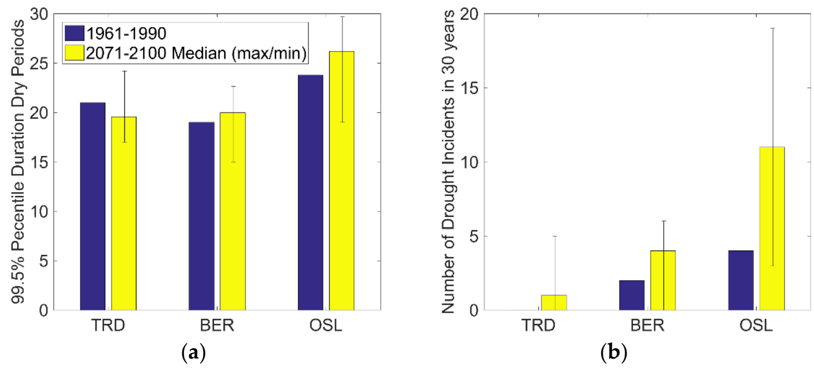


Figure 9. Green roof drought considerations for preset (year 1961–1990) and future (year 2071–2100, median, maximum and minimum of 10 projections) normal periods: (**a**) maximum duration of temperate season dry periods expressed by the 99.5% percentile; (**b**) number of drought incidents in 30 years.

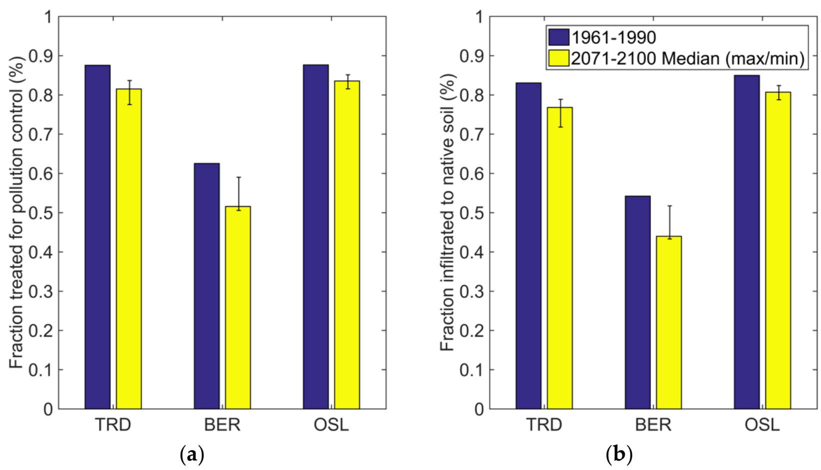
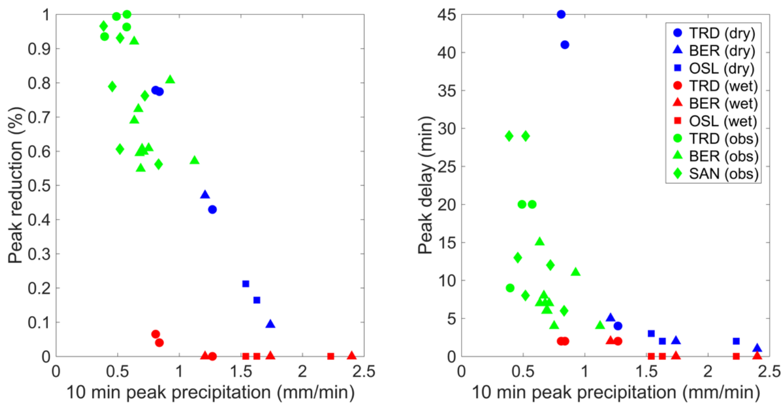


Figure 10. Bioretention cell performance for preset (year 1961–1990) and future (year 2071–2100, median, maximum and minimum of 10 projections) normal periods: (**a**) fraction of inflow treated for pollution control; (**b**) fraction of inflow infiltrated to native soil (volume control).

3.4. LID Performance: Peak Flow Control

Peak flow control in terms of peak reduction and peak delay was limited for the modelled green infrastructure alone (green roofs and bioretention cells) for the tested 20-year 1 h design events. The performance improved with reduced peak precipitation intensities/precipitation depth and when the highest peak intensity arrived early in the precipitation event (when the unit was not saturated yet) (Figures 11 and 12). The SWMM green roof modelling parameters were calibrated with field data with smaller peak intensities than the highest intensities tested here, limiting the accuracy of the model. Still, field observations on peak reductions for the largest observed events (Figure 11a) resemble the model results where the peak arrived on initial dry conditions giving peak reduction above 55%. This indicates that green roofs can contribute to some extent to peak flow control events for high intensity events. However, with only three year of observations the worst case situations are probably not captured. For the costal climates studies these could typically be high-intensity precipitation events inside a longer low intensity event giving initial conditions comparable to the modelled initial wet situation. For the highest modelled peak intensities, and when the peak arrived late in the precipitation event (initial wet) very low peak reductions and peak delays were found. The most likely explanation for this was that the green roofs were almost totally saturated, and when the flow inn increased, the same amount of water would have to be pushed out almost immediately by the hydraulic pressure. Bioretention cells were overflowed at most tested scenarios resulting in low peak reduction and peak delays (Figure 12c). A substantial part of the precipitation (11–35%) could be infiltrated even at these large design events. Fractions overflowing the unit resulting in no pollution control were high for the largest design events (up to 69%). The highest future scenarios represent an increase in precipitation for all locations, accompanied by a reduced detention performance for green roofs and bioretention cells. Green infrastructure is typically designed to target the most frequent precipitation events and cannot stand alone as a peak flow control measure for large design events. However, these measures can give valuable contributions, and with alternative sizing, or in combination with other stormwater measures, they can give a substantial contribution to peak flow control of large design events, as also suggested by Dietz et al. [8] and Rosa et al. [66].



(**a**) (**b**)

Figure 11. Green roof detention performance. Model results of design events (present, future max and future min) for initial dry and initial wet conditions, in addition to field observations for the locations Trondheim (TRD), Bergen (BER), Oslo (OSL) and Sandnes (SAN): (**a**) peak reduction; (**b**) peak delay.

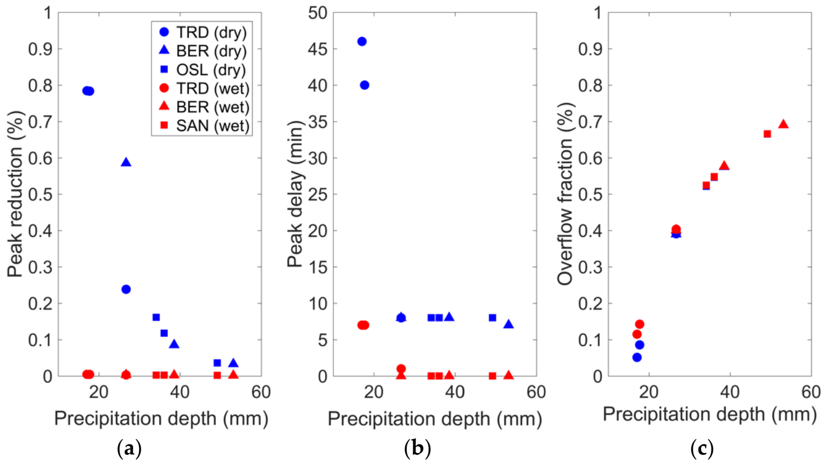


Figure 12. Bioretention cell detention performance. Model results of design events (present, future max and future min) for initial dry and initial wet conditions, for the locations Trondheim (TRD), Bergen (BER) and Oslo (OSL): (**a**) peak reduction; (**b**) peak delay; (**c**) volume fraction overflowing the unit.

Detention basins can be designed to meet any given peak runoff threshold resulting in variable volume requirements. Required detention basin volumes for a runoff area of 1000 m^2 and a runoff threshold of 20 l/s·ha were almost three times as high in Oslo (29 m^3) and twice as high in Bergen (22 m^3) compared to Trondheim (11 m^3) for the present climate (Figure 13a). All future scenarios increased the required detention basin volumes substantially compared to the present for Bergen, while smaller increases were found for most future scenarios in Oslo and Trondheim. The size increased by 50% for the maximum future scenario in Oslo, 100% in Trondheim and as much as 250% for the maximum future scenario in Bergen. The duration of the design event was longer for Bergen in present climate and increased even further for all future scenarios, indicating that the type of events being critical for stormwater design might change in the future from short duration events, commonly being used for design today, to longer duration events. Stricter runoff thresholds than applied here will result in longer durations of the design event and larger basin volumes.

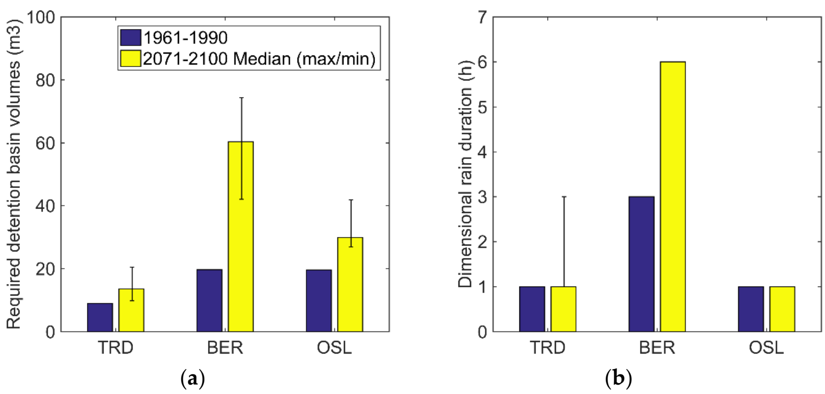


Figure 13. Stormwater detention basins for present and future situation (median, maximum and minimum of 10 projections), sized based on IDF curves, 20-year return period, 1000 m^2 impervious area and a runoff threshold of 20 l/s*ha: (**a**) required volumes; (**b**) dimensional rain duration.

3.5. LID Performance: Combined Measures

Detention basins are efficient in reducing peak runoffs at high-intensity events from single plots, while providing no stormwater treatment and little or no peak reduction at smaller more frequent events. Stormwater management based on detention basins alone require large volumes to handle a 20-year design event and combination of measures are preferable for volume and pollution control in addition to peak flow control.

The combined effect of different stormwater measures has been investigated for present and future design events, based on a 20-year return period 60-min duration design event, with a 10 min peak with the most unfavorable timing placed late in the precipitation event (Figure 14). The same areas, stormwater measures and methods as applied earlier were used in this comparison. Largest required volumes were found when only using a detention basin alone. The introduction of an extensive green roof before the detention basin reduced the required volumes. A slightly higher volume reduction was found by using a bioretention cell before the detention basin. A combination of both an extensive green roof and a bioretention cell reduced the required detention basin volume substantially and, in some cases, totally removed the need for the detention basin. The same pattern in volume reduction was found when applying a design event based on the future maximum and minimum scenarios. Most tested future scenarios gave an increase in required detention basin volumes and the largest increases were found for Bergen. The individual investigation of detention basins for Bergen showed that this was the only site where rain durations larger than 60 min were dimensional, giving even larger volume needs than shown in this combined investigation. Runoff thresholds are commonly based on a predevelopment runoff pattern, and, due to the climatic conditions, this would probably be set higher in Bergen compared to the other sites, and not similar as in this exemplification. The method still illustrates the consequences of the future precipitation scenarios and the efficiency of combining stormwater measures. The investigated measures also show the potential for upgrading existing detention basins designed for the present climate, by adding green roofs on conventional rooftops and directing runoff through bioretention cells prior to the detention basins, to perform sufficiently also in a future climate.

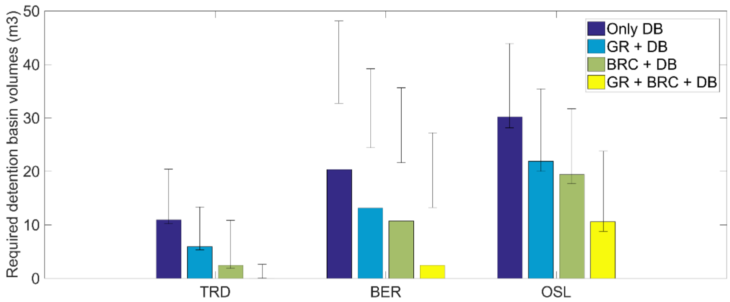


Figure 14. Required stormwater detention basin volumes for different combinations of green roofs (GR), bioretention cells (BRC) and detention basins (DB). Model results of design events for present (bar), future- max and min (error bars) for initial wet conditions, based on 1000 m^2 impervious area and a runoff threshold of 20 l/s·ha.

4. Conclusions

This study has assessed the performance of LID structures in present and a future climate for three different locations in Norway: the cities of Bergen, Oslo and Trondheim. The assessment was performed using existing regional climate projections of daily temperature and precipitation and scaling laws to construct future IDF curves, and an extensive modelling framework to investigate the full range of slow and rapid hydrological processes.

The climate projections indicated a substantial increase in average annual temperatures for all investigated future scenarios with median value increase ranging from 4.6–5.6 °C, while average daily precipitation increased most for Bergen with a median increase of 2.0 mm compared to 0.6 mm for Trondheim and 0.3 mm for Oslo.

The scaling of IDF relationships was performed on rainfall extremes extracted by the POT approach and fitted to the generalized Pareto distribution. A clear scaling relationship between daily and sub-daily extreme rainfall statistics was found, and the scaling model itself was assessed as improved from previous attempts to scale similar data sets. However, the GPD assumption did not hold for all the assessed extreme series. Future IDF curves constructed based on the obtained scaling relationships showed that there are large variations in projected intensity increase across locations, where projections for Bergen entail a much higher increase than Oslo and Trondheim. The implication of this is that local conditions should be considered in order to achieve optimal adaptation of stormwater management. Furthermore, climate factors were found to increase with return period, implying that an even higher safety requirement should be considered for stormwater design practices in vulnerable surroundings.

According to long-term water balance simulations, green roofs can contribute with reductions in annual stormwater runoff volumes by evapotranspiration in the range of 15–40% depending on local climate. Bioretention cells covering 5% of the catchment area with relatively low infiltration capacities in native soil (0.5 cm/h) were found to reduce stormwater runoff volumes by 54–85% and to filtrate as much as 63–88% for pollutant control. Future performance of green roofs was found to be comparable or improved due to increased evapotranspiration rates caused by increased temperatures, while future performance of bioretention cells was found to be slightly poorer due to increased precipitation amounts. The risk of green roof drought was found to increase in future scenarios, and can be reduced by increasing water storage capacities.

Detention basin volumes required to handle a 20-year event increased for almost all tested scenarios, but most for Bergen where the design events increased most in size. Green roofs and bioretention cells can contribute with peak reduction and peak delay for some of the tested 20-year return period, 1 h design events. However, for the largest and highest-intensity events or when the peak arrived on initial wet condition, little detention effect was found. Despite the poor performance alone on design events, green roofs and bioretention cells can make an important contribution to design events, reducing the required downstream detention basin volumes substantially if applied in series.

In this study, LID performance was assessed for selected climate scenarios. One major limitation of the study is the high level of uncertainty linked to climate projections. In addition, several assumptions were needed for the statistical analysis comprising the temporal downscaling, such as choice of independence criteria and threshold selection, introducing even more uncertainty. By coupling frameworks, this uncertainty was further propagated through the assessments of LID performance in water-balance and event-based models. The daily time step models used are continuous and will, therefore, capture the processes dependency of antecedent conditions, but can only be used to evaluate slow processes like evapotranspiration and infiltration. Assumptions had to be made to distribute the daily precipitation into the bioretention cell introducing uncertainties. However, future time series of higher time resolution were not available to make a more accurate model for long-term future performance. Performance during high intensity precipitation was based on synthetic design events created from IDF curves. This is a common design method for stormwater measures, but has the limitation of not including the antecedent conditions, which could be relevant for the performance of this type of LID measure. This was partly accounted for by introducing two different synthetic design events, where the peak arrived on different initial conditions.

No prediction of the future will be perfect, but assessing the uncertainty of projections is necessary to provide better decision support to practitioners. The inclusion of more scenarios, sensitivity analysis of GPD parameters, and testing the methodology on more data sets would be valuable for such an assessment. Evaluation of different stormwater measures and combinations are necessary for design of future resilient systems. In this study this was conducted with different tools, while a practitioner would prefer this to be integrated in one tool. Stormwater models have lately introduced modules for local stormwater measures, but more work is needed to improve these. Model outputs have to be tested further versus field observations to provide reliable material dependent model parameters. Long-term processes, e.g., evapotranspiration from green roofs, have to be represented more accurate in the model, and the possibility to model different combinations of stormwater measures both in series and in parallel, should be tested further.

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Paper IV

Long-term simulations of combined sewer overflows for climate adaptation planning

Erle Kristvik, Ashenafi Seifu Gragne, Tone Muthanna and Knut Alfredsen 2019

Manuscript ready for submission

This paper is awaiting publication and is not included in NTNU Open

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Paper V

Cost-effective solutions for climate adaptation of urban drainage systems

Clemens Strehl, Erle Kristvik, Juliane Koti and Tone Muthanna 2019

Submitted for review in *Urban Water Journal*

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Cost-effective solutions for climate change adaptation of urban drainage systems

Clemens Strehl[a]*, Erle Kristvik[b], Juliane Koti[c], Tone Merete Muthanna[b]

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This paper is awaiting publication and is not included in NTNU Open

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Appendix B Conference Presentations

Seasonal variations in climate and the performance of stormwater collection systems (Oral presentation)

Kristvik, E.[1], and Muthanna, T. M.

14th IWA/IAHR International Conference on Urban Drainage (ICUD)

10-15 Sep 2017, Prague, Czech Republic

Abstract: This study presents an assessment of precipitation-based climate indices for the city of Bergen, Norway, with focus on the link between seasonal variations of climate indices and generated stormwater. The assessment is performed on historical data as a first step to climate change impact assessments. Because the selected climate indices are based on daily precipitation amounts, the computational need is lowered and the assessment can serve as a supplement to impact studies that investigate changes in sub-daily precipitation extremes.

Comparison of two stochastic methods for disintegrating daily precipitation to a sub-hourly series (Poster presentation)

Kristvik, E.[1], Gragne, A. S., Muthanna, T. M., and Kpogo-Nuwoklo, K.

European Geoscience Union (EGU)

8-13 April 2018, Vienna, Austria

Abstract: The importance of sub-hourly precipitation series for modelling urban hydrologic systems and projecting impacts of changes in future climate cannot be emphasized enough. Nevertheless, availability of long-term historical records and local climate scenarios at finer temporal scales are limited. Several stochastic weather generators were developed during the past few decades to disintegrate precipitation records at sub-monthly and sub-daily scales. However, a few focused on generating sub-hourly series and literatures that compare performances on a finer temporal resolution are scarce. In order to generate precipitation series of five-minute intervals and make practical use of the existing climate projections, we apply and compare two stochastic methods. These are a non-parametric

[1]Presenting author

K-nearest neighbor (KNN) and a parametric Poisson cluster model (PCM) weather generator. The performance of each method was evaluated by assessing how well the generated series reproduced the historical statistics of the observed precipitation series at an hourly and five minutes scales. Results of the present study will be used in conjunction with an urban drainage system model for studying the impacts of climate change and formulating adaptation strategies.

BINGO Project: Impacts of Climate Change on the Urban Water System - A case study from Bergen (Oral presentation)

Muthanna, T. M., Kristvik, E.[1], Sægrov, S., Sekse, M.

4th European Climate Change Adaptation conference (ECCA)

28–31 May 2019, Lisbon, Portugal

Abstract: Climate change will impact the urban water systems' service level.The key issues in Bergen include sea level rise, flooding, variations in ground water level, and maintenance of sewer systems. The impacted sectors are tourism and waste water systems. In order to make plans that will add resilience to performance of the urban water system it is necessary to have both the long and medium short term in mind. Usually climate change studies run for a 50 or 100 years period, which can make it difficult for decision-makers to prioritize the urgency of the actions they need to take. The BINGO project attempted to overcome this by analysing the impacts of climate change on the water cycle for the short range (time horizon 2025), including those of extreme events, as well as for longer term series. In the Bergen case we have focused on two specific areas:

1. the drinking water supply;
2. the risk of combined sewer overflows.

This paper will focus on the second part, where three specific tasks have been performed:

1. Sewer systems modelling for impact of CSO today and in the near future;
2. The possibility to use urban streets as floodways to avoid CSOs;
3. Using rain gardens and nature based solutions to mitigate downstream CSOs.

The results showcase the vulnerability to CSOs in the Damsgaard research site, and the

mitigation needs. The flood way study showed potential, but also important aspects that need further evaluation. The use of nature based solutions in connection with the combined sewer can provide contributions to reduce the CSOs.

Digital Solutions for Early Phase Stormwater Planning (Poster presentation)

Stokseth, G., Kristvik, E.[1], Sandoval, S., Lohne., J., and Muthanna, T. M.

10th Novatech international conference

1–5 July 2019, Lyon, France

Abstract: Climate change and urbanization, in combination with insufficient drainage systems, lead to increased flooding in urban areas. The state of the art to alleviate such flooding consists in using sustainable urban design solutions (SUDS). Implementing such solutions proves, however, problematic, since the water management engineers typically enter the building process too late to influence the physical layout of major projects. In this paper, we examine an approach to early inclusion of drainage systems in development projects, by a review of existing practices and combining them with novel digital tools. Two real-life cases with different configurations were simulated by means of an existent SUDS model, in order to optimize the stormwater management at a building scale. The results showed a significant variation in the effect of the SUDS for the different building proposals and topographies, ranging from little to considerable flood reduction. This implies that SUDS are highly context dependent, which makes it important to include SUDS in early urban planning. This is paramount in order to ensure that SUDS serve the much-needed resilience they have proved to provide.

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Appendix C Co-Author Statements

NTNU

Encl. to app-lication for assessment of PhD thesis

STATEMENT FROM CO-AUTHOR

(cf. section 10.1 in the PhD regulations)

Erle Kristvik applies to have the following thesis assessed:

Climate-Informed Planning and Design of Urban Water Systems

*) 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: **Assessment of future water availability under climate change, considering scenarios for population growth and ageing infrastructure**, Kristvik E., Muthanna, T. M., and Alfredsen, K. (*Journal of Water and Climate Change 10.1 (2019)*)

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

Erle Kristvik was the main responsible for the input-output data analysis, result presentation and writing of the paper.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

…Trondheim 18.02.2020…... ……………………………………
Place, date Signature co-author, Tone M. Muthanna

*)
Statement from co-author on article: **Assessing the robustness of raingardens under climate change using SDSM and temporal downscaling**, Kristvik, E., Kleiven, G. H., Lohne, J., and Muthanna, T. M. (*Water Science & Technology 77.6 (2018)*)

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

Erle Kristvik has made significant contributions to method conceptualization and design for the temporal downscaling of climate data, discussion of results, comments through the writing process and was the main responsible for revision and prepapation of the final paper version.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

Trondheim 18.02.2020……….. ……………………………………
Place, date Signature co-author, Tone M. Muthanna

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

Erle Kristvik has contributed with the major part of the input-output data analysis, result presentation and writing of the paper.

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Place, date   Signature co-author, Tone M. Muthanna

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

Erle Kristvik has contributed with significant parts of the planning, research and writing phase and was the main responsible for the SUDS performance simulations and result presentation of such.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

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Erle Kristvik has contributed with the major part of the model set-up, data analysis, result presentation and writing of the paper.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

Trondheim 16/2-02 ....

Place, date Signature co-author, Knut Alfredsen

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As a co-author, I did the main part of the model set-up, data processing, results presentation and writing of the original paper draft.

Erle Kristvik has made significant contributions to method conceptualization and design for the temporal downscaling of climate data, discussion of results, comments through the writing process and was the main responsible for revision and prepapation of the final paper version.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

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Guro H. Kleiven
Signature co-author, Guro Heimstad Kleiven

NTNU

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As a co-author, I have contributed with supervision and coordination of the writing process and scientific paper production.

Erle Kristvik has made significant contributions to method conceptualization and design for the temporal downscaling of climate data, discussion of results, comments through the writing process and was the main responsible for revision and prepapation of the final paper version.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

Trondheim, 27/2-20
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Place, date

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Signature co-author, Jardar Lohne

Author contributions were included in Paper III

sustainability

MDPI

Article

Temporal Downscaling of IDF Curves Applied to Future Performance of Local Stormwater Measures

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Received: 7 January 2019; Accepted: 21 February 2019; Published: 26 February 2019

Author Contributions: E.K. was responsible for the work associated with preparation of the climate projections. B.G.J. was responsible for the work associated with the stormwater applications. T.M.M. has supervised, edited and contributed to conceptualization of this study.

NTNU

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As a co-author, I have contributed for sett ing up and simulation of the SWMM model, codding the KNN algorithm for disintegrating climate projections, discussion of the methods and results, and providing comments through out the paper writing process.

Erle Kristvik was the main author responsible for the conception of the paper, formulating the methods, analysing the input-output data, presentation of the results, and writing of the paper.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

21.02.2020
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As a co-author, I have contributed with the major parts of the planning, research and writing phase of the paper and was the main responsible for the cost analyses and results presentation of such.

Erle Kristvik has contributed with significant parts of the planning, research and writing phase and was the main responsible for the SUDS performance simulations and result presentation of such.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

Mülheim a.d.R., Germany 12.2.20
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C. Strehl
Signature co-author, Clemens Strehl

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As a co-author, I have contributed in the planning phase of this paper and with comments through the writing phase.

Erle Kristvik has contributed with significant parts of the planning, research and writing phase and was the main responsible for the SUDS performance simulations and result presentation of such.

I hereby declare that this article can form part of the named thesis by the PhD candidate, Erle Kristvik.

Duisburg, 19.02.2020
Place, date

Juliane Koti
Signature co-author, Juliane Koti