NTNU
Norwegian University of
Science and Technology

Assessing the hydraulic performance of a combined sewer system under climate change using temporal downscaling

Malene Yttersian Munkerud

Civil and Environmental Engineering
Submission date: June 2018
Supervisor: Sveinung Sægrov, IBM
Co-supervisor: Stian Bruaset, IBM
Erle Kristvik, IBM

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU), and it is a product of the course *TVM4905 Water and wastewater engineering, Master's Thesis*. The main topic of this paper is temporal downscaling of spatially downscaled daily AM values from Global circulation Models for prediction of future extreme precipitation, and assessment of the hydraulic performance of a combined sewer system under future climate change.

The study was conducted at the Department of Civil and Environmental Engineering. I would like to express my gratitude to my supervisor's professor Sveinung Sægrov, PhD candidate Erle Kristvik and postdoc Stian Bruaset. Kristvik has been of major importance in helping me understand the concept of downscaling, in teaching me about the programming language R and in providing feedback and advices about paper writing. Bruaset has contributed with good advices on important aspects when assessing the performance of a combined sewer system and has also provided feedback and advices on paper writing.

The study was made possible in part by the EU project BINGO - *Bringing INovation to onGOing water management – a better future under climate change* and in part by Klima 2050, Centre for Research-based Innovation.

I would also like to thank:

- Associate professor Tone Merete Muthanna for tips about paper writing
- Tomas Eidsmo (Trondheim municipality) for providing a Mike Urban model for Lerkendal sewage zone
- Merethe Døsvik (Danish Hydraulic Institute) for providing a licence for the Mike Urban Software
- Postdoc Ashenafi Seifu Gragne for helping me with R coding
- Guro Heimstad Kleiven for discussing the temporal downscaling statistics with me
- Professor John Sølve Tyssedal for explaining linear correlation analysis

Trondheim, June 11, 2018

Malene Yttersian Munkerud

Sammendrag

Urbane avløpssystem har lengde vært en essensiell del av den urbane infrastrukturen. I nyere tid har imidlertid myndighetene opplevd problemer med håndtering av økt avrenning forårsaket av økt mengde nedbør og økt intensitet på ekstreme nedbørshendelser på grunn av klimaendringer. En enda høyere økning er ventet i fremtiden, og dette vil medføre fare for flom, store mengder kombinert kloakkutslipp (Combined Sewer Overflows – CSOs) og skade på ulik infrastruktur. En vurdering av klimaendringers påvirkning på den hydrauliske ytelsen til det kombinerte avløpsnettet i Lerkendal avløpsområde i Trondheim, Norge, ble gjennomført i denne studien ved bruk av modelleringsprogrammet Mike Urban (utviklet av DHI – the Danish Hydraulic Institute).

Vanlig praksis for dimensjonering av avløpssystemer i Norge er å multiplisere et design regn (beregnet fra IVF kurver med en bestemt returperiode) med en klimafaktor. Størrelsen på denne er usikker, og varierer i ulike kommuner (mellom 1.2-1.5 er anbefalt). En klimafaktor på 1.2 benyttes i Trondheim i dag, men Norsk Klimaservicesenter (2016) anbefaler å benytte en klimafaktor på 1.4, i Trøndelag regionen, for ekstrem nedbør med varighet under 3 timer. Alternativt kan fremskrivninger for nedbør fra Globale klimamodeller benyttes, men disse har for grov oppløsning for direkte bruk i konsekvensanalyser og i dimensjonering. I følge Johannessen *et al.* (2013) finnes det ingen fremskrivninger med god nok oppløsning for Trondheim. Dette kan løses ved statistisk nedskalering, hvor separate metoder benyttes for romlig og temporal (tids) nedskalering. Da romlig nedskalerte data for Trondheim var tilgjengelige for nedlastning fra klimaservicesenter.no (Norsk Klimaservicesenter), var kun temporal nedskalering nødvendig i denne studien. Til dette ble Gumbel fordelingen (Extreme value type 1) og skaleringskonseptet benyttet. Resultatet fra nedskaleringen var Intensitet-Varighet-Frekvens kurver (IVF kurver) for fremtidig nedbør fra 10 klimamodeller og 2 utslippsscenarier (RCP4.5 og RCP8.5). En returperiode på 20 år ble benyttet til å lage et ensemble av fremskrivningene, siden denne returperioden benyttes i Trondheim for dimensjonering av avløpssystemet i dag. Observerte IVF kurver for denne returperioden med og uten klimafaktorer ble også produsert for sammenligning med de fremskrevne kurvene. Sammenligningen ble benyttet til å vurdere om dagens klimafaktor har en størrelse som er sikker nok med tanke på mulige klimaendringer. Observerte IVF kurver for alle returperioder ble også sammenlignet med skalerte observerte IVF kurver for å verifisere den temporale

nedskaleringen. Observert nedbørsdata brukt i denne studien er fra Risvollan målestasjon i Trondheim.

Nedskaleringen ga relativt gode estimater for varigheter ned til 10 minutter for IVF kurvene med 5-, 10- og 20- års returperiode, med noe underestimering for varigheter under 40 minutter og noe overestimering for varigheter over 40 minutter for IVF urven med en 20-års returperiode. Ensemblet med observerte IVF kurver med klimafaktorene 1.2 og 1.4, og de fremskrevne kurvene, indikerte at en klimafaktor på 1.4 samsvarer med klimascenariet med størst økning i intensitet. I simuleringene i Mike Urban ble det benyttet hyetografer produsert fra den observerte IVF kurvene med 20-års returperiode uten klimafaktor og med klimafaktorene 1.2 og 1.4, og fra fremskrivningen med høyest intensitet. Resultatene viste at det kombinerte avløpssystemet har for lav kapasitet for alle scenariene. Dette skyldes trolig at store deler av det kombinerte avløpssystemet er av høy alder og dermed er designet for tidligere klimaforhold. Simuleringene viste en lav forskjell mellom kummer og ledninger med underkapasitet og mengden kombinert kloakkutslipp for scenariene med klimafaktor 1.2 og 1.4. Dagens metode for dimensjonering av avløpssystemer kan være effektiv med tanke på lavere kostnader for utbygging og fornying, men kun dersom risikoen knyttet til en enda høyere økning i nedbørintensitet er akseptabel. Klimamodeller konstituerer ikke en øvre grense for klimaendringer, og siden det mest ekstreme scenariet i denne studien samsvarer med Norsk Klimaservicesenter sin anbefaling, vil det foreløpig være hensiktsmessig å bruke en klimafaktor på 1.4 i dimensjonering i Trondheim for å tilpasse seg de fremtidige klimaendringene. Mer arbeid må gjennomføres for å kunne trekke en endelig slutning på dette. En risikoanalyse og andre beslutningsverktøy vil være gode bidrag i videre vurderinger.

Selv om temporal nedskalering resulterte i et tilfredsstillende estimat for IVF kurven med en 20-års returperiode, er det nødvendig å produsere mer nøyaktige estimater. En bias korrigering av de romlig nedskalerte daglige AM verdiene for Trondheim (fra klimamodellene) mot de observerte dataene fra Risvollan målestasjon vil kunne bidra til å oppnå bedre estimater. Metoden som brukes i studien er imidlertid lett å implementere, og vil være gunstig for å teste ytelsen til dreneringssystemer under ulike klimaendringer. I dimensjonering vil usikkerhetene i IDF-kurver og avledede design hyetografer ha store effekter på påliteligheten av størrelsen på overvannsrør (Alfredsen og Hailegeorgis, 2017). Derfor er det viktig å bruke projiserte IDF kurver med forsiktighet, og til å informere analyser og videre beslutningstaking.

Table of contents

Thesis structure

The thesis is written as a paper and has in this sense an untraditional format. A manuscript of the paper (“Assessing the hydraulic performance of a combined sewer system under climate change using temporal downscaling“) is therefor the main content of the thesis. The paper will be submitted to the International Water Association (IWA) journal Water Science and Technology, with the aim of being published. In Appendix A to G, further descriptions about the work are included.

The work will be presented at the Nordic Hydraulic Conference in Bergen, which is held the 13^{th}-15^{th} of August 2018.

The programming language R was used for much of the work included in the paper. One of the scripts is attached in Appendix E. For assessing the hydraulic performance of the combined sewer system in the study area, the modeling tool Mike Urban, developed by the DHI (the Danish Hydraulic Institute), was used.

Some of the remaining scripts, Excel files used for data processing, and result files from Mike Urban can be accessed at Daim (https://brage.bibsys.no/xmlui/handle/11250/223328).

Assessing the hydraulic performance of a combined sewer system under climate change using temporal downscaling

Malene Yttersian Munkerud

Department of Civil and Environmental Engineering, The Norwegian University of Science and Technology (NTNU), 2018

Abstract

In recent years, climate change has lead to an increasing number of high intensity rain events causing flooding in urban areas around the world. Studies of different future climate scenarios indicate that this increase will continue both in intensity and frequency. This study was carried out to create future IDF estimates for precipitation extremes in Trondheim, Norway, and to evaluate the hydraulic performance of the combined sewer system in Lerkendal drainage zone in Trondheim under climate change.

Temporal downscaling of spatially downscaled daily AM values from Global Circulation Models (GCMs) using the scaling concept and the Gumbel distribution was applied in the study. The hydraulic performance of the combined Sewer system was assessed using the modelling tool MIKE Urban.

The results from the downscaling, for the highest precipitation intensity increase, corresponded with using a climate factor of 1.4, which also is recommended by the Norwegian Centre for Climate Services to be used in dimensioning of drainage systems in the area. The results from the simulations indicated that the hydraulic capacity of the sewer system is insufficient, and that measures have to be done in the zone for adapting to the future climatic changes. The method applied in the study is easy to implement and would be beneficial for testing the performance of drainage systems under different climate change scenarios, to be a part of a risk analysis, and to inform decisions made in the planning and dimensioning of sewer systems.

Keywords - Climate change, Temporal downscaling, Gumbel-distribution, Scaling concept, IDF-curves, Hydraulic Capacity

1. Introduction

Urban sewer systems have for a long time been an essential part of the urban infrastructure. It has secured human health, contributed to development of modern societies and enabled denser city development (Arnbjerg-Nielsen *et al.* 2013). However, many parts of the existing stormwater or combined sewer systems have not been designed to accommodate for increased volumes of runoff caused by increase in precipitation due to climate change (Nilsen *et al*. 2011). Climate change is expected to lead to higher amounts of precipitation and especially increase in the intensity of extreme precipitation (Hansen-Bauer *et al.* 2015). Due to the increase in precipitation intensity already caused by climate change, municipalities have experienced challenges with the handling of stormwater because of the insufficient capacity of combined sewer systems. Insufficient capacity can cause combined sewer overflows (CSOs), and possibly flooding of urban streets and basements, which again leads to contamination of recipients, structural damage of infrastructure and danger to human health (among others; Nilsen *et al.* 2011; Tapsell *et al.* 2002). A Climate change impact assessment of the hydraulic performance of a combined sewer system in an urban catchment in Trondheim, Norway, was conducted in this study to inlighten the possible challenges the municipality will face in the future.

A common practice for estimating the future design rainfall intensity essential for the dimensioning of urban sewer systems in Norway is to apply a climate factor (safety factor) (Hansen Bauer et al., 2015) when calculating the design event. A climate factor describes the expected relative increase in rainfall intensity. To achieve the desired future dimensioning intensity, the climate factor is multiplied with the current dimensioning intensity. Researchers have discussed whether this method is sufficient enough since there are uncertainties connected to the necessary magnitude of the climate factor to be used in practice (Nilsen *et al.* 2011; Hansen-Bauer *et al.* 2015). There are several methods available for estimation of climate factors, but there is no common practice for determining the magnitude of these to date. Normally, a climate factor between 1.2 and 1.5 is used for dimensioning of urban sewer systems in Norway (Johannessen *et al.* 2013; Paus *et al.* 2014), depending on the municipal guidelines.

An alternative approach to using climate factors is using output from Global Circulation Models (GCMs), which on a global scale (or large scale, e.g. 100x100km^2) simulates future climate scenarios (Hansen-Bauer *et al.* 2017). These do though produce projections that are too coarse for direct use in local hydrological or hydraulic impact assessments, e.g. assessing the future hydraulic capacity of drainage systems. To solve this, downscaling techniques can be used for treating the projections from the GCMs (among others; Nguyen *et al.* 2007;

Nilsen *et al.* 2011; Herath *et al.* 2016; Kleiven *et al.* 2018), and thereby translate the large-scale climate (predictor) to a local scale climate (predictand) (Council, 2011). There are several methods available for downscaling of projections from GCMs, where Change Factor Methods, Statistical Downscaling and Dynamical Downscaling are among these (Ekström et al., 2015). The Change Factor method is relatively easy to implement and highly applicable in impact research. However, only the climate change signal from the GCM host is presented with no further regional detail. Therefor, the output from the downscaling does not account for local climate features, such as those influenced by mountains, latitude, distance to coastline and difference in elevation (Ekström et al., 2015). To include a finer scale of temporal and spatial details in the climate change signal, Statistical and Dynamical Downscaling can be used. Statistical Downscaling methodologies are however much less demanding than Dynamical Downscaling, in terms of e.g. computer resources. Statistical downscaling have in previous studies provided accurate estimates of sub-daily Annual Maximum (AM) values for precipitation from GCM daily AM values (among others; Nguyen *et al.* 2007; Herath *et al.* 2016; Kleiven *et al.* 2018). These downscaled sub-daily AM estimates can be used for developing future Intensity Duration Frequency (IDF) curves, which are essential in the dimensioning of urban drainage systems. Herath *et al.* 2016 and Kleiven *et al.* 2018 used the Statistical DownScaling Method – Decision Centric (SDSM – DC) for the spatial downscaling, and the GEV distribution and the concept of scale invariance for the temporal downscaling. "Scale invariance symmetry implies that the statistical properties of rainfall at different scales are related to each other by a scale-changing operator involving only the scale ratio" (Bougadis and Adamowski, 2006. p.2). In statistical downscaling of future projections from GCMs, it is assumed that the future statistical relationship between e.g. daily and shorter duration rainfall is the same as for the observational rainfall.

In Trondheim, the municipality of the case study area of Lerkendal, a climate factor of 1.2 is used in combination with an IDF curve with a return period of 20 years for the dimensioning of the sewage system (Johannessen *et al*. 2013). The Norwegian Centre for Climate Services (NCCS) (2016) however suggests the temporary use of a climate factor of 1.4, for the region of Trøndelag, for extreme precipitation with durations under 3 hours. According to Johannessen *et al.* (2013), there exist no long-term local projections of the high spatial- and temporal resolution needed in assessing future requirements to the hydraulic capacity of the drainage system in the Trondheim area. The development of methodologies that cope with this is therefor necessary in order to give a better basis for planning and dimensioning of urban drainage system. For this study, spatially downscaled daily precipitation data from the NCCS (Norwegian Centre for Climate Services) was available (Wong *et al*. 2016). Hence, only temporal downscaling of the GCM projections was necessary. A statistical approach that utilizes the statistical relationships between the large-scale climate and the local climate was applied in the study. A version of the GEV distribution, the Extreme value Type 1 (EV1), also referred to as the Gumbel distribution, and the scaling concept were used for the production of IDF curves for future scenarios. The methods applicability to propagate IDF curves was considered, as they are essential in the planning and dimensioning of urban drainage systems. Projections were created for the period 2071-2100. In order to assess the future performance of the sewage system in Lerkendal drainage zone, the urban hydraulic performance-modelling tool Mike Urban was used. Mike Urban is developed by DHI (Danish Hydraulic Institute) and is designed specially for use in urban areas (DHI, 2012). It is a physically based model designed to aid in design of urban water drainage systems.

The paper addresses the following questions based on the above:

1. To which extent can available spatially downscaled local data for daily precipitation and temporal downscaling, using the Gumbel-distribution and the scaling concept, be used to produce IDF-curves for Trondheim?

2. How does the current practice of multiplying a design precipitation event with a climate factor compare with the projections from the applied temporal downscaling method?

3. How well is the performance of the sewer system expected to be in the Lerkendal catchment in future years?

This study aims at creating better estimates for the future change in precipitation intensities in the Trondheim area, and to evaluate the current and future hydraulic performance of the sewer system in the Lerkendal catchment. The results from the temporal downscaling and the sewer system assessment can be used as information in the planning of rehabilitation and renewal of the sewage system, and to assess whether current methods used in the dimensioning of sewer systems are safe enough, considering possible increase in intensity of extreme precipitation in the future and possible consequences related to this.

2. Study area and data

Lerkendal catchment is an urban multi land use catchment with a combined sewer system and a high degree of clay deposits. The zone transports wastewater amounts corresponding to 10800 PE (Person Equivalents) and has an area of 254 ha (Asplan Viak, 2010). The area consists of approximately 50% combined sewer system, but most of the separated system is currently inactive since much of the storm water is transported into the combined sewer system downstreams. Furthermore, there is today a discharge of wastewater to Nidelva, the receiving water, equivalent to approximately 861 PE. This is mainly due to wastewater discharges via combined sewer overflows (CSOs) during precipitation events. An areal view of the zone can be seen in Appendix G.

Precipitation data from Risvollan measurings station was used in this study. The given station was chosen based on proximity to the study site (Lerkendal drainage zone), length of the record, and available sub-daily resolution. Precipitation data with one minute resolution for 31 years (1987-2017) were downloaded from eklima.no (the Norwegian Metrological Institute - MET, 2018).

Spatially downscaled daily precipitation data was downloaded from the NCCS. The data are based on 10 different Global Circulation Models (GCMs) using scenarios RCP4.5 and RCP8.5 (Wong *et al*. 2016) (where RCP is short for "Representative Concentration Pathway"), leaving a total of 20 GCM projections. RCP8.5 represents a scenario where the increase in green house gas emissions continues as they are today, and RCP4.5 represents a scenario that requires drastic cuts in green house gas emissions after 2050 (Hansen-Bauer *et al*. 2015). The data has been bias corrected by the NCCS (Wong *et al*. 2016) based on observed data (found by interpolation of observations of the same spatial resolution as for the GCMs) for the Trondheim area.

3. Methods

The method was divided into tree main parts involving; (1) Production of IDF-curves from observational data from Risvollan measuring station in Trondheim, and with the use of climate factors 1.2 and 1.4; (2) A temporal downscaling approach using available spatial downscaled local data for Trondheim, the Gumbel-distribution and the scaling concept; and

(3) Simulation of the performance of a sewer system using MIKE Urban (MOUSE module) and design precipitation events constructed based on the developed IDF-curves. The applied method is described in Figure 1.

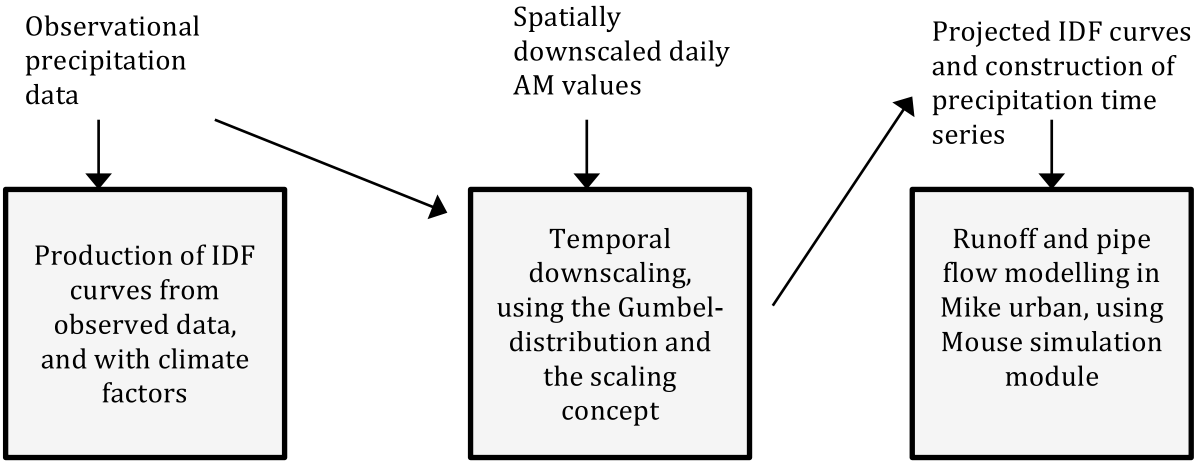


Figure 1: Flow chart describing the applied method.

3.1. Downscaling of precipitation

Downscaling of precipitation is commonly done by separate spatial- and temporal downscaling techniques. In this method only temporal downscaling was used due to the already available spatially downscaled daily precipitation from the NCCS.

3.1.1. Temporal downscaling - IDF fitting

IDF curves from observed data was needed in order to validate the temporal downscaling procedure. Annual Maximum (AM) valuses for durations ranging from 2 minutes to 24 hours were found using R studio, an open source program for statistical computing.

A version of the GEV distribution, The Extreme Value type I (EVI), also called the Gumbel distribution, and the method of moments for parameter estimation was chosen for the fitting of IDF curves and calculation of the Gumbel parameters in this study. The reasons for choosing the Gumbel distribution for IDF curve fitting and the method of moments for parameter estimation were; (1) the observed IDF curves and the scaled observed IDF curves showed the best agreement when applying the Gumbel distribution in terms of the method of moments; and (2) the observed IDF curves developed by using the Gumbel distribution was in agreement with the observed IDF curves developed by MET (see Appendix A). The observed IDF curves was derived from observed AM values for all durations, and the scaled observed

IDF curves was derived by using the daily observed AM values and the scaling factor. The following sections describe the procedures for development of observed and scaled IDF curves.

3.1.1.1. Construction of IDF curves for observed data

The cumulative distribution for the GEV distribution is given as (Coles 2001):

$$G(X) = \exp\left[-\left\{1 + \xi \frac{(x-\mu)}{\sigma}\right\}^{-\frac{1}{\xi}}\right] \qquad (1)$$

for $\xi \neq 0$. μ, σ and ξ, are correspondingly the location, scale and shape parameters of the GEV distribution. The Gumbel distribution results when the ξ variable in equation (2) is zero.

The Gumbel distribution requires computation of the first two moments, the mean and the standard deviation. The method of moments estimates for the parameters are given as (Maidment, 1993):

$$\sigma(t) = 0.7797s(t) \qquad (2)$$

$$\mu(t) = \bar{x}(t) - 0.45s(t) \qquad (3)$$

where x(t) and s(t) are the mean and the standard deviation of the observet data set (AM values) for the different durations t.

The returnlevels needed for construction of IDF estimates was computed using the Gumbel distribution. The returnlevels are given by (Rust *et al.*, 2008):

$$Z_T(t) = \mu(t) - \sigma(t) * \log[-\log(1 - \mathrm{p})] \qquad (4)$$

where p is the desired cumulative probability (1/T) and T is the return period. The return levels were further converted from mm to mm/h to get the observed IDF curves.

3.1.1.2. **Estimating the scaling exponent**

From the assumption that extreme rainfall is characterised by the property of scale invariance, also defined as "strict sence simple scaling" by Gupta and Waymire (1990), it can be stated that equality in the probability distribution of the rainfall depth (X) observed at two different time scales holds. This can be written as (Rosso and Burlando, 1996):

$$X_{\lambda t}(\tau) \overset{d}{=} \lambda^{\beta} X_t(\tau) \tag{5}$$

where d denotes equality in the probability distribution, λ is a scale factor, β is a scaling exponent, and τ is the period of lengt (eg. a specific year) in which the cummulated ranfall is recorded for duration t. This means that $X_t(\tau)$ and $X_{\lambda t}(\tau)$ display the same distribution when rescaled by a factor of λ^{β}. Since the extreme storm probabilities are examined, the maximum depth of the rainfall which is recorded in a given period τ with the different durations t must be found. For this study, these maximum values are the AM values, H_t, for the different durations in a given year. The probability distribution of H_t must accordingly be searched for. If

$$H_{\lambda t} \overset{d}{=} \lambda^{\beta} H_t \tag{6}$$

this also implies that the raw moments, also known as non-central moments (NCMs), of any order are scale invariant, that is

$$E[H_{\lambda t}^{n}] = \lambda^{n\beta} E[H_t{}^{n}] \tag{7}$$

where n denotes the order of the moment (Burlando and Rosso, 1996). Since the latter is a weaker property than “strict sence simple scaling”, it is by Gupta and Waymire (1990) refferd to as “wide sence simple scaling”. Wide sence simple scaling can be easily checked from the data, and therefor this working assumtion was considered reasonable for this study. To investigae the scalingproperties of the raw moments, double logarithmic plots of the raw moments against their duration t was examined. A simple scaling regime is evident when this plot is linear. Further the exponets of the trendline from the double logarithmic plot is plottet against the order of the moment (n =1, 2, 3) as described by Bougadis and Adamowski (2006) and Burlando and Rosso (1996). The slope of the linear function describing the graph for the exponets versus the order of moment is then the scaling exponent (also called scaling factor).

3.1.1.3. Construction of scaled IDF curves from observed data and GCMs

To relate the parameters of the Gumbel distribution at two different timescales t and λt (eg. daily and subdaily) the following equations were used (Nguyen *et al*. 2002):

$$\sigma(\lambda t) = \lambda^{\beta}\sigma(t) \tag{8}$$

$$\mu(\lambda t) = \lambda^{\beta}\mu(t) \tag{9}$$

where λ is given by the different durations devided by 24 hours, and β is the scaling exponent.

For construction of the scaled observed IDF curve, the daily AM values was used to calculate the parameters of the Gumbel distribution by using equations (2) and (3). Equations (8) and (9) were then used to calculate the parameters for all the subdaily durations. The returnlevels were calculated from equation (4) and further converted from mm to mm/hr. The scaled observed IDF curves was then compared to the observed IDF curves for assessing the accuracy and applicability of the temporal downscaling method.

The construction of future IDF estimates from the different GCMs follows the same procedure as for the development of the scaled observed IDF curves. Only the input daliy AM values for observed precipitation data were replaced by the spatially downscaled daily AM values from the GCMs. All IDF curves was developed using R studio (see appendix E for script).

To compare the different future IDF estimates, an ensemble of IDF curves for the 20-year return period was created to assess the spread of the projections. Due to the fact that a 20-year return period with a climate factor of 1.2 is used in dimensioning of sewer systems in Trondheim today (Johannessen *et al.* 2013), only the 20-year returnperiod was examined.

3.1.1.4. Observed IDF curves with climate factors

To assess today's practice for dimensioning of drainage systems using climate factors, the produced observed IDF curve for the 20-year return period were multiplied with climate factors of 1.2 (Used in Trondheim municipality today, among others) and 1.4 (recommended by the Norwegian Centre for Climate Services –NCCS, 2016). This makes it possible to assess whether current methods are safe enough considering possible increases in rainfall due to climate change.

3.2. Sewer system assessment

An existing Mike Urban model describing Lerkendal sewage zone (made available by Trondheim municipality, 2017) was used in this study to assess the performance of the sewer system under future climate change. The Danish Hydraulic Institute (DHI) provided a license for the Mike Urban software.

3.2.1. Simulation in Mike Urban

Modelling of urban sewer systems using Mike Urban is a two step process; (1) modelling of the runoff; and (2) modelling of the pipe flow (DHI, 2012). The MOUSE calculation engine was chosen for the modelling of the collection system, as it is a well recognised and widely used tool. Figure 2 illustrates a flow chart describing the modelling of a sewage system with MOUSE.

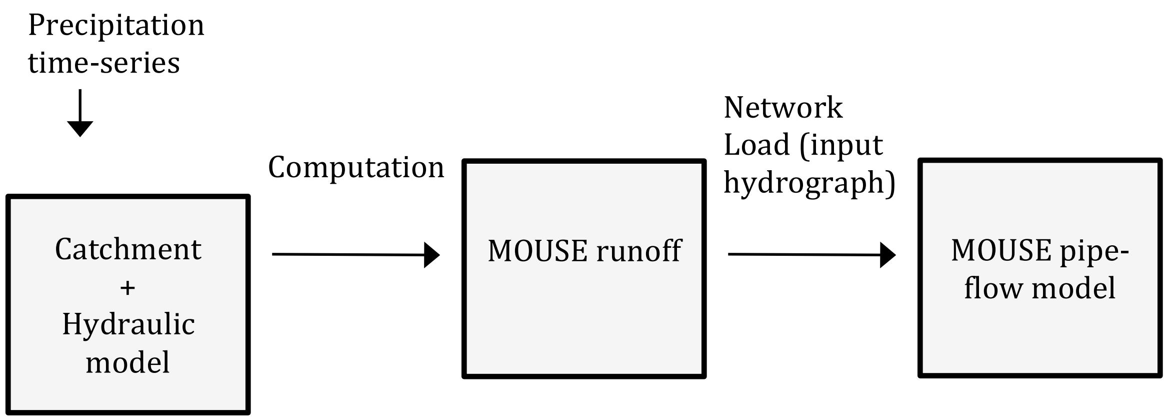


Figure 2: Flow chart describing the modelling of a sewage system in MOUSE.

For the runoff modelling, the RDII (Rainfall dependent Inflow and Infiltration) module was used. This module consideres the soils hydraulic memory from previous rain events. The RDII module therefore reproduces a more realistic picture of the runoff, as it is normal to also experience rain before an extreme event (see Mike Urban manuals for further discription of the RDII module).

The runoff calculations were done by using the Time area method (RDI+A), and the network calculations were done by using the Saint Venant equations for dynamic flow (DHI, 2012).

When assessing the results from the simulations, three criterias were used; (1) total amount of flooded links; (2) total amount of flooded nodes; and (3) total amount of weir outflow (CSOs).

3.2.2. Creating time series

To simulate the runoff and to produce the input hydrograph needed for the pipe flow simulations in Mike Urban, a precipitation time series is needed. Symmetrical hyetographs was developed with duration of one hour (Lindholm *et al.* 2012) to include the highest intensities. A calculation step of 5 minutes was decided based on the accuracy of the IDF curves produced by temporal downscaling. A return period of 20 years, the dimensioning return period for urban sewer systems in Trondheim, was used to create three hyetographs; one without a climate factor, one with a climate factor of 1.2 and one with a climate factor of 1.4. The climate factors were chosen based on the results from the temporal downscaling. A fourth hyetograph was created from the worst-case GCM projected IDF curve for comparing purposes.

Two days of uniformly distributed rain, approximately equal to the average daily rainfall of the month with the highest total precipitation amounts, was included prior to the extreme events. The prolonged rainfall will cause some saturation of the soil before the extreme event, and hence, because of the reduced infiltration capacity, increase the risk of flooding (Nilsen *et al*. 2011).

4. Results and discussion

When investigating the results, the methods applicability and accuracy was assessed for each step separately and combined.

4.1. Temporal downscaling

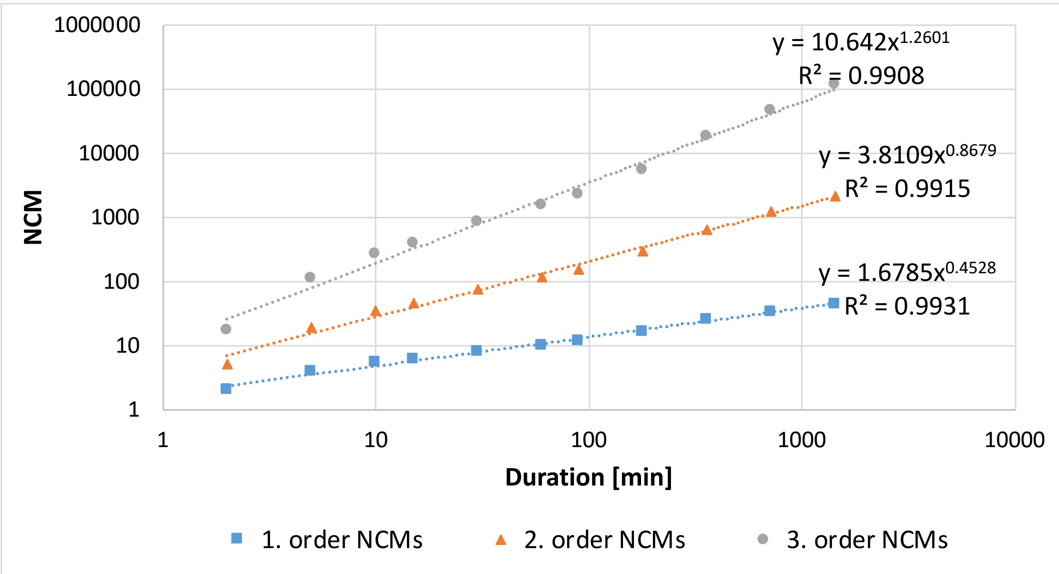
4.1.1. Scaling exponent

The double logarithmic plot of the calculated NCMs versus their duration is shown in Figure 3a). Linearity of the graphs is evident with a squared coefficient of correlation, R^2, above 0.99

for all three orders. This indicates that one scaling regime exists for the rainfall (Bougadis and Adamowski, 2006). As expected, the lowest durations have the worst fit. The difference in the characteristics of short duration rainfall and long duration rainfall is often quite different, hence also the scaling relationships are different for short and long durations.

As described in the methods section, the scaling exponent is equal to the slope when plotting the exponents of the trend lines in Figure 3a) against the order of the moment. This can be seen in Figure3b). The resulting value for the scaling exponent is then 0.4037. Often, precipitation extremes follow a multi-scaling process as described by Bougadis and Adamowski (2006). However, since the exponent of the NCMs follow a linear function, with a squared correlation coefficient above 0.9997, this indicates that the simple scaling assumption exists for the rainfall.

a)



b)

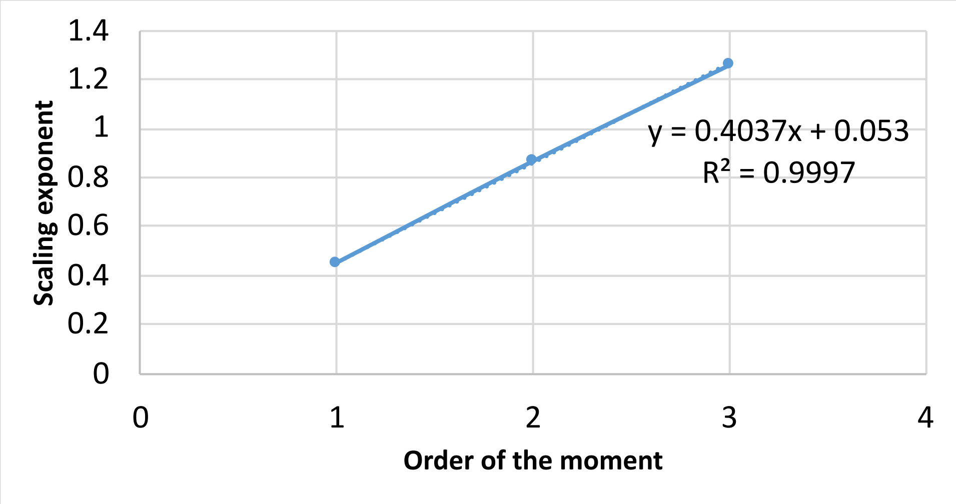


Figure 3: Graphical description on how to find the scaling exponent. a) Double logarithmic plot of the NCMs versus duration (min) showing the scaling properties of the rainfall. b) Plot of the exponents, from the double logarithmic NCM plot, against the order of the moment. The scaling exponent is equal to the slope.

Lack of data and variations from the trendline can lead to uncertainties in the model, even though the squared correlation coefficients in the double logarithmic plot (Figure 3a) and in the exponent plot (Figure 3b) give a good indication that the models have a linear correlation. Hypothesis tests (one sided t-tests), as the one described by Bruaset and Sægrov (2018), were conducted to evaluate with what certainty it can be claimed that there is a linear correlation between the output (y) and input (x). This can be seen in Appendix B. For the double logarithmic plot, a certainty of at least 99.95% of linear correlation in the data for the 1.order, 2.order and 3.order regression lines were found. For the exponent plot, a linear correlation with a certainty of 99% was found. This underlines the existence of one simple scaling regime for the rainfall.

4.1.2. Observed and scaled observed IDF curves

The accuracy of the scaling procedure was examined by comparing the observed IDF curves to the scaled observed IDF curves. The temporal downscaling gave good results for durations down to 10 minutes, as shown in Figure 4a). The lowest durations showed the poorest fit, as expected due to the deviation of the NCMs from the fitted line in the double logarithmic NCM plot for short durations. Also, the Gumbel distribution does not include the time independent shape parameter. Distributions that have shape parameters will, according to Hailegeorgis and Alfredsen (2017) and Friederichs (2010), provide better predictions of the tails of distributions and hence the extreme quantiles. The results are however satisfying for the intensities within durations of 10 to 60 minutes, which are the essential values for creating a precipitation time series, with a calculation step of 5 minutes, for later use in the Mike Urban simulations. Using the Gumbel distribution was therefor considered reasonable in this study.

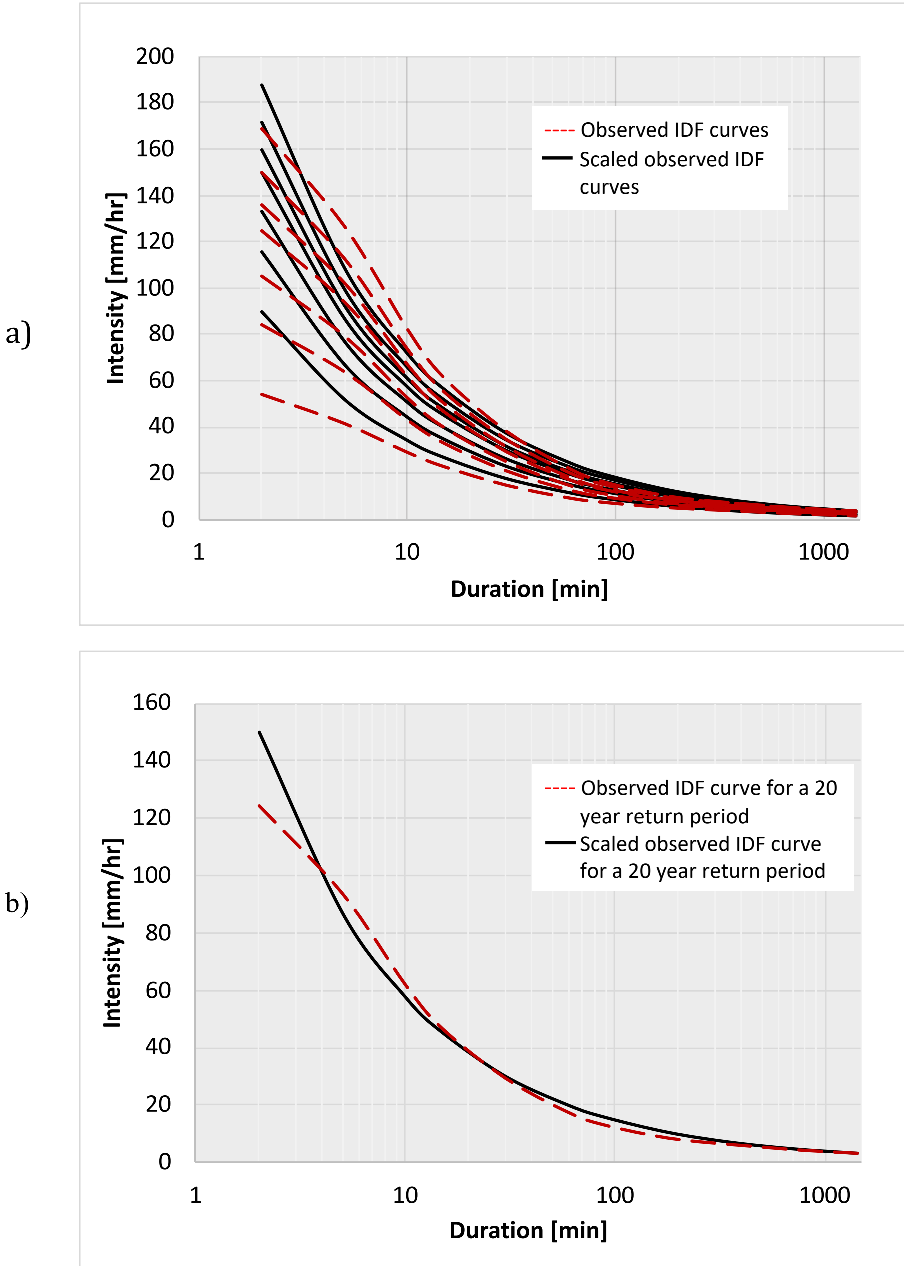


Figure 4: Observed and scaled observed IDF curves describing the accuracy of the scaling procedure. a) Observed and scaled observed IDF curves for all return periods. b) Observed and scaled observed IDF curves for the 20-year return period.

The results from the comparison between the observed and scaled IDF curves show the best fit for the 5-, 10-, and 20-year return periods. The 20-year return period is of most interest, as it is the dimensioning return period for sewer systems in Trondheim. The scaled and observed IDF curve for this return period was compared as shown in Figure 4b). The comparison indicates a small underestimation for the scaled IDF-curve for durations ranging between 5 and 20 minutes, and a small overestimation for durations between 20 and 120 minutes. This will cause uncertainties in the temporal downscaling of the spatially downscaled AM values, which must be taken into account when assessing the results.

4.1.3. Projected IDF curves

An ensemble of the resulting IDF curves for the 20-year return period was constructed for all the GCMs for durations down to 10 minutes. This can be seen in Figure 5. The figure also includes the observed IDF curve from Figure 4b), and the observed IDF curve multiplied with the climate factors 1.2 and 1.4.

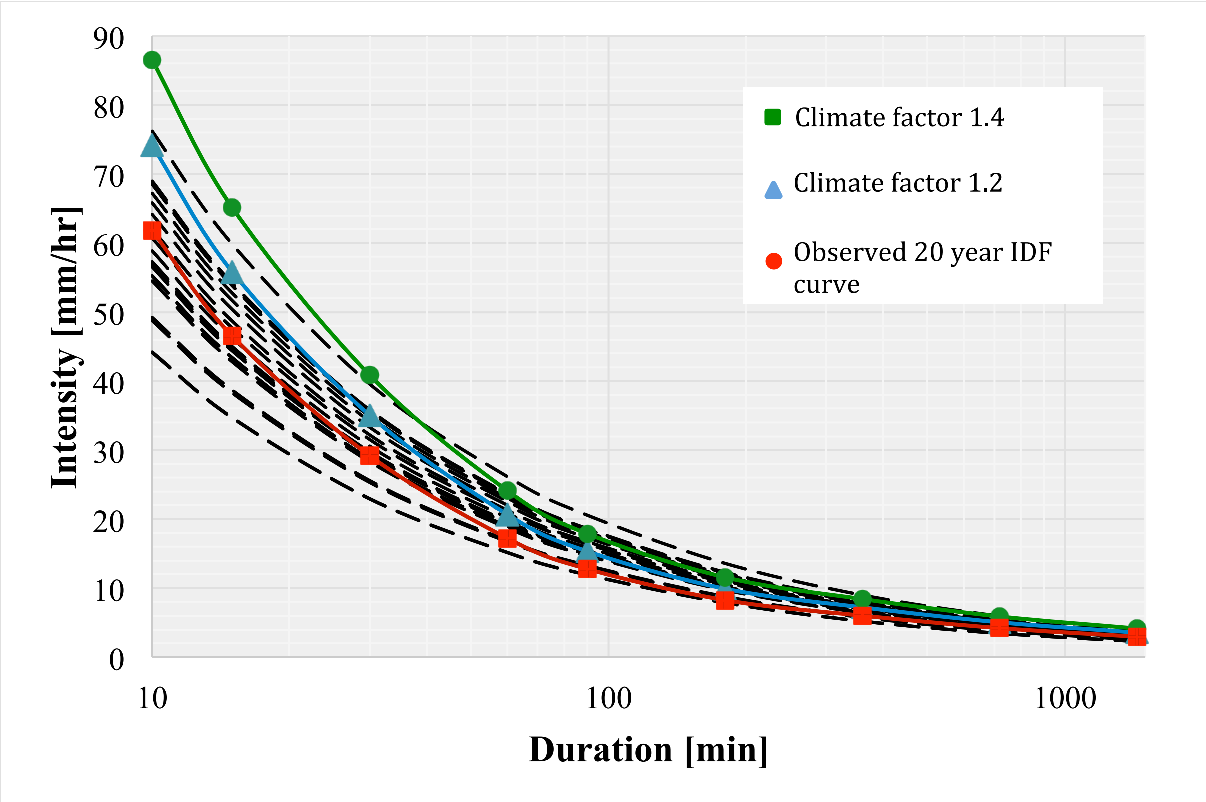


Figure 5: Ensemble of IDF curves for the 20 year return period for all the 20 GCMs (black striped lines), including the observed IDF curve and the observed IDF curve multiplied with climate factors of 1.2 and 1.4.

The results from the temporal downscaling of the different GCMs show a vide spread, as seen in Figure 5. By comparing the observed IDF curve multiplied with a climate factor of 1.2 with the projections, it can be seen that using a climate factor of 1.2 results in higher intensities than for most GCMs (with one exception) for durations between 10 and 30 minutes. It is though exceeded by several of the scenarios for longer durations. The slight overestimation of intensities for durations above 30 minutes and underestimation for duration below 30 minuetes for the scaled observed IDF curve (shown in Figure 4) must be taken into consideration. Hence, the multiplication with climate factor 1.2 for the observed IDF curve might actually cover most of the GCM outputs if a perfect fit between the observed and observed scaled IDF curve had been achieved. The observed IDF curve multiplied with a climate factor of 1.4 has the highest intensities for durations between 10 and 40 minutes, and only one projected IDF curve show higher intensities for durations above 40 minutes. Some of the scenarios show even lower precipitation intensities in future years and the mean of the projected IDF curves corresponds with the observed IDF curve multiplied with a climate factor of 1.1 (illustrated in Appendix C).

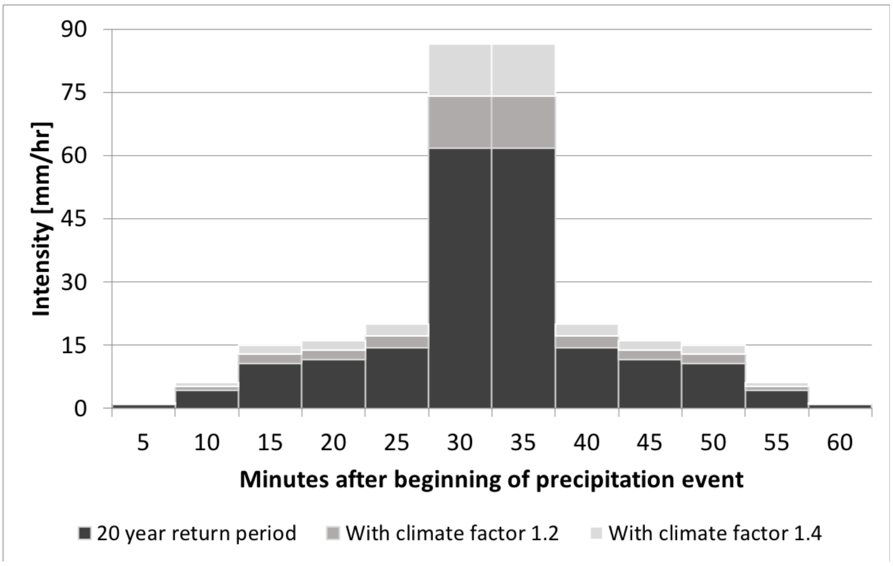
In this study, further assessments are based on the GCM output and the comparison with the IDF curves for the 20-year returnperiod multiplied with the climate factors. In this way, the GCMs contributes to finding a possible magnitude for climate factors to be used in dimensioning of urban sewer systems. A perfect fit between the observed and scaled observed IDF curves was not achived, but by looking at the results it is possible to assume that the observed IDF curve with a climate factor of 1.4 might cover all the IDF curves from the GCMs in furher assessments. However, the steepness of the IDF curves from the observed precipitation data is higher than for the GCMs. Hyetographs created from the observed IDF curves as time series input for later assessments will therefor have a higher relative difference between the peak intensities and the intensities in the rest of the timeseries than for the hyetographs created from the projected IDF curves (this can be seen in Figure 6 in the next section). Applying the GCMs directly could therefor give different results for the hydraulic performance of the sewer system than by applying the observed IDF curves. To assess this, the projected IDF curve with the highest intensisites (worst-case GCM) and the observed IDF curve with a climate factor of 1.4 was used for creating two hyetographs as timseries input in the runoff simulations in Mike Urban. In addition two hyeatographs from the observed IDF curve for the 20 year return period and with a climate factor of 1.2 (relevant as it is the dimensioning design event in Trondhiem) were used.

4.2. Sewer system assessment

4.2.1. Produced hyetographs

The hyetographs created as timseries input in Mike Urban are shown in Figure 6a) and b). They are based on the results from the comparison between the climate factors and the IDF curves from the GCMs, and the worst-case scenario GCM.

a)



b)

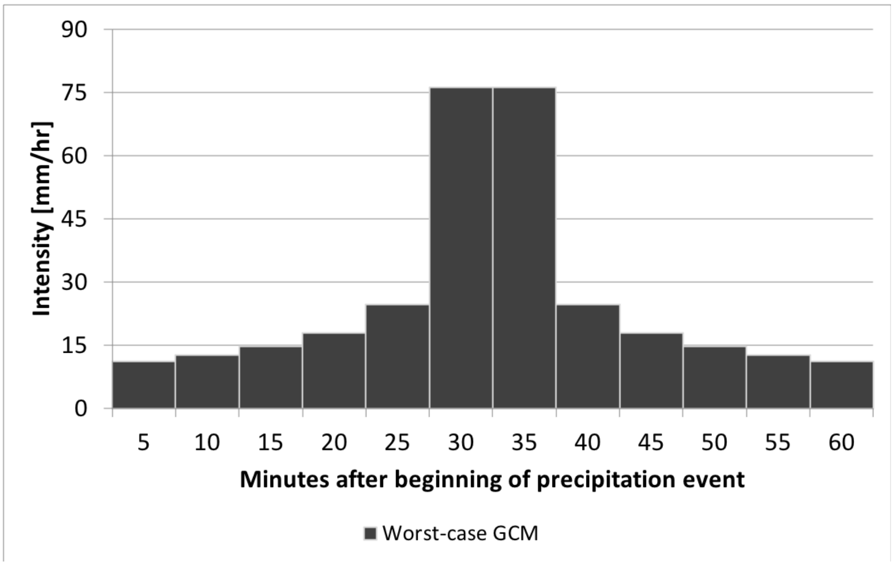


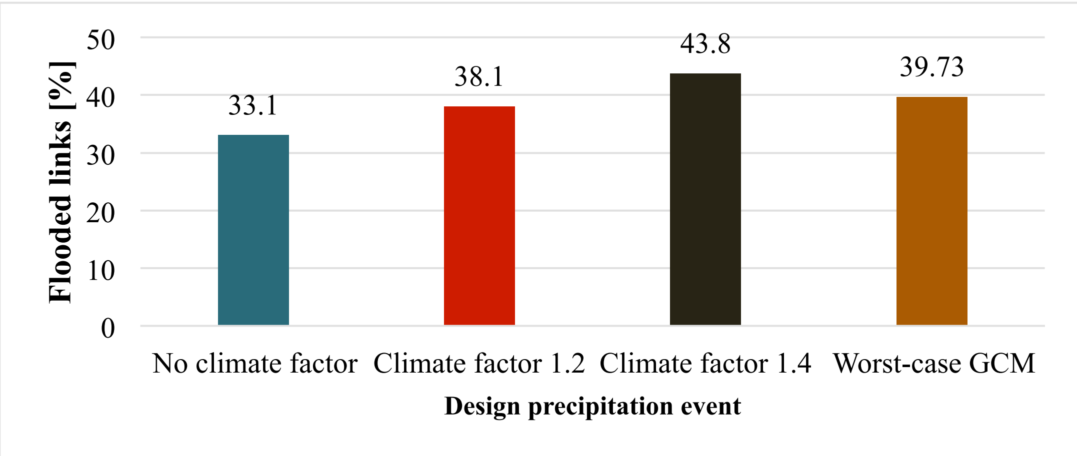
Figure 6: Hyetographs applied in the Mike Urban simulations. a) Includes the hyetographs for the observed 20 year returnperiod, and the hyetographs with climate factor 1.2 and 1.4. b) Shows the hyetograph for a 20 year returnperiod for the worst case GCM.

Two days of uniformly distributed rain was included prior to the extreme event in the simulations. The month with the highest precipitation ammount is September, and the daily mean was found to be approximatly 4mm/day (YR, 2018). Though it is possible that this value will increase in future years, a percent increase was not included in the precipitation timeseries since the intensity of extreme precipitation of short duartion is expected to increase more than precipitation events with low intensity and longer durations (Hansen-Bauer *et al.* 2015; Førland *et al.* 2015).

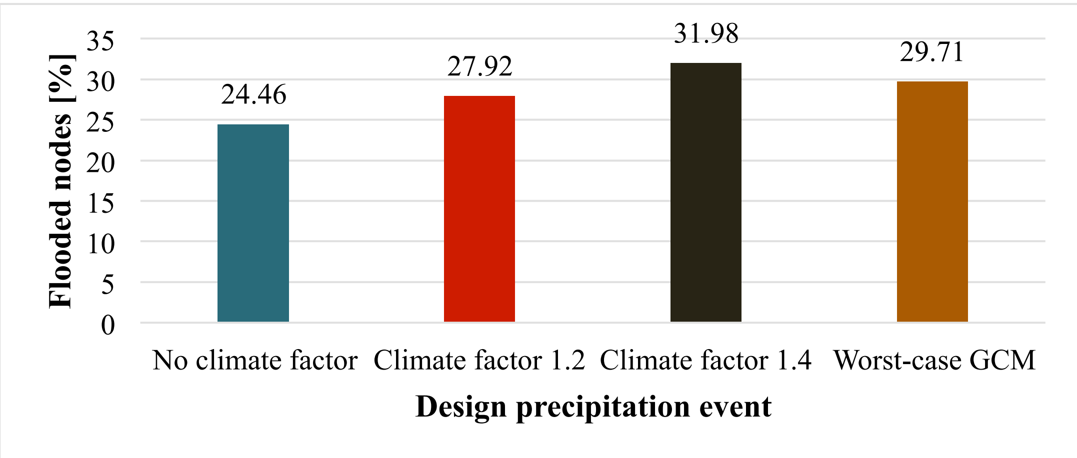
4.2.2. Mike Urban simulations

The results from the simulations in Mike Urban were assessed based on the criteria's described in the methods section and can be seen Figure 7 (and table C1 in Appendix D). The simulation results were extracted as shape files from the Mike urban software and further processed in Microsoft Excel.

a)



b)



c)

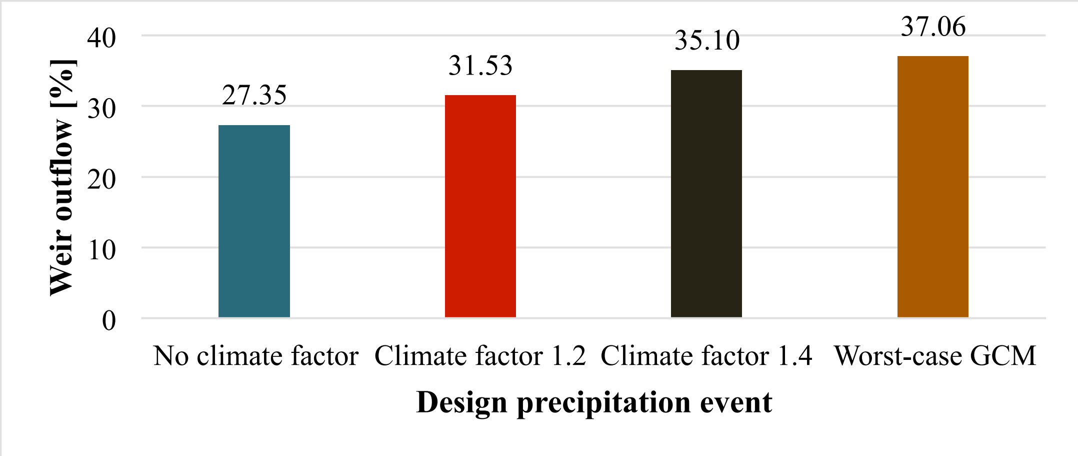


Figure 7: Simulation results for the hydraulic performance of the sewer system in Lerkendal drainage zone. a) Describes the amount of flooded links in the area under the different design precipitation events used. The calculations are based on the total length of flooded links. b) Describes the amount of flooded nodes in the area. c) Describes the amount of Weir outflow (CSOs) calculated based on total inflow volume (m^3) to the network during the event and total weir outflow (m^3).

The results indicate that the current situation in Lerkendal drainage zone is critical when considering the hydraulic performance of the sewage system (assuming that there are no replaced links or any further separation of the system after the model was created). This can be explained by the fact that many of the sewage links in the zone are of old age, and hence the system has been dimensioned for previous climatic conditions. The sewage system will experience flooding during all the scenarios. The flooding of links and nodes, and the amount of weir outflow (CSOs) have a linear increase corresponding to the increase in intensity for all simulations that are based on the observed IDF curves with and without climate factors. The results from the worst-case GCM, deviate from this linearity due to the difference in the shape of the projected IDF curve compared to the observed ones. For the links and the nodes, the worst case GCM show a lower percentage of flooding than for the simulations with climate factor 1.4. The GCM however exceeds the climate factor of 1.4 for the percentage of weir outflow. This indicates that high peak intensities, as for the hyetograph with climate factor 1.4, results in a higher percentage of flooded links and nodes, and that lower difference between the peak intensities and the intensities in the rest of the time series will result in more overflow (as for the worst-case GCM). This indicates that good IDF estimates and the shape of these are of great importance to the response we receive on the drainage network, precisely because the outcome is so different for the different shapes. In dimensioning, the uncertainties in IDF curves and derived design storm hyetographs will have large effects on the reliability of the sizing of stormwater pipes (Hailegeorgis and Alfredsen, 2017). Therefore, it is important to use projected IDF curves with caution and use them to inform the analysis and further decision-making.

An areal view over flooded links and nodes can be seen in Appendix E for the scenario with the observed IDF curve with a 20-year return period, and for the scenario with climate factor 1.4. The affected areas with flooded links and nodes correspond, and as expected the severity differs. Measures in this zone will be to make the separation system effective by building stormwater pipes in areas with combined sewer systems. Making the separation system active will reduce emissions through CSOs considerably, and decrase flooding of links and nodes. Other measuers can also contribute to redused CSOs and reduse the risk of flooding. Such measures are disconection of roofpipes so that more water can infiltrate into the soil, and other infiltration, retention and detention based solutions such as green or blue/grey roofs and rain gardens.

4.3. Discussion

One GCM scenario is not more likely than the other, and nor do they constitute an upper or lower limit of climate change. There are several uncertainties connected to the downscaled climate projections. This includes uncertainties that stem from the emission scenarios, the downscaling techniques (both spatial and temporal), and the GCMs capability to represent the climatic changes caused by the different emission scenarios (Hansen-Bauer *et al*. 2015). Also, the bias correction that was carried out by the NCCS is a source of uncertainty since it is based on interpolation of observed precipitation data for a spatial area equal to the spatial area for the GCM projections. Therefor, the observed precipitation data from Risvollan measuring station used in this study will not be in perfect agreement with the observed data used for the bias correction of the GCM projections. However, even though there are uncertainties connected to each scenario, an ensemble, as the one in Figure 5, will decrease these uncertainties since it covers a wide range of possible outcomes.

The modelling tool, the calibration of parameters, and the assumptions made for the specific area model in Mike Urban are also sources of uncertainty in the results. It can nevertheless be stated that the sewage system is experiencing insufficient capacity and that measures have to be done in the zone for adapting to the climatic changes, regardless of the actual future increase in precipitation. The difference between the flooding and the amount of CSOs for the events with climate factors 1.2 and 1.4 are not significantly high, therefor a climate factor of 1.2, also the current climate factor used in Trondheim, might be sufficient in the dimensioning of the sewage system. A risk analysis will be beneficial for assessing if the risk connected to a higher intensity increase is in an acceptable range, especially when considering the consequences it may have. However, as mentioned, the GCMs does not constitute an upper limit for climate change, and the most extreme scenario in this study corresponds with the climate factor recommended by the Norwegian Centre for Climate Services. It would therefor be appropriate to temporarily use a climate factor of 1.4 in dimensioning in Trondheim for adapting to future climate change. It is though important to use downscaled climate projections with care. They should be used to inform the analysis that is to be conducted, and not drive them (Brown and Wilby 2012). Hence, the results can be used to inform further assessments of the risk connected to climate change and how climate change can affect the future performance of drainage systems, and to inform further decision-making.

5. Conclusion

In this study the hydraulic performance of the combined sewer system in Lerkendal catchment (Trondheim, Norway) was assessed under future climate change, using temporal downscaling. Temporal downscaling was applied to create future IDF estimates for Trondheim, and observed IDF curves were created to evaluate the accuracy of the temporal downscaling technique. Climate factors of 1.2 and 1.4 were multiplied with the observed IDF curve with a 20-year return period (the dimensioning return period in Trondheim municipality) for comparing with the projected IDF curves for this return period. The comparison was used to evaluate the necessary magnitude of a climate factor to be used in the dimensioning of sewer systems in the municipality, and for assessing the hydraulic performance of the system under future climate change scenarios. Precipitation time series were created from the IDF curve with the 20-year return period without and with the climate factors 1.2 and 1.4, and from the projected 20-year IDF curve from the worst-case GCM. These were used as input for the simulations in Mike Urban.

The scaled observed IDF curves developed by using the temporal downscaling method and daily observed AM values, represented durations down to 10 minutes well for the 5-, 10- and 20-year return periods. However, the downscaling resulted in a small underestimation of intensities for durations between 10 and 20 minutes and a small overestimation for durations above 20 minutes for the 20-year return period (the return period examined in this study). The temporal downscaling method`s inability to represent all return periods and short durations well, will result in propagation of uncertainties in further assessments if the future projections are applied directly in impact assessments. Therefor the projections were used to inform further analysis. The simulations in Mike Urban showed that the difference between the scenarios with climate factors 1.2 and 1.4 is not considerably high for the flooding of links and nodes, and for the amount of weir outflow (CSOs). However, it cannot be claimed with any high level of certainty that the current practice is sufficient enough, considering the currently unknown level of risk connected to an even higher increase in precipitation. As the most extreme projection corresponds to using a climate factor of 1.4, which is recommended by the NCCS (2016) for durations below 3 hours, the temporary use of a climate factor of 1.4 for dimensioning is advised.

Even though the temporal downscaling resulted in a satisfying estimate for the 20-year return period, more work is needed to produce even more accurate estimates. A bias adjustment of the GCM output to fit the observed data from Risvollan measuring station could produce more reliable estimates to be used directly in impact assessments. The method applied in the study, where available spatially downscaled AM values from GCMs are used, is however easy to implement and would be beneficial for testing the performance of drainage systems under different climate change scenarios and in being a part of a risk analysis.

Acknowledgement

The study was made possible in part by the EU project BINGO - *Bringing INovation to onGOing water management – a better future under climate change* and in part by Klima 2050, Centre for Research-based Innovation.

References

ASPLAN_VIAK. 2010. *Saneringsplan Lerkendal* [Online]. Available: https://www.asplanviak.no/prosjekt/10133/ [Accessed 27.04.2018].

BROWN, C. & WILBY, R. L. 2012. An alternate approach to assessing climate risks. *Eos, Transactions American Geophysical Union,* 93**,** 401-402.

BRUASET, S. & SÆGROV, S. 2018. An Analysis of the Potential Impact of Climate Change on the Structural Reliability of Drinking Water Pipes in Cold Climate Regions. *Water,* 10**,** 411.

COLES, S. 2001. An Introduction to statistical Modeling of Extreme Values. *Springer-Verlag, London, UK.*

COUNCIL, N. R. 2011. *Advancing the science of climate change*, National Academies Press.

DHI 2012a. Mike Urban, collection system. *MIKE by DHI (the Danish Hydraulic Institute)*.

DHI 2012b. MOUSE Reference Manual, Pipe Flow. *MIKE by DHI (the Danish Hydraulic Institute)*.

DHI 2012c. MOUSE Reference Manual, RDII. *MIKE by DHI (the Danish Hydraulic Institute)*.

EKSTRÖM, M., GROSE, M. R. & WHETTON, P. H. 2015. An appraisal of downscaling methods used in climate change research. *Wiley Interdisciplinary Reviews: Climate Change,* 6**,** 301-319.

FRIEDERICHS, P. 2010. Statistical downscaling of extreme precipitation events using extreme value theory. *Extremes,* 13**,** 109-132.

FØRLAND E., H.-B. I., HAUGEN J. E., HYGEN H. O., HAAKENSTAD H., ISAKSEN K. OG DYRRDAL A. V. 2016. Background information for “Klima i Norge 2100”. *Miljødirektoratet,* NCCS report no.1**,** 50.

FØRLAND E., M. J., DYRRDAL A., GRINDE L. OG MYRABØ S. 2015. Dimensjonerende korttidsnedbør. *Naturfareprosjektet Dp 5 Flom og vann på avveie, Norges vassdrags- og energidirektorat (NVE)***,** 92.

GOOGLE-MAPS. 2018. *Map over Lerkendal* [Online]. Available: https://www.google.com/maps/@63.4120794,10.4012982,14.21z [Accessed 20.04.2018].

GUPTA, V. K. & WAYMIRE, E. 1990. Multiscaling properties of spatial rainfall and river flow distributions. *Journal of Geophysical Research: Atmospheres,* 95**,** 1999-2009.

HELBÆK, M. 2011. Statistikk - Kort og godt. *Universitetsforlaget*, 182.

KLEIVEN, G. H., KRISTVIK, E., LOHNE, J. & MUTHANNA, T. M. 2018. Assessing the robustness of raingardens under climate change using SDSM and temporal downscaling. *Water Science and Technology,* 77**,** 1640-1650.

LINDHOLM, O., ENDRESEN, S., SMITH, B. T. & THOROLFSSON, S. T. 2012. 2012. Veiledning i dimensjonering og utforming av VA-transportsystem. . Norsk Vann Rapport nr.193. Hamar.

MAIDMENT, D. 1993. *Handbook of Applied Hydrology*, McGraw-Hill New York.

MET (the Norwegian Metrological Institute). 2018. Observational precipitation data for Risvollan measuring station. *[Online]. Available: eklima.no [Accessed 29.01.2018].*

NGUYEN, V., NGUYEN, T.-D. & ASHKAR, F. 2002. Regional frequency analysis of extreme rainfalls. *Water science and technology,* 45**,** 75-81.

NGUYEN V. T. V., N. T. D. O. C. A. 2007. A statistical approach to downscaling of sub-daily extreme rainfall processes for climate-related impact studies in urban areas. *Water science and technology: water supply,* 7**,** 183-192.

PAUS K. H. (COWI), F. E. J. M., FLEIG A. (NVE), LINDHOLM O. (NMBU), ÅSTEBØL S. O. (COWI) 2014. Metoder for beregning av klimafaktorer for fremtidig nedbørintensitet *Miljødirektoratet, COWI***,** 27.

ROSSO, R. & BURLANDO, P. 1996. Scaling and muitiscaling models of depth-duration-frequency curves for storm precipitation. *Journal of Hydrology,* 187**,** 45-64.

RUST, H. W., KALLACHE, M., SCHELLNHUBER, H. J. & KROPP, J. P. 2010. *Confidence intervals for flood return level estimates assuming long-range dependence*, Springer-Verlag, Berlin.

TAPSELL, S. M., PENNING-ROWSELL, E. C., TUNSTALL, S. M. & WILSON, T. L. 2002. Vulnerability to flooding: health and social dimensions. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* 360**,** 1511-1525.

WONG W. K., H. I., LAWRENCE D. OG BELDRING S. 2016. Gridded 1 x 1 km climate and hydrological projections for Norway. *Norwegian Water Resources and Energy Directorate, NVE,* Report no. 59.

WONG, W. K. 2016. *Spatially downscaled AM values for Trondheim* [Online]. Norwegian Centre for Climate Cervises (NCCS)/Norwegian Water Resources and Energy Directorate (NVE). Available: https://nedlasting.nve.no/klimadata/kss [Accessed 15.02.2018].

YR. 2007-2018. *Average precipitation data. Cooperation between NRK and the Norwegian Metrological Institute* [Online]. Available: https://www.yr.no/ [Accessed 20.04.2018].

Appendix A – Observed IDF curves developed in the study and by MET

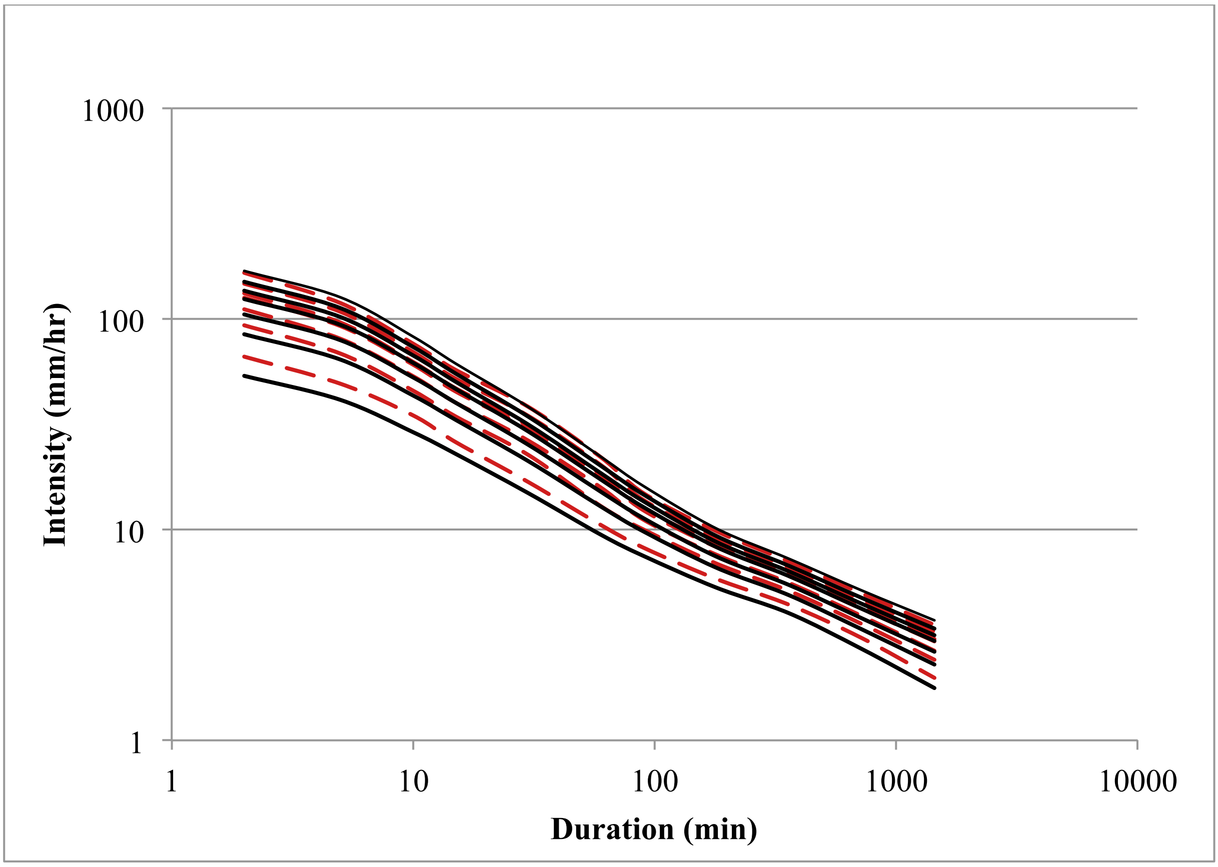


Figure A1: Comparison of IDF curves developed in this study (by using the Gumbel distribution and the Method of moments for parameter estimation) and IDF curves developed by MET (Norwegian Metrological Institute) (IDF curves developed by MET is avaiable at klimaservicesenter.no)**.**

Appendix B – Hypothesis test

Both the trendlines in the double logarithmic plot and the exponent plot in Figure 3, can be described by linear regression:

$$y = a + bx \tag{10}$$

The trendlines in the double logarithmic plot do have a power function, but as the function can be transformed by applying log to both sides we get log(y) = a + b*log(x). This gives a linear regression for the NCMs against duration. As we have two unknown variables, a and b, the degree of freedom is n – 2 (n = number of data). A hypothesis test, referred to as one-sided t-test, can be conducted for linear regression models to evaluate with what certainty it can be claimed that there is a linear correlation between the input (x) and output (y) (Bruaset and Sægrov, 2018). To test for linear correlation, a null hypothesis and a working hypothesis have to be defined:

$$H_0: \rho_0 = 0, \quad H_1: \rho > 0 \tag{11}$$

Setting $\rho_0 = 0$ means testing for any linear correlation in the data, and setting $\rho > 0$ means that a rights tailed test is conducted. The test parameter is defined in equation (12) (Bruaset and Sægrov, 2018):

$$t = \frac{R - \rho_0}{\sqrt{\frac{(1-R^2)}{(n-2)}}} \tag{12}$$

n = number of data in the analysis

n -2 = degrees of freedom

ρ_0 = expectance value for R

R = correlation coefficient

The significance level, α, is the level of uncertainty that can be accepted in the model. For this analysis, α was set equal to 0.0005 for the data in the double logarithmic plot and equal to 0.01 for the data in the exponent plot. This correspondingly indicates that there are a 99,95% and a 99% certainty that there is a linear correlation in the data sets. The critical limit value,

$t_{\alpha,\, n\text{-}2}$, was found from the quantile table for the t-distribution (Helbæk, 2011). When $t > t_{\alpha,\, n\text{-}2}$ we reject the null hypothesis which will indicate a linear trend within the limits that are set. The variables used as input in equation (12) and the results from the hypothesis tests are shown in Table B1.

Table B1: Results from linear correlation analysis (t-test) for NCM against duration and exponent against the order of the moment

Test	**R**	**R^2**	**t_α**	**t**	**n**	**Reject?**
1.order log-log plot	0.9965	0.9931	4.781	35.99	11	YES
2.order log-log plot	0.9957	0.9915	4.781	32.4	11	YES
3.order log-log plot	0.994	0.9908	4.781	31.1	11	YES
Exponent plot	0.99985	0.9997	31.821	57.72	3	YES

Appendix C – Mean of projected IDF curves

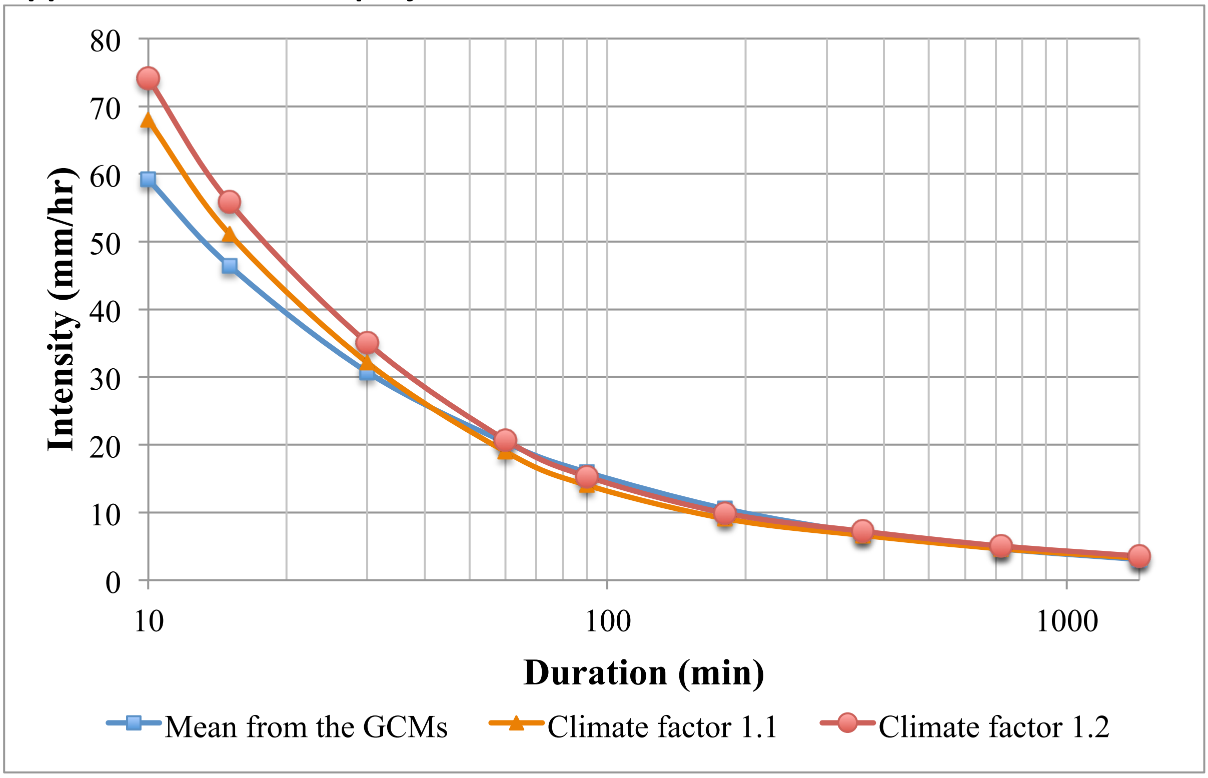


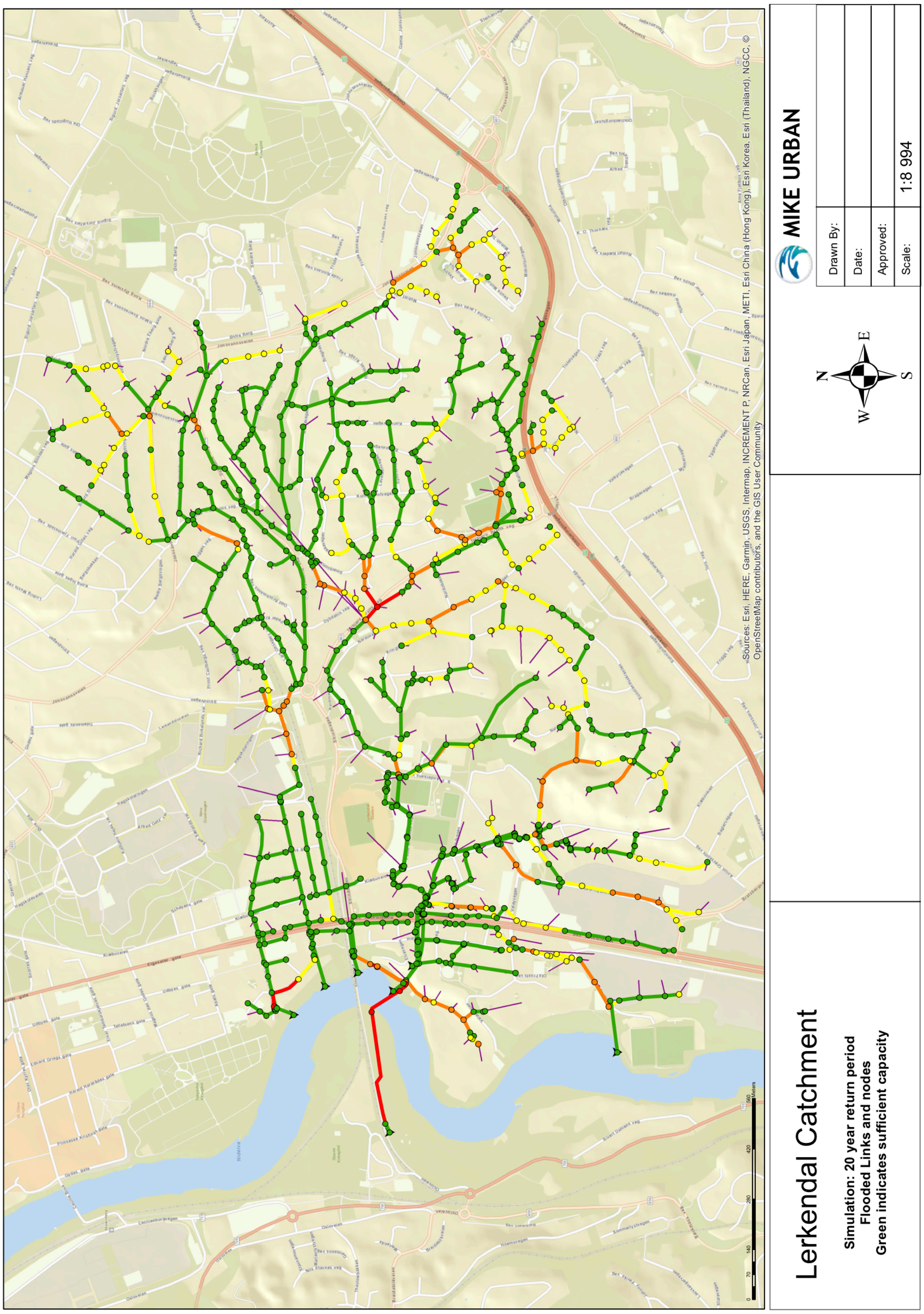
Figure C1: Plot showing the mean of the projected IDF curves for the 20-year return period compared to the observed IDF curve (for the 20 year return period) multiplied with climate factors 1.1 and 1.2.

Appendix D – Simulation results from Mike Urban

Table D1: Simulation results from Mike Urban for the nodeflood, linkflood and weir outflow.

Scenario	Nodeflood [%]	Linkflood [%]	Weir outflow volume [m^3]	Inflow [m^3]	Weir outflow [%]
No climate factor	24,46	33,1	11493	42016	27,35
Climate factor 1.2	27,92	38,1	14339	45474	31,53
Climate factor 1.4	31,98	43,8	17225	49068	35,10
Worst-case GCM	29,71	39,73	18964	51172	37,06

Appendix E – Areal view for Mike Urban simulations



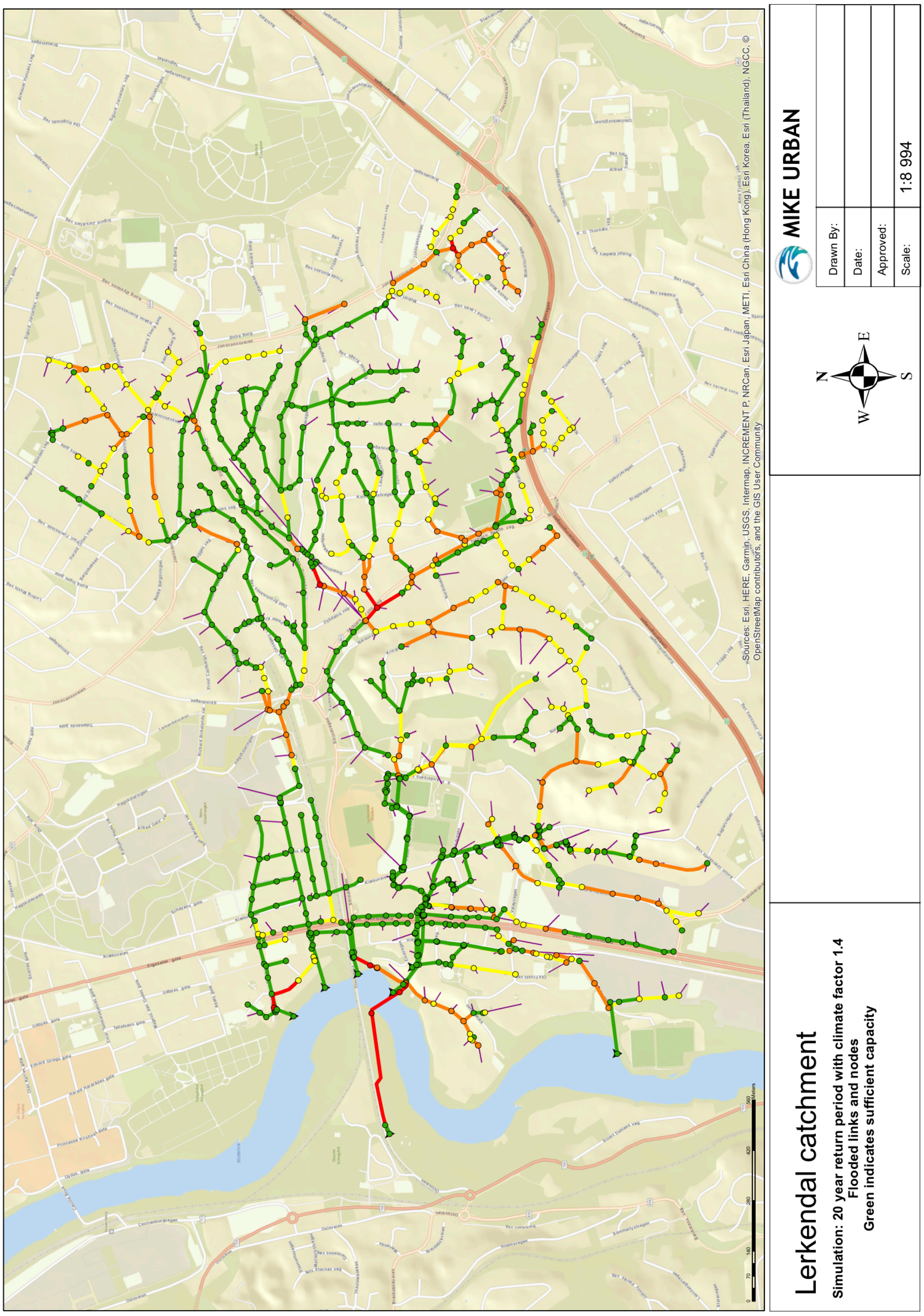


Figure E1: Flooded links and nodes in Lerkendal catchment from simulations of the scenarios with correspondingly the observed IDF curve with a 20 year return period, and with a climate factor of 1.4. Links and nodes with no flooding are marked in green. Yellow indicates 0-0.5m flooding above groundlevel, orange indicates 0.5-1m flooding above groundlevel, and red indicates >1m flooding above groundlevel. The red link crossing the river, Nidelva, is concidered a diving link that is pressurized, and hence it will be filled at all times. (The maps with result layers from MIKE Urban were processed in ArcMap).

Appendix F – Script for temporal downscaling of the GCMs

```
###Script for downscaling of the GCMs
###Malene Yttersian Munkerud, Supervised by Erle Kristvik
###10.04.2018

require("evd")
library(reshape)
library(ggplot2)

#Set working directory
setwd("/Users/maleneym/Documents/R-Script/nystart/AM fra Klimamodeller/RCP8.5")

#Import the AM data from the GCM
###############################################
#Change input file for different GCMs

An.max <- read.table("CNRM_CCLM_8.5.txt", header = T, sep = "")
An.max <- An.max[85:114, 1]
An.max <- as.matrix(An.max)
row.names(An.max) <- c(2071:2100)
colnames(An.max) <- as.character("AM")
rownames(An.max) <- as.numeric(c(2071:2100))

#Estimate the Gumbel parameters for daily AM values
#####################################################

par <- data.frame(mu=rep(0,11), beta = rep(0,11))
rownames(par) <- as.character(c(2, 5, 10, 15, 30, 60, 90, 180, 360, 720, 1440))

mean <- apply(An.max, 2, FUN=mean)
st <- apply(An.max, 2, FUN=sd)

par[11,1] <- mean -(0.45*st)
par[11,2] <- 0.7797*st

############## Scaling procedure

sfactor <- c(0.4037, 0.4037)

dur <- c(2, 5, 10, 15, 30, 60, 90, 180, 360, 720, 1440)
lambda <- dur/(24*60)

T_return <- c(2, 5, 10, 20, 30, 50, 100)

p <- 1/T_return

svector <- c(sfactor[1], sfactor[1], sfactor[1],
          sfactor[1], sfactor[1], sfactor[1],
          sfactor[1], sfactor[2], sfactor[2],
```

```
            sfactor[2])
scale <- lambda[1:10]^svector

# Estimating the parameters for the other durations based on the scaling factor
par.sc <- par
par.sc[1, ] <- par[11,]*scale[1]
par.sc[2, ] <- par[11,]*scale[2]
par.sc[3, ] <- par[11,]*scale[3]
par.sc[4, ] <- par[11,]*scale[4]
par.sc[5, ] <- par[11,]*scale[5]
par.sc[6, ] <- par[11,]*scale[6]
par.sc[7, ] <- par[11,]*scale[7]
par.sc[8, ] <- par[11,]*scale[8]
par.sc[9, ] <- par[11,]*scale[9]
par.sc[10, ] <- par[11,]*scale[10]
par.sc[11, ] <- par[11, ]

#Calculating the returnlevels, scaled

Xt.sc <- rbind((par.sc$mu[1]-par.sc$beta[1]*log(-log(1-p))),
          (par.sc$mu[2]-par.sc$beta[2]*log(-log(1-p))),
          (par.sc$mu[3]-par.sc$beta[3]*log(-log(1-p))),
          (par.sc$mu[4]-par.sc$beta[4]*log(-log(1-p))),
          (par.sc$mu[5]-par.sc$beta[5]*log(-log(1-p))),
          (par.sc$mu[6]-par.sc$beta[6]*log(-log(1-p))),
          (par.sc$mu[7]-par.sc$beta[7]*log(-log(1-p))),
          (par.sc$mu[8]-par.sc$beta[8]*log(-log(1-p))),
          (par.sc$mu[9]-par.sc$beta[9]*log(-log(1-p))),
          (par.sc$mu[10]-par.sc$beta[10]*log(-log(1-p))),
          (par.sc$mu[11]-par.sc$beta[11]*log(-log(1-p))))



#Calculation of the projected IDF curves

xIDF <- c(2, 5, 10, 15, 30, 60, 90, 180, 360, 720, 1440)
sc.IDF <- (Xt.sc/xIDF)*60 ##mm/hr

#Write to csv file
write.csv(sc.IDF, file = "scaledIDF_gumbel.csv")
```

Appendix G –Areal view over Lerkendal drainage zone

Figure G1: Areal view over Lerkendal drainage zone (Google Maps, 2018).