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A regionalisation technique for urban ungauged catchments

A case study from Norway

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Description of Project Thesis project spring 2017

Candidate name: Jonas Staven Mittet

Subject: Stormwater

Title: A regionalisation technique for urban ungauged catchments – a case study from Norway

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Background

Modelling the runoff generation in urban areas is more complex than modelling natural catchments due to the heterogeneity in land covers urban development projects result in. In addition to alteration of the natural land use of urban areas, the means the runoff is transported changes to be through manmade open or closed channels. In the past decades, several computer models have been developed for predicting the runoff generation, and transportation from urban and non-urban catchments. One common future of these models is that they describe different processes (hydrologic or hydraulic) through mathematical equations, which cannot completely be extracted from physiographic information or be solved analytically. Hence, calibration of the model parameters that relate the precipitation the catchment received with the discharge measured at the outlet is essential.

The present study is part of the BINGO project (www.projectbingo.eu) and Klima2050, whose goal in the Bergen research site is to assess the impact of climate change and increased frequency of weather extremes on the CSO discharge of the Damsgård area through modelling. In general, all modelling exercises are confronted with uncertainties. However, the challenge is much exacerbated in urban catchments due to continued human interference and unavailability of adequate discharge records in different sections of the developed areas. One of the main challenges associated to modelling the stormwater system of the Damsgård area is the lack of data. The lack of local runoff data to calibrate model parameters reduces reliability of mathematical expressions that designate hydrologic functioning of ungauged catchments.

The main objective of the present study is to evaluate the existing model and the potential to formulate a regionalisation technique for setting up a model for the ungauged section

Objectives

The main objectives of the project are:

1) To what extent does the existing model compare to observed flow?
2) In applying this method, which parameters are the most sensitive?
3) To what extent can this combined calibration and regionalisation technique be applicable for ungauged catchments?

Collaboration partners: Bingo

Location: The project thesis will be conducted at the Department of Civil and Environmental Engineering.

Advisors: Tone Merete Muthanna and Ashenafi Seifu Grange

Preface

This report is the final product of the course “TVM4905 Water and wastewater engineering, Master’s thesis” at the Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering. The purpose of this report was to suggest a technique that integrates a regionalisation concept into model calibration of Storm Water Management Model.

First of all I would like to express my deepest gratitude to Postdoctoral Fellow Ashenafi Seifu Gragne for his guidance, support and all the interesting conversations throughout this study. I would also like to thank my supervisor Associate Professor Tone Merete Muthanna for advice and feedback during this process, and for giving me the opportunity to work with this topic.

In addition, I would like to thank Researcher Jardar Lohne for his help with language editing and manuscript preparations.

The present study was made possible by the BINGO project - *Bringing INovation to onGOing water management – a better future under climate change* (projectbingo.eu) and by Klima 2050, Centre for Research-based Innovation (klima2050.no).

Trondheim, June 9, 2017

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Jonas Staven Mittet

Thesis structure

Normally a Master thesis at NTNU will result in an extensive report covering the studied topic. However, the final product is presented as a scientific publication/article in this thesis. The intention behind this choice is to (hopefully) reach a larger audience.

The manuscript presented in this thesis will be the foundation of a paper planned to be submitted to the the International Water Association (IWA) journal *Water Science and Technology*. The format of the manuscript is therefore mainly based on the framework of this scientific journal and can be seen in Appendix A.

The work has been accepted for presentation at the conference *Embrace the Water* in Gothenburg, Sweden. A poster was therefore made and can be accessed by using the QR-code in Appendix B.

Sammendrag

Som følge av klimaendringer kommer mange områder til å oppleve endringer i det hydrologiske systemet. Dette vil i sammenheng med flere tette flater, på grunn av urbanisering, resultere i hyppigere forekomster av ekstreme nedbørshendelser og flom. En viktig del av prosessen med å forberede seg til disse endringen er å modellere de hydrologiske systemene slik at man kan estimere avrenning fra nedbørsfeltene. Dette gjøres som regel i databaserte modeller som Storm Water Management Model (SWMM), der historisk nedbørsdata ofte benyttes til å kalibrere modellen.

I mange områder har man ikke tilgang på historisk nedbørsdata, noe som redusere modellens evne til å estimere avrenning nøyaktig. For å kompensere for dette bruker man regionalisering. Dette er en metode som estimere modellparameterne i det umålte nedbørsfeltet ved å bruke informasjon fra hydrologisk like nedbørsfelt. Den vanligste metoden for regionalisering kalles to-stegs-regresjonsmetoden. Her kalibreres modellparameterne første, for deretter å knyttes opp mot nedbørsfeltets karakteristikk. Dette overføres så til det umålte nedbørsfeltet. Ulempen med denne metoden er at det finnes mange sammensetninger av modellparametere og nedbørsfeltets karakteristikk som kan gi like gode resultater for modellen. Man kan derfor få svake eller falske sammensetninger, noe som resulterer i en dårlig estimering av avrenningen for det umålte nedbørsfeltet.

I et forsøk på å unngå disse svake sammensetningene har dette studiet hatt som mål å foreslå en ny metode som kombinerer regionalisering og kalibrering i SWMM. Dette er gjort ved å implementere overføringsfunksjoner (transfer function) i metoden. Overføringsfunksjonene er avledet ved å, på forhånd, anta en sammenheng mellom modellparameterne og nedbørsfeltets karakteristikk. Når modellen kalibreres vil derfor parameterne av overføringsfunksjonene kalibreres istedenfor modellparameterne. Ved å holde dette forholdet uendret for hele området vil overføringsfunksjonene gi ulike modellparametere for hvert nedbørsfelt.

Den foreslåtte metoden ble testen på fire nedbørsfelt i Damsgård, Bergen. Resultatene viste at de observerte og simulerte avrenningskurvene for hvert nedbørsfelt samsvarte bra. Modellen responderte bedre på høy vannføring enn ved lav vannføring, noe som er forventet ved bruk av Nash – Sutcliffe (Nash and Sutcliffe 1970) som objektiv funksjon. Ved å foreta en sensitivitetsanalyse på modellparameterne ble det funnet at de mest sensitive parameterne er bredde, gropmagasinering, minste infiltrasjonskapasitet og andel tette flater. For nedbørsfelt ble det funnet at de sensitive nedbørsfeltene ikke kan motta parametersett fra andre

nedbørsfelt uten at det påvirker ytelsen til modellen. Nedbørsfelt med lav sensitivitet kan derimot motta parametersett fra andre nedbørsfelt. Ved å sammenligne ulike fysiske karakteristikker i hvert nedbørsfelt ble det forsøkt å finne mønster som kunne knyttes opp mot overførbarheten av modellparameterne. Resultatene fra dette viste at antall beboere i et område og lengden til utløpet var det som i størst grad påvirket overførbarheten til et nedbørsfelt.

Table of content

A regionalisation technique for urban ungauged catchments – a case study from Norway

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Abstract

Accurate estimation of rainfall-runoff in an urban area is essential for flood disaster prevention and control. A Storm Water Management Model was therefore applied to four small urban catchments in Damsgård, Bergen, Norway. In an effort to extend the modelling works to the ungauged parts of Damsgård, a technique that integrates a regionalisation concept into model calibration was tested. The SWMM parameters were calibrated along regionalisation-parameters that establish certain mathematical relationships (transfer functions) between selected SWMM parameters and catchment characteristics. The Shuffle Complex Evolution algorithm was integrated into the calibration of the model to estimate the parameters of the model, with the Nash-Sutcliffe Efficiency criterion as an objective performance measure. The calibrated model predicted the observed outputs with reasonable accuracy. Hence, the parameters derived from the transfer functions could be further used to test the applicability of the proposed methodology. A pattern between the catchments physiographic characteristics and the parameter sets of the transfer functions was observed. The two characteristics identified to affect the transferability the most were the number of residents, and the length to outlet. The results demonstrate that it is possible to combine the regionalisation of an ungauged catchment with the calibration of SWMM.

Key words: Calibration, Climate Changes, Parameter estimation, Regionalisation, SWMM, Urban catchments

1. Introduction

Due to climate changes many regions will experience altering hydrological systems, affecting both water quantity and quality (IPCC 2014). Precipitation will increase and heavy rainfall events will intensify (Hanssen-Bauer et al. 2015). When adding the effects of urbanization, which typically results in an increase in impervious surface areas, higher peak flows, and higher surface runoff volumes are expected.

In the process of adaption to climate change, it is important to be able to model the present system, and estimate the generated runoff as accurately as possible. Several computer-based models have been developed for this purpose, including the Storm Water Management Model (SWMM) (Rossman 2015), and Mike Urban (DHI 2016). SWMM is one of the most widely used urban rainfall-runoff models. Typically using SWMM one can calibrate the model parameters of the drainage system (and/or drainage catchment) with the use of recorded runoff data. In general, all modelling exercises are confronted with uncertainties arising from the selection of calibration techniques and models (Pianosi and Wagener 2016). The challenge is much exacerbated in urban catchments due to continuous human interference and the lack of availability of adequate discharge records in different sections of the developed areas. The lack of local runoff data to calibrate model parameters reduces reliability of mathematical expressions that designate hydrologic functioning of ungauged catchments (e.g. Merz et al. 2006) and, subsequently, poses a great challenge in simulating the impacts of urban developments on the hydrologic behaviours of the catchments.

Regionalisation is a method used to compensate for the lack of data in a catchment (Blöschl & Sivapalan, 1995). In this process, model parameters for an ungauged catchment are estimated with the use of information from hydrologically similar catchments (Sivakumar and Berndtsson 2010). The similarity between the gauged and ungauged catchment can be established based on proximity (i.e. selecting a close by catchment assumed to exhibit a hydrologic response similar to the ungauged catchment) or based on catchment characteristics such as size, land use, topographic information, etc.

Several regression-based regionalisation methods that estimate rainfall-runoff model parameters for continuous streamflow simulation have been developed (He et al. 2011), using the most widely used two-step regression method. Through regression, a relationship between each model parameter and climatic, and physiographic data is established. When the model parameters have been estimated they can be used in an established regional model to predict discharge in an ungauged catchment. A disadvantage with this approach however, is that there are many possible sets of parameters that could lead to the same model performance. Therefore, a relationship between a parameter and a physical characteristics tends to be weak or even false. (Beven 2000)

Another approach is to expresses the model parameters as functions of the catchment characteristics using transferable functions which form is assumed a-priori. The model is then calibrated for all the catchments in the area. By establishing such relationships, the model is calibrated for the parameters of the transfer function instead of the model parameters. The transfer function stays unchanged throughout the study area, but produce different model parameters for each subcatchment. Through this process, unique parameter sets are possible to establish. This approach was implemented in a study by Hundecha and Bárdossy (2004) to assess the effects of land use change on runoff. However, few or no studies applying this approach in an existing urban area was found.

Before establishing the parameters of the transfer function, one has to make sure that the parameters are able to accurately reflect the properties they are supposed to represent in the system (Sivakumar and Berndtsson 2010). Many of the parameters have to be derived through calibration against historical recorded data, since they cannot be measured directly. During calibration the parameters are adjusted repeatedly to find the model parameters that result in a minimal discrepancy between observed and predicted values.

In earlier days, model calibration was typically carried out manually. With this approach, the user adjusts the parameters manually in a guided trial-and-error procedure. Assessment of the calibration is based on the visual comparison of simulated and observed hydrographs. As manual calibration depends on the individual user it is a highly subjective approach, which typically produces different model parameters for the same watershed. For the inexperienced hydrologists the approach is also considered to be quite time-consuming (Madsen 2000). The improvement witnessed in computational power in the last few decades has resulted in automation of model calibration process. In an automatic calibration, a computer is used to adjust the parameters according to a specified search scheme, and numerical measures of model performance (Madsen 2003). As compared to manual calibration, automatic calibration is faster and avoids the subjectivity.

A general framework for automatic calibration was developed by Madsen (2003), and a similar one is mentioned in Sivakumar and Berndtsson (2010). They outline three essential elements. These are (1) an initial estimate of the parameters, (2) the implementation of an objective function, and (3) the introduction of an optimisation algorithm for automatic calibration. The initial estimates of the parameters is a main challenge for the application of SWMM hence, several studies are dedicated to different methods of parameter estimation in urban rainfall-runoff models (Shen and Zhang 2014; Jain et al. 2016).

Sivakumar and Berndtsson (2010) define an objective function as an aggregate statistical summary quantifying the "goodness-of-fit" between the simulated and observed hydrologic variable(s). Several such functions have been developed depending on which aspect of the simulated and observed behaviour that is emphasised (peak flows, low flows, etc.)). For example, the most frequently used criteria in hydrologic modelling is the Nash-Sutcliffe efficiency (NSE) criteria (Nash and Sutcliffe 1970). It performs well for peak flows, but is less suited for low flows (Krause et al. 2005). When using objective measures for performance evaluation, the subjectivity of manual calibration is avoided.

In addition, an optimisation algorithm is necessary for automatic calibration. It searches the surface within the given parameter space to find the best parameter set. In general, optimisation algorithms can be divided into local and global search methods. The local search methods are often found insufficient for rainfall-runoff models, as they may be trapped in a local optimum instead of finding the global optimum. Therefore, global search methods have been developed, including the Shuffled Complex Evolution (Duan et al. 1992) and the A Multi-Algorithm Genetically Adaptive method (Vrugt and Robinson 2007). A successful application of the Shuffled Complex Evolution (SCE) was demonstrated by Barco et al. (2008), with the automatic calibration of four parameters in the SWMM.

The conventional way of modelling an ungauged catchment is through calibration of a model and subsequently regionalising this to the ungauged catchment. This is typically performed in two separate steps, and can be quite time-consuming as the regionalisation cannot be formulated before the model is calibrated. The ambition of this paper is therefore to propose a methodology that combines these two steps of regionalisation and model calibration in SWMM. The technique was applied to a set of small urban catchments in Bergen, Norway. The proposed method and its challenges will be addressed according to the following research questions:

- To what extent does the existing model compare to observed flow?
- In applying this method, which parameters are the most sensitive?
- To what extent can this combined calibration and regionalisation technique be applicable for ungauged catchments?

1.1. Description of study area and data

The Damsgård area is located along the Puddefjord in Bergen City, Norway, on the foot of the Løvstaket Mountain (Appendix C). Steep slopes characterise the research catchment, with elevation ranges from sea level to 468m above mean sea level. Built-up areas (i.e. buildings and roads) cover about 48.3 % of the area while about 44.5 % of the catchment is forested. Extensive flash floods from the hillsides pose a serious threat to the residential areas in Damsgård. The Bergen Municipality is examining to what extent separating the exciting combined sewer system in the area will adequately solve the current flash flood damages. The municipality has a model that covers most of city, however the system in some part of the study area is not included in the existing Mike Urban-based model. In addition there are no flow records available for the areas outside the exciting model.

The four gauging stations selected for testing the proposed method are located in the western part of Damsgård. SSLILLED and SSTOSCANA lie on the hillside, while SSBRO and SSKONOW lie adjacent to the fjord (Figure 1).

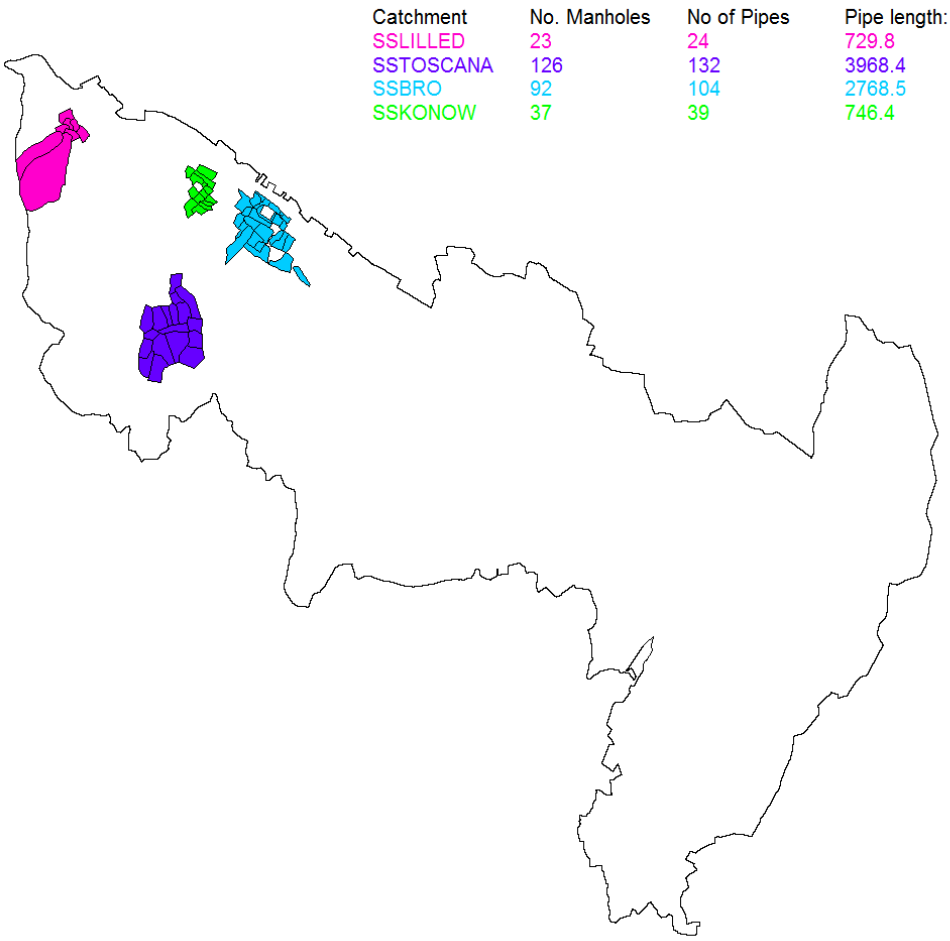

Figure 1 The Damsgård area with studied catchments and characteristics of the drainage system

2. Method

To solve the scope defined in this case study, two elements have been assessed. The first element is the calibration of the SWMM and the second element is the regionalisation. The elements were, however, combined into one with the use of transfer functions. The transfer functions were used to establish different equations between the SWMM model parameters and the catchment characteristics. Subsequently, the relationship can be transferred to an ungauged catchment. This method is limited to the surface runoff parameters of the model. All models implemented in this study have simulation interval of 5 minutes.

2.1. Calibration

For the calibration of the SWMM, an automatic calibration was selected to avoid subjective assessments. To perform the automatic calibration of the model, the general framework formulated by Madsen (2003) was adopted. The formulation involves the following key elements:

- Model parameterisation and choice of calibration parameters
- Specification of calibration criteria
- Choice of optimisation algorithm.

When establishing the required parameters, they were divided into physiographic and hydrological parameters sets. The physiographic parameters such as area and slope could be measure, and hence did not require calibration. The hydrological parameters, however, are not measurable and therefore derived through calibration of the model or calculated from the land use. Although the interface between the two categories appear absolute, the interface is vague and can depend on the viewpoint of the user (Choi and Ball 2002).

In total 14 parameters were calibrated in this study. A summary of the classifications and methods used in this study is given in table 1.

*Table 1 Methods used to derive the main parameters. Parameters marked with * are explained below.*

Parameter	Source	Formula /approach
Area	Raster data	
Slope	Raster data	Median value from 10 x 10 m raster data.

% Zero imperviousness	Raster data	Percent of impervious area without depression storage. Area covered by buildings was identified as the percentage of area with zero depression storage.
%Imperviousness	Raster data	Imperviousness was set equal to the area of roofs and roads.
N-Impervious *	Calculated from land use	(1) $N_I = \frac{n_{roof} * A_{roof} + n_{road} * A_{road}}{A_{Impervious}}$
N-Pervious *	Calculated from land use	(2) $N_P = \frac{n_{Forrest} * A_{forrest} + n_{Green} * A_{Green}}{A_{Pervious}}$
Width*	Calibrated	(3) $W = a * \left(\frac{A}{L}\right)^b$
Depression storage, Impervious *	Calibrated	(4) $I_P = i * c * (Slope)^{-d}$
Depression storage, Pervious *	Calibrated	(5) $I_I = c * (Slope)^{-d}$
Infiltration	Calibrated	Horton infiltration Parameter: e, f, g, h
Effective precipitation coefficient	Calibrated	Accounts for interception Parameter: j
Min. flow correction	Calibrated	Correction for minimum flow Parameter: k
Imperviousness, transfer function	Calibrated	$l + m * Imperviouness^n$

2.2. Width

The width of each subcatchment was determined by calibration. However, to perform the calibration, initial estimated values were required. The initial width estimate for each subcatchment was obtained by determining the average maximum length of overland flow and dividing the area by this length (Rossman 2015).

$$W = \frac{A}{L}$$

The maximum length was obtained by using a Euclidian distance formula, where the coordinates for a vertex and outlet was used to calculated the distance.

As mentioned by Beven (2000), the classical approach for parameter estimation does not lead to a unique set of parameters. Therefore, transfer functions have been implemented in this study. The transfer functions are derived from initially assuming a relationship between the catchment characteristics and the model parameters. When calibrating the model with these relationship, the parameters of the functions will be calibrated instead of the model parameters. By holding the parameters fixed throughout the study area, the transfer functions will produce different model parameters for each subcatchment. The transfer function implemented in this section is based on the function for the width of the subcatchment. It has a linear parameter (a) and an exponential parameter (b) in order to achieve the best possible fit for the transfer parameters.

2.3. Manning values (M)

An urban subcatchment is typically composed of both pervious and impervious surfaces. Due to little variation in land cover types, only four Manning values were chosen in this study. Two values for impervious land cover and two for pervious land cover. From Statens Vegvesen [National Public Roads Administration] handbook N200 (2007), recommended values for Norwegian conditions can be derived. Since each subcatchment has different spatial distribution of land cover types, the value for each subcatchment can be computed based on the area weight of the subcatchment. There are two major impervious land cover types in the study area, namely roof and road. The value (M) for roof is set to 65 and the value for road is set to 68 (Statens Vegvesen 2007). The n-impervious for each subcatchment is calculated as illustrated above (formula 1)

For pervious land cover types, sparsely vegetated areas (Park, Lawn, etc.) and densely vegetated areas were chosen as the two major pervious land cover types. Manning values of 25 and 20 was selected for the sparsely and the densely vegetated areas, respectively (formula 2).

2.4 Depression storage

Some rainfall will be stored in both the pervious and impervious surfaces as depression storage. Kidd (1978) developed a method to use the slope of a subcatchment to compute the depression storage. Two modified versions of this method were used to calibrate the depression storage of the impervious and pervious surfaces (see table 1). The parameters c, d and i are found through calibration. The i-parameter in the formula for pervious depression storage is used to separate the impervious and pervious depression storage values.

2.5. Calibration criteria and Optimisation algorithm

In order to search for optimum parameter values, the Shuffle Complex Evolution (Duan et al. 1992) algorithm was implemented in this study. For the optimisation, an appropriate objective function was essential. Since the peak flow was of main interest in this study the Nash-Sutcliffe efficiency coefficient (NSE) was selected (Nash and Sutcliffe 1970). Additionally, NSE is a widely used objective function. Thus, the results should be easily comparable to similar studies. The optimisation algorithm and the objective function was incorporated into a script to perform the automatic calibration. The script can be seen in Appendix D, and an overview of the script is illustrated in figure 2.

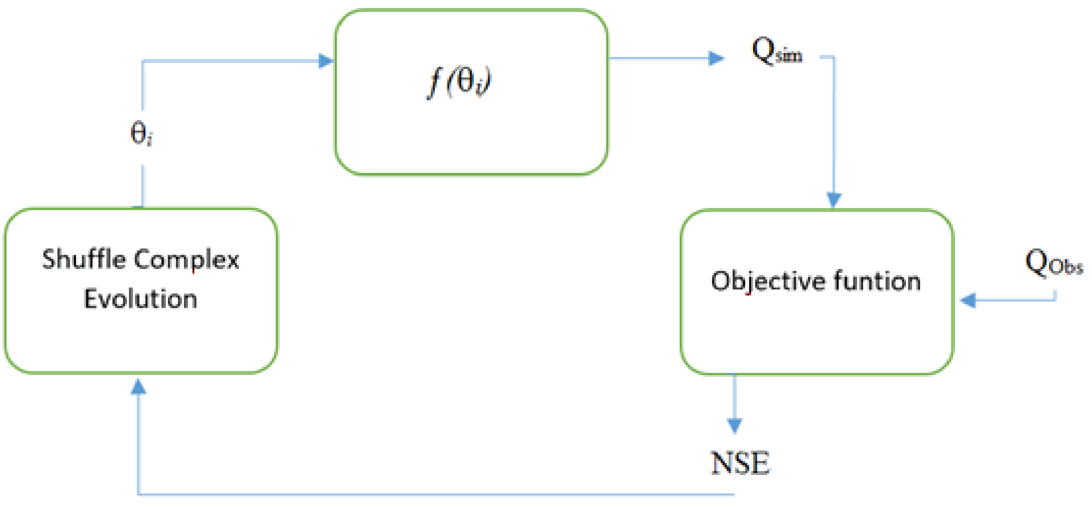

Figure 2 Overview of the scrips used to auto calibrate the model.

3. Results and Discussion

Overall, the calibrated model predicted the observed runoff with reasonable accuracy. Hence, the parameters derived from the transfer functions were used to test the applicability of the proposed methodology. The results from this case study demonstrate that it is possible to estimate the regionalisation and the SWMM model parameters jointly. In the following, the elements constituting the analysis are examined in more detail.

3.1. Calibration performance

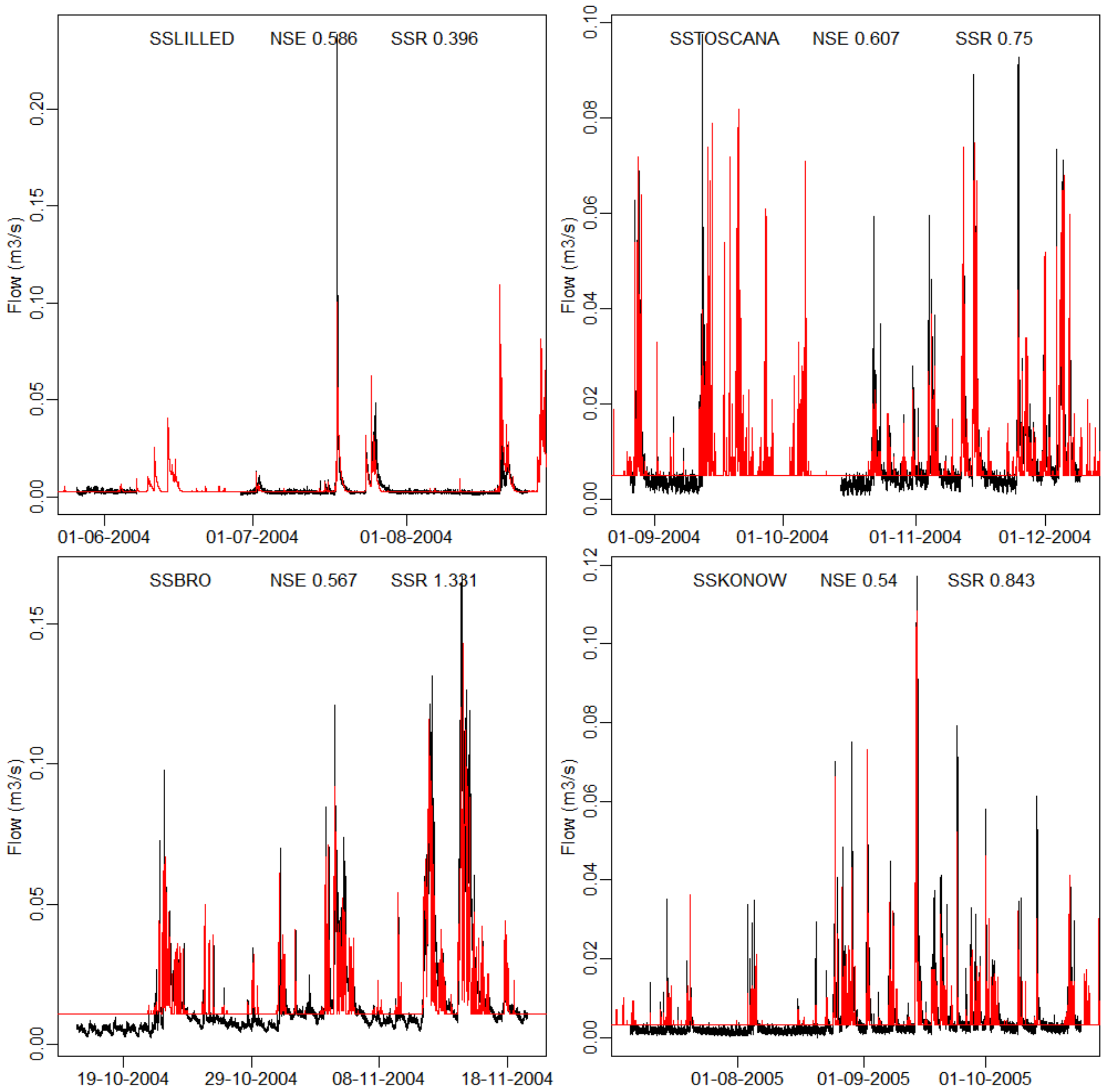

Figure 3 Simulated (red) and observed discharge for the catchments using the proposed method. NSE and SSR values are attached for each catchment.

Four catchments in the Damsgård area were simulated. In order to see the performance of the calibrated model, the simulated and observed runoff hydrographs for each catchment were plotted, with the corresponding NSE- and SSR-values attached. All the catchments had similar performance, with NSE-values ranging from 0.54 for the SSBRO to 0.607 for the SSTOSCANA. Figure 3 shows that the model performed well with respect to peak flows, but struggled to reproduce the low flows. This might be due to the use of the NSE, which is biased to higher flows as an objective function. Clearly illustrating the importance of considering the objectives of the modelling in the choice of objective function. Compared to rural areas, where surface runoff typically is the main (or only) concern, an urban area is considerably more complex, due to the urban water systems with combined sewers. Consequently, it is difficult to compare the model to similar studies in natural watersheds, where higher NSE- values can be achieved. The poor performance in the low flows, might also be due to inaccurate estimate of the sewer flow in the systems. It can clearly be noted from Figure 3 that the simulated low flows lack the diurnal variation the observed flow exhibits. Furthermore, unaccounted for infiltration into the combined sewer system could be one more reason for poor performance in low flows. In order to compensate for the poor performance in the low flows, a correction parameter (K) was defined in the calibration process. This correction factor is shown as a straight line in the hydrograph, and served to secured a minimum flow.

Another challenge in the calibration of the model was the lack of observed runoff data during the runoff series. The available data-set had intermittent data series due to available equipment limitations in the sampling campaigns. This may have affected the results of the simulations, but to which degree is unknown.

3.2. Sensitivity

A sensitivity analysis was performed to assess the sensitivity of the calibration parameters of all four catchments. Only the parameters resulting in NSE-values larger than 0 were implemented in the analysis, as these are the values that contribute to improved performance of the model. Figure 4 shows the expected parameter range and the corresponding NSE-values. Equally, it highlights the single best performing parameter within each range.

In regards to the SSLILLED, most of the catchments best performing parameters are located within a narrow range. This implies that the catchment is highly sensitive, and the performance will suffer greatly outside the specific range. When considering the other three catchments, the SSTOSCANA is slightly more sensitive than SSBRO and SSKONOW, as can be seen from a narrower range for some of the parameters. However, none of the three catchments show high sensitivity as the range can be considered wide for most of the parameters.

When investigating the parameters, none showed sensitivity across all four catchments. Therefore, parameters were considered as sensitive if they showed signs of sensitivity in more than two catchments. This resulted in b, c, e, k and n being considered as sensitive. Through their transfer functions these parameters represent the width (b), depression storage (c), minimum infiltration capacity (e), minimum flow correction (k) and imperviousness (n). Except for k, all of the sensitive parameters can be measured directly in urban areas. Hence, they can easily be obtained and assessed for an ungauged catchment. The sensitive parameters found in this study correlate with the Barco et al. (2008), where they concluded that the depression storage and imperviousness are the most sensitive parameters.

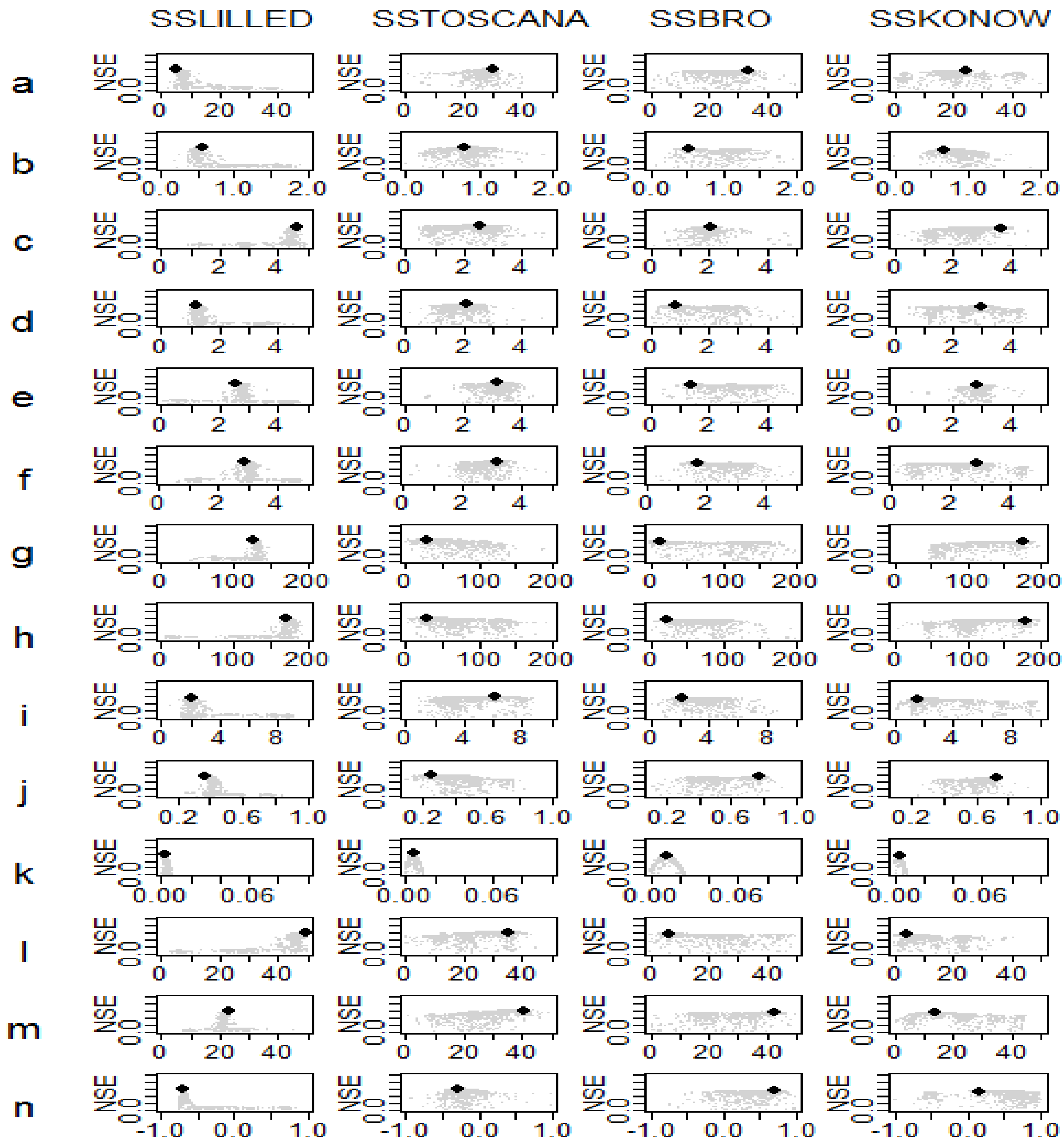

Figure 4 Sensitivity analysis of the catchments. Each box shows within which parameter range the catchments perform the best. The black spot in each box represents the single parameter value that results in the highest NSE-value.

3.3. Transferability

To evaluate the performance of the suggested method, the best parameter set of each catchment was directly transferred to the three other catchments. This implied that the best parameter set of a catchment was used to model the three remaining catchments before being tested with the parameter sets from the other catchments. The obtained NSE-values from the transferability test are shown in table 2.

Table 2 NSE - values for the best parameter set of each catchment when transferred from catchment to catchment

	SSLILLED	SSTOSCANA	SSBRO	SSKONOW
SSLILLED	0.586	< 0	0.445	0.49
SSTOSCANA	0.069	0.607	0.135	0.458
SSBRO	< 0	< 0	0.567	< 0
SSKONOW	0.063	0.15	0.18	0.54

As mention above, the SSLILLED is a sensitive catchment. This correlates with the performance in table 2, since it performed poorly when a parameter set from another catchment was used. The donor ability of SSLILLED, however, is good with acceptable performance in both SSBRO and SSKONOW. For SSTOSCANA, the performance was -0.388 and hence the parameter set from SSLILLED is not applicable for this catchment. Poor performance was also the result when SSTOSCANAs parameters were applied to SSLILLED. A possible explanation for the poor correlation between the two catchments is the different seasons the runoff data is extracted from. As shown in figure 3, the time series for SSLILLED is during the summer, while the time series for SSTOSCANA is during the autumn. Seasonal variation in runoff may therefore affect the calibrated parameters, resulting in lower transferability between the catchments.

3.4. Overall discussion

The applicability of the method was assessed by comparing the characteristics of the four catchments with the transferability. By investigating the characteristics of the four catchments, variables and patterns between the catchments were identified. Differences in the transferability performance was then linked directly to the characteristics.

In figure 5, the physiographic characteristics of each catchment were compared to one another. Significant differences in the range of the characteristics were observed between the catchments. For instants, the largest subcatchment area is 8.16 ha while the smallest is 0.08 ha. The mean values (thick black line) however, showed less variability across the catchments. Hence, for the physical characteristics the identification of variables and patterns were based on mean values.

From figure 5, four characteristics with a pattern of variability was observed. These characteristics were the number of residents, length to outlet, area to length ratio (width), and elevation. Considering the low variation in mean area the width was primarily dependant on the length, hence the width was not included in this part. Except for elevation, all the characteristics had similar values in SSLILLED, SSBRO and SSKONOW. However, in SSTOSCANA the values were slightly higher. SSLILLED and SSTOSCANAs donor values from table 2 were therefore compared to this observed difference in characteristics values. This showed that the variability in the number of residents and the length to outlet affected the transferability the most. Since the elevation for SSLILLED and SSTOSCANA was similar, no correlation between the transferability and elevation could be found.

No similarities were found between then characteristics of the drainage system (figure 1), and the transferability in table 2. This does not mean, however, that only the physical characteristics of the catchments affect the applicability of the method. For example, considering that an increased number of residents often results in an increase in imperviousness (due to more buildings and infrastructure), one would expect some correlation between the imperviousness and the number of residents. The imperviousness, on the other hand, is similar for all the catchments. An assumption can therefore be that the correlation between residents and the transferability is due to the increased number of residents connected to the drainage system.

Due to the limited number of catchments being compared in this study uncertainties in the results are expected. All the data needed for the identified sensitive parameters (the width, depression storage, minimum infiltration capacity and imperviousness) is however easily accessible for end-users such as municipalities and consulting companies, resulting in a user-friendly methodology. Further research on the area, including the comparison of more catchment, should be done to reduce the uncertainties.

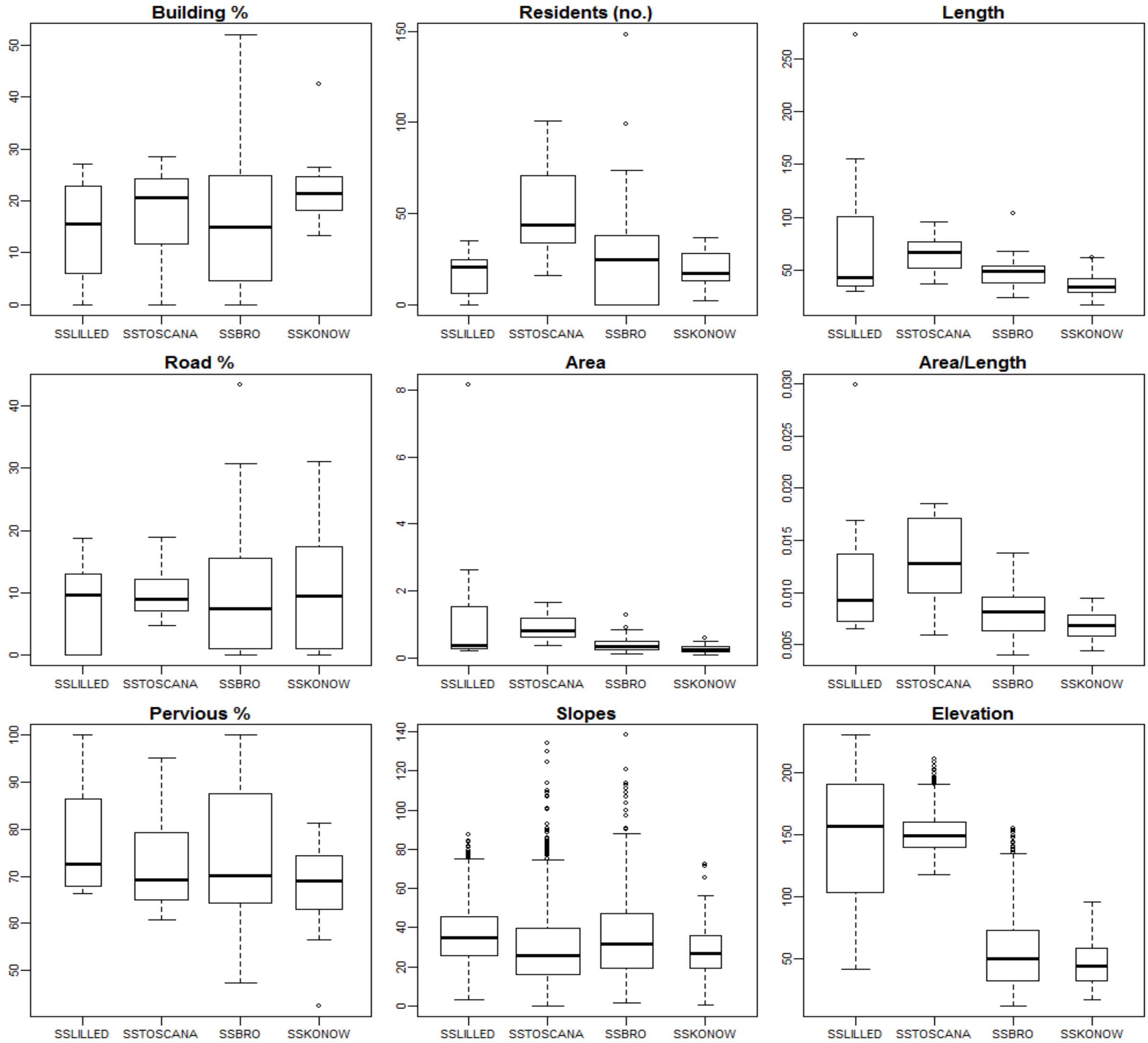

Figure 5 The physical characteristics of a catchment compared to another. The black line represents the mean value.

4. Conclusion

To estimate rainfall-runoff relationships in the Damsgård area (Bergen, Norway), SWMM was applied. Due to the lack of runoff data in the ungauged areas of the catchment, a regionalisation method was incorporated with the calibration of the model, based on the use of transfer functions. The transfer functions were used to establish relationships between the hydrological model parameters and the catchments characteristics in the gauged catchments.

After the calibration, the model performed well with respect to peak flows, but struggled with the low flows. This was as expected with the use of Nash-Sutcliffe efficiency coefficient, showing how significant the choice of objective function can be for the performance of the model. Since this study focused on the capacity aspects, the peak flow is of main interest. Hence, the model performance was considered sufficient.

The sensitivity analysis showed that the width, depression storage, minimum infiltration capacity and imperviousness are the most sensitive parameters in a catchment. These parameters are easily accessible and can be measured directly in an urban area. Hence, they are easy to obtain and assess for an ungauged catchment.

When assessing the transferability of a catchment's parameter sets, it was observed that the catchments with low sensitivity performed well when receiving parameter sets from another catchment. However, one of the insensitive catchment was not able to receive parameters from one of the catchments with best performance. A possible explanation for this is the different seasons the runoff data was extracted from.

By comparing the physical characteristics of the four catchments with the transferability, the applicability of the methodology was assessed. This showed that the number of residents and the length to outlet were the two characteristics affecting the transferability of a catchment the most.

The study revealed that the presented technique has a promising potential to resolve the challenges in modelling ungauged urban catchments. However, further investigation is recommended to address the shortcomings uncovered.

5. Acknowledgements

The present study was made possible by the BINGO project - *Bringing INovation to onGOing water management – a better future under climate change* (projectbingo.eu) and by Klima 2050, Centre for Research-based Innovation (klima2050.no).

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Appendix A – Framework for Article

Guidelines for Full Paper for Embrace the Water 2017

Deadline for full paper is April 30.

Full papers should be maximum 10 pages (including diagrams, tables and pictures) and preferably written in English. The full paper should contain:

- Title, author name(s), full postal addresses for each author
- Abstract
- Keywords
- Main text: Introduction, Methods, Results and Discussion Conclusions
- References

Example:

Name of paper (Arial 14 pt bold)

Name of author*, Name of author 2 ** (10 pt Arial)

* Name, Adress, Institution/Organisation, email adress
(Contact information for author 1)

** Contact information for author 2

Abstract. Here you are to write the abstract in English. The abstract shall be ½ - 1 page. You can write two; one in English and one in one of the Scandinavian languages (Norwegian, Danish or Swedish), but one has to be English. (9 pt Arial)

Keywords: 3-6 keywords (9 pt Arial)

Headings 1 (Arial 12 pt bold)

Here the main text starts and it shall be in – 10 pt Times New Roman. Length of text, with figures and tables, are to be maximum 10 pages for full paper. Please do not use any pagination in the document. Maximum document size is 5 Mb. The paper has to be in one of the Scandinavian languages (Danish, Norwegian or Swedish) or in English, at your convenience. All the papers together with abstracts will be published in a digital media that will be delivered to the participants at the start of the conference.

Heading 2 (Arial 10 pt bold)

Heading 3 (Arial 10 pt italic)

Table 1 Table text shall be above the table (9 pt Arial)

Figure 1 Figure text shall be below the figure (9 pt Arial)

References (Arial 12 pt bold)

Here is shown model for references (9 pt Times New Roman).

Andrews, J.F. (1993). Modeling and simulation of wastewater treatment processes. *Wat. Sci. Tech.* **28**(11/12), 141–150.

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Guidelines for Full Paper for peer review for IWA Journals

NOTE! If you want to submit your full paper for peer review for possible selection to an appropriate IWA Journal followed by publication, the full paper will have to follow the instructions from IWA Publishing. For more information go to: www.iwaponline.com/i2a.htm

The two possible IWA Journals are Water Science & Technology and Water Practice & Technology. When submitting your paper please state which of the two journals you think is most appropriate.

In short, some of the instructions are noted here:

- Research Papers: The maximum acceptable length of a Research Paper is 5 000 words (350 words for each normal-sized figure or table you include). Please do not exceed this limit or your paper may be rejected.
- Preparation of the typescript
  - Text should be typed single-spaced on one side of the paper only. Do not exceed the dimensions given above. Please use a 12pt Times justified typeface. The main body text should be typed flush left with no indents. Insert one line space between paragraphs, and two line spaces between paper title, authors' names, and addresses on the first page.
  - The title of the paper, author's name(s), affiliation(s), author's full postal address(es) and e-mail, abstract and keywords should be clearly set out on the first page of the article.
  - If any figures or tables are not already fixed in their correct position in the text, insert a brief note specifying which figure should be placed there.
- Content

Papers should be well structured: i.e. they must comprise:

(1) Title, author name(s), full postal addresses for each author. Include the e-mail address for the corresponding author only.
(2) Abstract: No more than 200 words briefly specifying the aims of the work, the main results obtained, and the conclusions drawn.
(3) Keywords: 3-6 keywords (in alphabetical order) which will enable subsequent abstracting or information retrieval systems to locate the paper.
(4) Main text: For clarity this should be subdivided into:
(i) Introduction - describing the background of the work and its aims.

(ii) Methods - a brief description of the methods/techniques used (the principles of these methods should not be described if readers can be directed to easily accessible references or standard texts).

(iii) Results and Discussion - a clear presentation of experimental results obtained, highlighting any trends or points of interest.

Do not number or letter section headings.

(5) Conclusions: A brief explanation of the significance and implications of the work reported.

(6) References: These should be to accessible sources. Please ensure that all work cited in the text is included in the reference list, and that the dates and authors given in the text match those in the reference list. References must always be given in sufficient detail for the reader to locate the work cited (see below for formats). Note that your paper is at risk of rejection if there are too few (<10) or too many (>25) references, or if a disproportionate share of the references cited are your own.

Please see: www.iwaponline.com/i2a.htm for the full instructions!

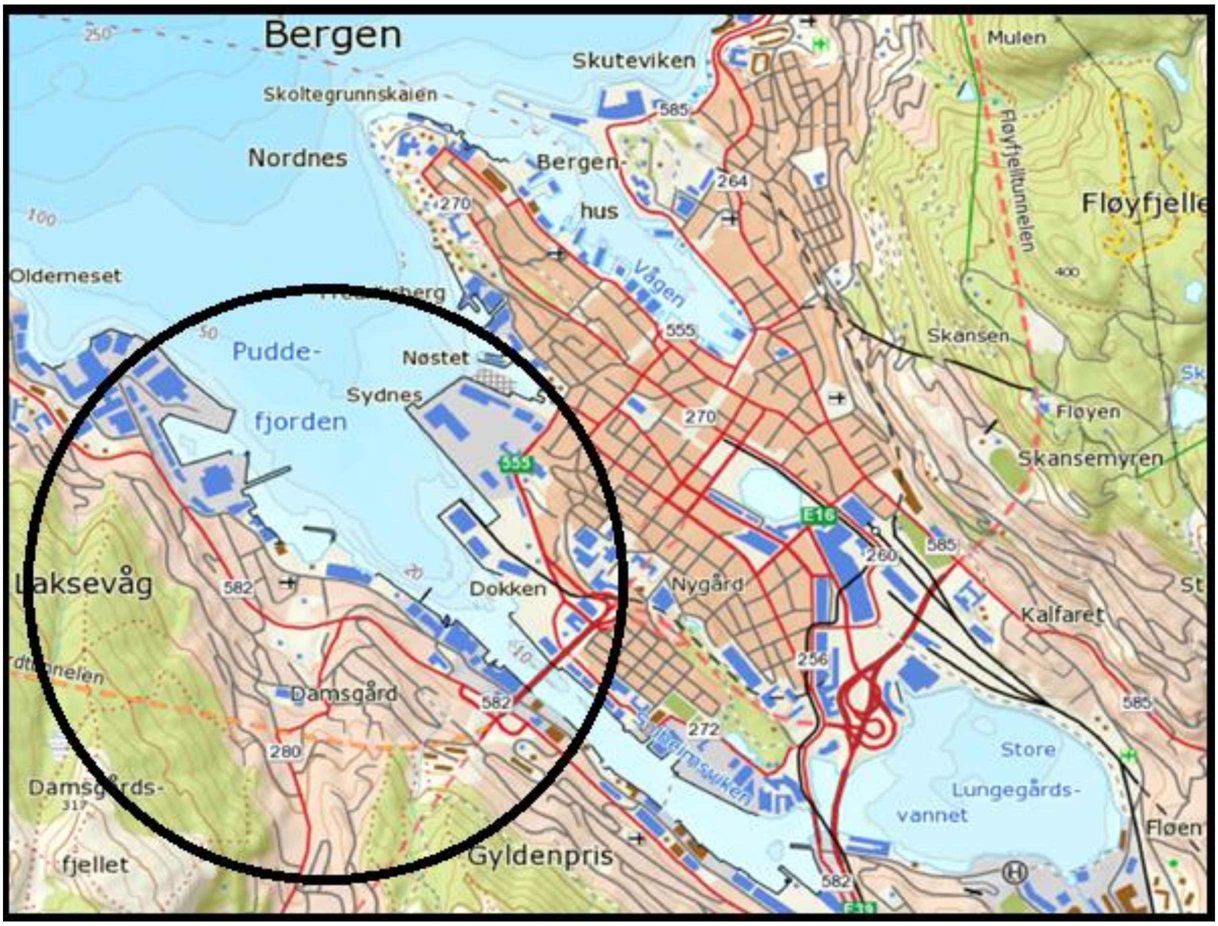
Appendix B – Poster

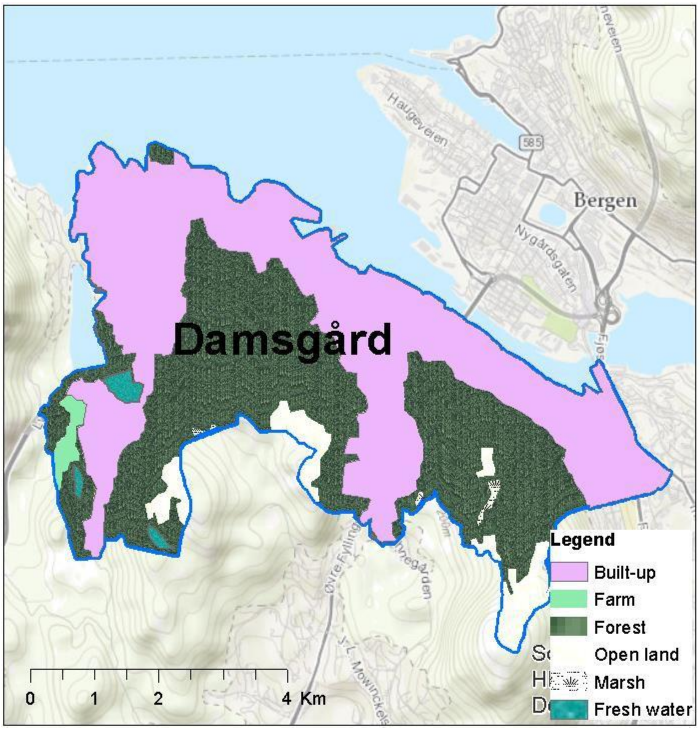
A poster was made to present the thesis at the *Embrace the Water 2017* conference in Gothenburg, Sweden. Due to the size of the original poster (A0) a QR-code has been generated to easily access the poster. It is also possible to access the poster through:

https://static1.squarespace.com/static/54ff1c6be4b0331c79072679/t/59315f27725e25becb0fc532/1496407854589/Mittet_RegionalisationUrbanCatchment.pdf

Appendix C – Study Site

The study site in Damsgård, Bergen, Norway.





Appendix D – Script

```
rm(list=ls())

library(zoo)
require(rgdal)
library(hydroGOF)
library(hydromad)
require(raster)
# install.packages("hydromad",
repos="http://hydromad.catchment.org")

setwd("C:/Users/jonassta/Documents/BINGO_SWMM")

a.stn <-
c("SSBMV","SSBRO","SSDAM","SSKONOW","SSKROHN","SSLILLED","SSTO
SCANA") #- data available

## Function for converting a set of lines into a table
CovTable <- function(it_l, rf) {
  i.spr <- unlist(strsplit(ot.swm[-rf+it_l[1]], ""))
  p.spr <- subset(1:length(i.spr), i.spr==" ")
  p.be <- rbind(c(1, 1+p.spr), c(p.spr, length(i.spr)))
  d.df <- matrix(" ", ncol=ncol(p.be), nrow=length(it_l))
  for(j in 1:nrow(d.df)) {
    dmmm <- unlist(strsplit(ot.swm[it_l[j]],""))
    for(v in 1:ncol(d.df)) {
      dmm2 <- dmmm[p.be[1,v]:p.be[2,v]]
      v.va <- dmm2[dmm2!=" "]
      if(all(!is.na(v.va)))
        d.df[j,v] <- noquote(paste(v.va, sep="", collapse=""))
    }
  }
  return(list(d.df, p.be))
}

## Function for extracting indexes for different entries
indexEXT <- function(entry) {
  i.dummy <- match(entry, ot.swm)
  l.blnky <- subset(1:length(ot.swm), ot.swm=="")
  i.dummy <- c(I(3+i.dummy):I(-1+l.blnky[l.blnky>i.dummy][1]))
  return(i.dummy)
}

## Function for calibrating the sewer model (SWMM)
CSModel <- function(thet) {
  write.table(thet, "param.txt", col.names = F, row.names = F)
  ## Function for converting tables into .inp file format
  FillLine <- function(r, t.dat) {
    dummy2 <- rep(" ", t.dat[[2]][nrow(t.dat[[2]]),
ncol(t.dat[[2]])])
```

```
    f.inf <- t.dat[[1]][r,]
    for(i.tm in 1:length(f.inf)) {
      i.rpm <- unlist(strsplit(f.inf[i.tm], ""))
      if(length(i.rpm)!=0) {
        l.rpm <- min(length(i.rpm),
length(t.dat[[2]][1,i.tm]:t.dat[[2]][2,i.tm]))
        dummy2[t.dat[[2]][1,i.tm]:I(t.dat[[2]][1,i.tm]+l.rpm-
1)] <- i.rpm[1:l.rpm]
      }
      if(length(i.rpm)==0)
        dummy2[t.dat[[2]][1,i.tm]:t.dat[[2]][2,i.tm]] <-
rep(f.inf[i.tm],length(t.dat[[2]][1,i.tm]:t.dat[[2]][2,i.tm]))
    }
    dummy2 <- paste(dummy2, sep=" ", collapse="")
    return(dummy2)
  }

  ## 1. Assign variables: parameter values
  W_sc <-
round((thet[1]*(i.sc$Tot_A*10000/i.sc$Leng)^thet[2]), 1)
# Width
  W_sc <- as.character(ifelse(W_sc>=1000, floor(W_sc), W_sc))
  ds_i <- round((thet[3]*(i.sc$Slp/i.sc$Leng)^(-thet[4])), 3)
# depression storage: impervious
  ds_p <- round((thet[9]*thet[3]*(i.sc$Slp/i.sc$Leng)^(-
thet[4])), 3)    # depression storage: pervious
  Mn_R <- round(thet[5], 3)
  Mx_R <- round((Mn_R+thet[6]), 3)
  Dcay <- round(thet[7], 3)
  Dr_T <- round(thet[8], 3)

  Ef_P <- format(round((thet[10]*P_ins$Value), 2),
scientific=F)        # Effective precipitation
  write.table(rbind(";; Rainfall data",";; staID YYYY MM dd HH
MM Value"),

"C:/Users/jonassta/Documents/BINGO_SWMM/Data/Precip/P_Florida.
dat", col.names=F, row.names=F, quote=F)
  write.table(data.frame(staID=P_ins$staID, YYYY=P_ins$YYYY,
mm=P_ins$mm, dd=P_ins$dd, P_ins$HH, MM=P_ins$MM, Prec=Ef_P),

"C:/Users/jonassta/Documents/BINGO_SWMM/Data/Precip/P_Florida.
dat", col.names=F, row.names=F, append=T, quote=F)

  ## Formerly - Constant Paramerers
  Pr_im <-
round((thet[12]+(thet[13]*((i.sc$Bld_A+i.sc$Rod_A)/i.sc$Tot_A)
^thet[14])),2) # % Impervious
  Pr_im <-
ifelse(((i.sc$Bld_A+i.sc$Rod_A)/i.sc$Tot_A)==0,0,Pr_im)
```

```
  Pr_im_ <- as.character(ifelse(Pr_im>=1000, floor(Pr_im),
Pr_im))

  ## 2. Edit the input file
  ## "[SUBCATCHMENTS]"
  i.SCA <- indexEXT(entry="[SUBCATCHMENTS]")         ## Index
"[SUBCATCHMENTS]" entry lines
  t.SCA  <- CovTable(it_l=i.SCA , rf=1)
  t.SCA[[1]][,6] <- W_sc
  t.SCA[[1]][,5] <- Pr_im_
  for(i in 1:nrow(t.SCA[[1]]))
    ot.swm[i.SCA[i]] <- FillLine(r=i, t.dat=t.SCA)

  ## "[SUBAREAS]"
  i.SBA <- indexEXT(entry="[SUBAREAS]")         ## Index
"[SUBAREAS]" entry lines
  t.SBA <- CovTable(it_l=i.SBA, rf=1)

  t.SBA[[1]][,2:6] <- cbind(format(Mn_ip, scientific=F),
                            format(Mn_pr, scientific=F),
                            format(ds_i, scientific=F),
                            format(ds_p, scientific=F),

format(round(Pr_im*(i.sc$Bld_A/i.sc$Tot_A),1), scientific=F))
  for(i in 1:nrow(t.SBA[[1]]))
    ot.swm[i.SBA[i]] <- FillLine(r=i, t.dat=t.SBA)

  ## "[INFILTRATION]"
  i.INF <- indexEXT(entry="[INFILTRATION]")         ## Index
"[INFILTRATION]" entry lines
  t.INF <- CovTable(it_l=i.INF, rf=1)

  t.INF[[1]][,2:6] <- cbind(format(rep(Mx_R, length(i.INF),
scientific=F)),
                            format(rep(Mn_R, length(i.INF)),
scientific=F),
                            format(rep(Dcay, length(i.INF)),
scientific=F),
                            format(rep(Dr_T, length(i.INF)),
scientific=F),

format(rep(0,length(i.INF)),scientific=F))
  for(i in 1:nrow(t.INF[[1]]))
    ot.swm[i.INF[i]] <- FillLine(r=i, t.dat=t.INF)

  writeLines(ot.swm, con=paste("Temp/", stn,"_AF.inp",
sep=""))

  ## 3. Run the SWMM model: excute the .bat file
  system(paste("swmm_",stn,".bat", sep=""))
```

```
  ## 4. Evaluate simulation vs observation
  m.out <- readLines(paste("Temp/swmm_", stn,".rpt", sep=""), warn=F)
  c.end <- subset(1:length(m.out), m.out=="  ")
  b.sim <- as.numeric(5+match(paste("  <<< Node ", n_stn, " >>>", sep=""), m.out))
  e.sim <- as.numeric(I(-1+(c.end[c.end>b.sim][1])))
  m.out <- noquote(m.out[b.sim:e.sim])
  t_sim <- unlist(lapply(m.out, substr, 3, 22))
  #s.sim <- as.numeric(unlist(lapply(m.out, substr, 29, 33)))
  s.sim <- rep(thet[11],length(t_sim))+as.numeric(unlist(lapply(m.out, substr, 29, 33)))
  c.set <- match(t.rec, t_sim)     ## Calibration set
  e.NSE <- round(NSE(s.sim[c.set], h.rec),3)
  e.SSR <- round(ssq(s.sim[c.set], h.rec),3)
  #plot(h.rec[1:length(c.set)], ylim=range(h.rec[1:length(c.set)],s.sim[c.set]), type='l')
  #lines(s.sim[c.set], col=2)
  #lines(s.sim[c.set], col=3, lty=3)
  #legend("top", legend=c(e.NSE,e.NSE), bg="white", ncol=1)
  w.fle <- rbind(c(e.NSE, e.SSR, thet))
  #w.fle <- rbind(c(e.NSE, e.SSR, gwf, dwf, rdq, rdm, pfr))
  write.table(w.fle, paste("Cal_",stn,"_CS_model.txt",sep=""), sep="\t", quote=F, append=T, col.names=F, row.names=F)

  out <- e.NSE

  return(out)
}

for(s in 3:length(a.stn)) {
  stn <- a.stn[s]      #"SSBMV"
  ot.swm <- readLines(con=paste("InpFiles/", stn,"_AF.inp", sep=""))                                ## Read the reference input file
  s.ct <- readOGR(dsn="Data/SubCatch_system", layer=paste(stn,"_catch", sep=""), drop_unsupported_fields=T)
## Catchment

  a.MnHl <- readOGR(dsn="Data/GIS", layer="Manhole", drop_unsupported_fields=T)                             ## All manholes
  s.link <- readOGR(dsn="Data/GIS", layer="Pipe", drop_unsupported_fields=T)                               ## link/pipes - Damsgaard
  d.slpP <- raster("Data/GIS/Slpe_DamsgÃ¥rd")
## Slope calc.: a 10 m resolution raster
  L.covr <- raster("Data/GIS/lu_rasterpj")
## LUse LCover.: a 10 m resolution raster 10-BuilUp, 20-Farm, 30-Forest
```

```
  i.sc <- data.frame(ID=as.character(s.ct$ID),
Tot_A=as.numeric(s.ct$TOTAL_AREA),
Rod_A=as.numeric(s.ct$ROAD_AREA),
                     Bld_A=as.numeric(s.ct$BUILD_AREA),
Pop=as.numeric(s.ct$PERSON))

  sl_p <- extract(d.slpP, s.ct)
  L_cov <- extract(L.covr, s.ct)
  i.sc$Slp <- i.sc$Leng <- i.sc$Forst <- i.sc$Grass <-NA
  for(sc in 1:nrow(s.ct)) {
    i.sc$Slp[sc] <- as.numeric(quantile(sl_p[[sc]], p=0.5))
    xy.xy <- s.ct@polygons[[sc]]@Polygons[[1]]@coords
    yx.yx <-
as.numeric(a.MnHl[match(as.character(s.ct$ID)[sc],
as.character(a.MnHl$ID)),]@coords)
    i.sc$Leng[sc] <- mean((((xy.xy[,1]-
yx.yx[1])^2)+((xy.xy[,2]-yx.yx[2])^2))^0.5)
    dummy <-
c(length(L_cov[[sc]][(L_cov[[sc]]==10|L_cov[[sc]]==20)]),
length(L_cov[[sc]][(L_cov[[sc]]==30)]))
    i.sc$Grass[sc] <- (dummy[1]/sum(dummy))*(i.sc$Tot_A[sc]-
sum(i.sc$Rod_A[sc]+i.sc$Bld_A[sc]))
    i.sc$Forst[sc] <- (dummy[2]/sum(dummy))*(i.sc$Tot_A[sc]-
sum(i.sc$Rod_A[sc]+i.sc$Bld_A[sc]))
  }

  n_stn <-
unlist(strsplit(ot.swm[indexEXT(entry="[OUTFALLS]")], " "))[1]
## Node corresponding to gauging station

  ## Historic records
  h.rec <-
read.table(paste("Data/Flow/",stn,"_Vannforing.txt", sep=""),
header=T)
  t.frm <-
as.POSIXct(paste(h.rec[,1],h.rec[,2],h.rec[,3],h.rec[,4],h.rec
[,5],h.rec[,6], sep="-"),
                      format="%Y-%m-%d-%H-%M-%S", tz="UTC")
  t.rec <- toupper(format(t.frm, format="%b"))
  t.rec <- ifelse(t.rec=="OKT", "OCT", t.rec)
  t.rec <- ifelse(t.rec=="DES", "DEC", t.rec)
  t.rec <- ifelse(t.rec=="MAI", "MAY", t.rec)
  t.rec <- paste(paste(t.rec,format(t.frm,
format="%d-%Y"),sep="-"), format(t.frm, format="%H:%M:%S",
tz="UTC"))
  h.rec <- h.rec$Value

  ## Precipitation
```

```
load("C:/Users/jonassta/Documents/BINGO_SWMM/Data/Precip/P_ins
t.RDat")     # P_ins

  ## Simulation time steps
  t.sim <- as.POSIXct(c("2004-01-01 00:00:00", "2005-12-31
23:55:00"),format="%Y-%m-%d %H:%M:%S", tz="UTC")
  t.sim <- seq(t.sim[1], t.sim[2], 5*60)

  ## Constant Paramerers
  Mn_ip <-
round(((i.sc$Bld_A/65)+(i.sc$Rod_A/68))/apply(i.sc[,3:4], 1,
sum), 6)    #Mannings for impervious
  Mn_pr <-
round(((i.sc$Forst/20)+(i.sc$Grass/25))/apply(i.sc[,6:7], 1,
sum), 6)    #Mannings for pervious
  #Pr_im <- round(100*(i.sc$Bld_A/i.sc$Tot_A))
#Percentage impervious
  Mn_ip <- ifelse(!is.nan(Mn_ip), Mn_ip, 1)
  Mn_pr <- ifelse(!is.nan(Mn_pr), Mn_pr, 1)

  ## Initial, lower and upper parameter values
  p.int <- c(1, 1,
             1, 1,
             3, 0.5,  50, 100,1,
             0.6, 0.006,  0,   1,  1)
  p.lwr <- c(0, 0.001,
             0, 0,
             0, 0.1,   0,   0, 0,
             0.1,     0,  0,   0, -1)
  p.upr <- c(50, 2,
             5, 5,
             5,   5, 200, 200, 10,
             1,   0.1, 50, 50,  1)
    # write.table(rbind(c("NSE","SSR", paste("P",
1:length(p.int), sep=""))),
paste("Cal_",stn,"_CS_model.txt",sep=""),
  #             sep="\t", quote=F, append=F, col.names=F,
row.names=F)

  m.opt <- SCEoptim(FUN=CSModel, par=p.int, lower=p.lwr,
upper=p.upr, control=list(fnscale=-1))

  o.par <- m.opt$par
  # aaa__ <-
read.table(paste("Cal_",stn,"_CS_model.txt",sep=""), header=F)
  # aaa__[1] <- 18.3266169   #18.3266169
  #aaa__[2] <- 4   #8.4303822
  # aaa__ <- aaa__[order(aaa__[,1], decreasing = T),]
  #P.sim <- CSModel(thet=as.numeric(aaa__[1,-c(1:2)]))
  P.sim <- CSModel(thet=o.par)
```