IMPACT OF CLIMATE CHANGE ON URBAN DRAINAGE SYSTEM PERFORMANCE

by

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ABSTRACT

Statistical downscaling is used to generate synthetic point rainfall series suitable to be used for hydraulic analysis and design of urban drainage systems. Thereby, future changes of rainfall properties as predicted by regional climate models are transferred to fine temporal and spatial scales. We analyzed the impact of altered rainfall patterns as one major future driving force on the performance of one selected drainage system. We considered the main sources of uncertainties associated with (i) the short observation period with regard to rainfall extremes and (ii) the transfer of climate predictions to fine scales. The analysis reveals that the performance of urban drainage systems may vary significantly both under current and future climate conditions and that there is a clear tendency that system performance will deteriorate under future climate.

1 INTRODUCTION

High temporal resolution historical rain series commonly serve as model input for hydraulic models used for the design and performance assessment of existing and planned urban drainage systems. The need for high temporal resolution in rainfall is due to the rapid runoff response of urban catchments to variability in rainfall and hence their vulnerability with respect to flooding and combined sewer overflow (CSO) during high intensity rainfall.

There is concern that in the future rainfall patterns will substantially change the performance of drainage systems, requiring the implementation of adaptive measures. A wide range of global and regional climate models (GCMs, RCMs) predict changes in rainfall, but do not have the proper temporal and spatial resolution for urban drainage models. Methodologies as discussed in (Onof and Arnbjerg-Nielsen 2009) are available, and are aiming to describe changes in point rainfall properties at fine time scales based on changes at coarser scales as forecasted by RCMs.

Main objective of the study is to investigate the impact of future rainfall anticipated by different combinations of GCMs and RCMs on the hydraulic performance of a selected drainage system in Switzerland. Focus of these preliminary results is the effects of the input uncertainty, created by the downscaling of different RCM results, on the performance of a drainage system regarding urban flooding.

2 GENERATION AND ANAYSIS OF FUTURE RAINFALL SERIES

2.1 Model Approaches

The downscaling of rainfall predicted by RCMs involves different steps and methodologies. We used the Neyman-Scott Rectangular Pulse (NSRP) Model (Rodriguez-Iturbe et al. 1987; Cowpertwait 1991) for stochastic rainfall modelling and the parameterization as described in (Fatichi et al. 2011). The model is capable to generate rainfall series reproducing the statistical properties of observed rainfall intensities on an hourly scale. The rainfall generator is calibrated to a 30 years point rainfall series measured at a station in the proximity of the considered urban catchment in Switzerland.

Simple scaling of specific present rainfall properties as suggested by (Kilsby et al. 2007) is used to adapt the model parameters of the NSRP model according to the changes in rainfall statistics as predicted by RCMs. We used the results from 10 selected combinations of GCMs and RCMs provided by the ENSEMBLE project (van der Linden and Mitchell 2009) under the SRES A1B emission scenario

(Nakicenovic and Swart 2000) for the future reference period from 2036 until 2065. Thereby, we include the model structure uncertainty of different GCMs and RCMs.

Multiplicative random cascade models were used to disaggregate rainfall to higher resolution while preserving similar important characteristics of observed rainfall such as high resolution rainfall extremes as analysed by (Molnar and Burlando 2005). We used the random cascade model of canonical type as described by (Molnar and Burlando 2005). The model is trained to the observed 10 min rainfall data and applied to the rain series generated by the NRSP model.

2.2 Generated Rainfall Series

To capture the uncertainty due to the stochastic output from the rainfall and rainfall disaggregation model, we generated 100 realizations of 30 year rainfalls series with the NSRP model for the control period (1981-2010). Accordingly, 100 realizations for the future reference (2036-2065) were generated by the NSRP model with each of the 10 sets of parameters conditioned on the output from the ENSEMBLE model chains. In a second step, with each of the simulated rainfall series 100 realizations of 10 min rainfall series were generated by disaggregation. Thus, altogether respective 10 000 (control period) and 100 000 (future reference period) realizations of 30 year rainfall series with a temporal resolution of 10 min were generated to reflect the variability of rainfall extremes.

Since our focus is on urban flooding, preservation of rainfall extremes is of major importance. Figure 1 shows observed and simulated annual rainfall maxima for durations T= 1 h and T= 24 h of the control period. The simulated annual rainfall maxima are considerably underestimated on an hourly base in particular for large return periods. However, on a daily base rainfall extremes are well preserved in the simulated data. Thus, generated rainfall series aggregated to nearly a daily scale (1280 min) were used as input for the disaggregation model to be disaggregated to rainfall series with a temporal resolution of 10 min. (Disaggregation is attained by successive subdivision of rainfall from a coarse to a finer time scale where the finer scale corresponds to half of the coarser scale. The coarsest time scale is chosen to be 1280 min allowing for disaggregation in 7 subsequent steps.)

To analyse the performance of the random cascade model we used the calibrated model to disaggregate observed data aggregated to a 1280-min time resolution. In Figure 2, observed and simulated mean annual rainfall maxima of duration T are shown. The annual rainfall maxima H_T for different durations T are derived from the 10-min data and in case of the simulated data determined from 100 realizations. It is obvious that the model systematically overestimates annual rainfall depths for durations T>20 min.

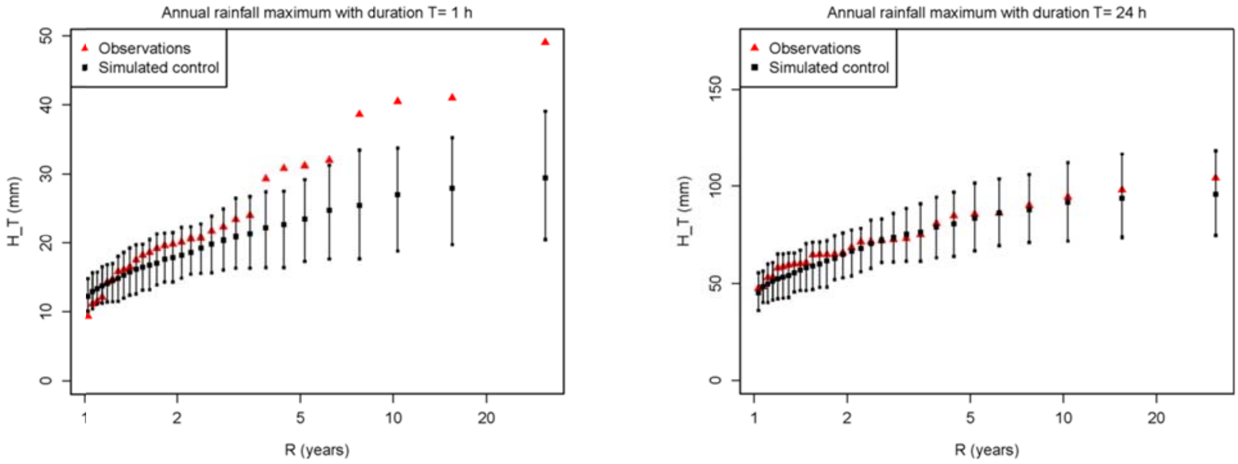

Figure 1. Observed and simulated annual maximum rainfall depths for duration T=1 h (left) and T=24 h (right) for different return periods R. Simulated rainfall extremes are given for the control period (1981-2010). The squared points give the mean rain depth over 100 realizations and the bars describe ranges corresponding to the 10 and 90 % quantiles.

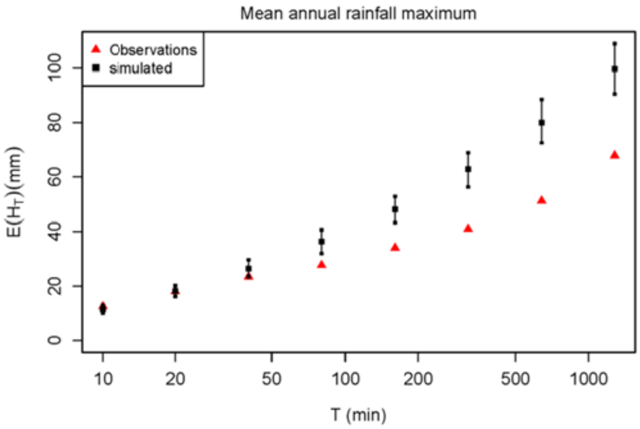

Figure 2. Observed and simulated mean annual rainfall maxima for different durations *T*. The squared dots give mean $E(H_T)$ over 100 model runs; bars give ranges corresponding to the 10 and 90 % quantiles.

Results of the combined model are shown by Figure 3 in terms of annual rainfall maxima with durations of *T*= 20 min and *T*= 1 h and compared with observed data. The results for the simulated future rainfall represent all 100 000 generations and hence the variability induced by the different outputs from the 10 ENSEMBLE model chains and the downscaling.

For rainfall durations *T*= 20 min (Figure 3, left), rainfall extremes are well preserved by the combined model for the control period. All observations are within the range of the simulated 10 and 90 % quantiles and distributed around the means. However, as one may expect from the results shown in Figure 2, a considerable bias is introduced by the disaggregation model for more extreme annual rainfall maxima and rain durations *T*> 20 min. This is reflected in Figure 3 (right) were results are given on an hourly scale.

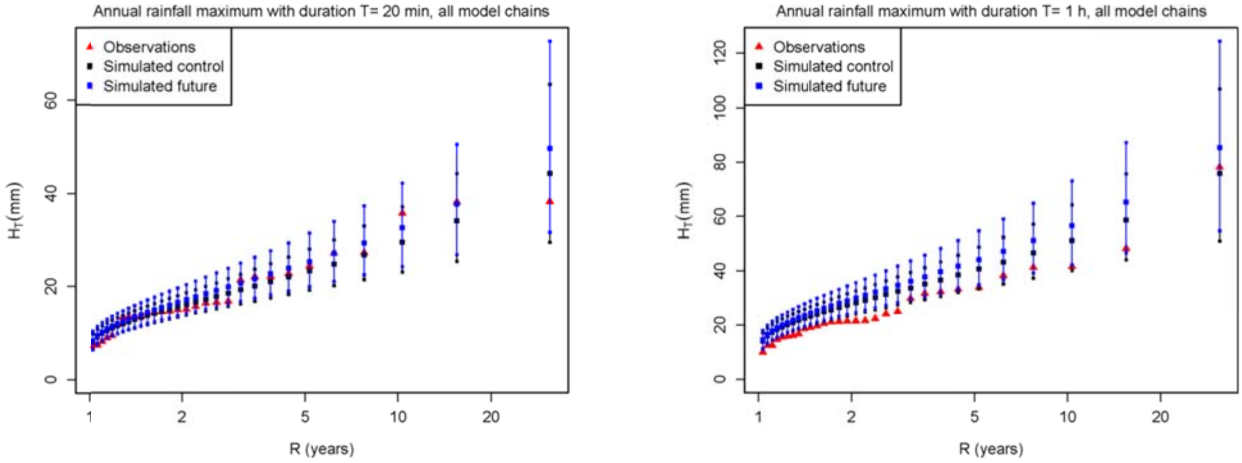

Figure 3. Observed and simulated annual maximum rainfall depths for duration *T*=20 min (left) and *T*=1 h (right) for different return periods *R*. Simulated rainfall extremes are given for both the control (1981-2010) and future reference period (2036-2065). Statistics of future rainfall is shown for output of the combined models using 10 different parameterizations of the rainfall generator according to the output of the 10 ENSEMBLE model chains. The squared points give the mean rain depth over 10 000 realizations for the control period and 100 000 realizations for the future reference period. The bars describe ranges corresponding to the 10 and 90 % quantiles.

3 IMPACT OF FUTURE CLIMATE ON SYSTEM PERFORMANCE

Both observed and simulated present and future rainfall series are used as model input of a hydrodynamic model (Rossman 2010) of the selected urban catchment. As common in current design practice of smaller urban drainage systems, point rainfall intensities are assumed to be spatially evenly distributed over the entire catchment area. We quantify system performance in terms of percentages of manholes at which the design criterion is not met over the simulated period of 30 years. The applied design criterion states that flooding of a manhole is accepted to occur at most once in 5 years.

Due to the high computational demand of the applied hydraulic model, only a limited amount of model runs have been conducted so far to obtain a first picture of the impact of climate change and prediction uncertainty of the hydraulic model due to uncertain model input. For this, we selected three 30 year rainfall series for both the control and future reference period with ‘high’, ‘medium’ and ‘low’ rainfall extremes. All annual rainfall maxima for return periods *R* between 4.4 and 15.5 years and durations *T* between 10 and 60 min of the selected series have values approximately equal to the 90, 50 and 10 % quantiles over all realizations of generated rainfall.

Figure 4 gives percentages of manholes at which the design criterion is not fulfilled. Results are shown for the cases of using (i) the observed and (ii) the selected simulated rainfall series as input to the hydraulic model. From the figure we conclude the following:

1. The percentage of manholes not meeting the requirements under observed rainfall is within the range obtained by using simulated rainfall from the control period but is below that obtained in the ‘medium’ scenario.
2. Prediction uncertainty is considerable in particular with respect to the future reference period. (The percentage of manholes not living up to the requirements varies between 1.3 and 7.4 % (control period) and 1.3 and 15.8 % (future reference period)).
3. The impact of climate change on system performance is the more pronounced the higher the quantiles of rainfall extremes represented by the selected rainfall series.

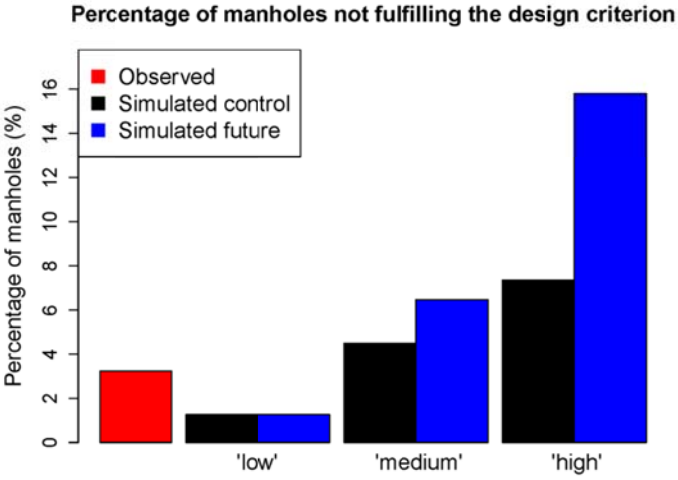

Figure 4. Percentages of manholes not meeting the design requirement in case of using (i) observed rainfall and (ii) simulated rainfall as input to the hydraulic model. Results from using simulated rainfall data are given for the control and future reference period as well as for three scenarios representing realizations of simulated rainfall series with ‘low’, ‘medium’ and ‘high’ rainfall extremes.

4 CONCLUSIONS

The NSRP model was used to generate continuous rainfall on an hourly base. However, rainfall extremes were preserved insufficiently on this scale. The generated rainfall series were thus aggregated to a nearly daily scale at which rainfall extremes were well reproduced. In order to improve the results of the combined model for rainfall generation and disaggregation, using output of the NSRP-model on different scales to be disaggregated to a 10-min scale could be tested.

The bias of the simple model used for disaggregation resulting in considerable overestimation of rainfall extremes with durations *T*> 20 min is unacceptable. Even in case of smaller sewer networks, rain events with durations *T*> 20 min may be critical with respect to urban flooding. Thus, the model used so far should be substituted by a more complex model. Using a multiplicative random cascade models of microcanonical type with cascade parameters dependent on time scale and rainfall intensity may be an appealing option. As reported by (Rupp et al. 2009), considering dependency on time scale and rainfall intensity in rainfall disaggregation improves the ability to reproduce many characteristics of rainfall.

Annual rainfall maxima calculated for the future reference period based on output from 10 ENSEMBLE model chains are shifted towards higher values compared to those of the control period. Furthermore, the uncertainty is increased in particular in case of large return periods.

Long-term planning of urban drainage infrastructure requires the consideration of future rainfall patterns as well as inherent uncertainties to assure a desired system performance. The need for considering uncertainties relies on the fact that the prediction uncertainty due to uncertain model input is considerable and on average approximately in the same order of magnitude as the importance of climate change. In the present paper, a first, mere qualitative assessment of uncertainty has been done. In order to assess the importance of climate change and input uncertainty thoroughly we suggest to perform Monte Carlo simulations based on a whole sample of simulated continuous historical rainfall series from both the control and future reference period. The analysis may be worth to be performed with different sewer networks as the vulnerability to increasing rainfall extremes likely differs between different systems. Furthermore, knowledge on the overall importance of climate change in the context of long term planning of sewer systems could be gained by setting climate change in relation to other future drivers as such triggered by population increase and economic growth.

5 RERERENCES

Onof, C. and Arnbjerg-Nielsen, K. (2009) Quantification of anticipated future changes in high resolution design rainfall for urban areas. Atmospheric Research 92(3), 350-363.

Cowpertwait, P.S.P. (1991) Further developments of the Neyman-Scott clustered point process for modeling rainfall. Water Resour. Res. 27(7), 1431-1438.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James, P., Smith, A. and Wilby, R.L. (2007) A daily weather generator for use in climate change studies. Environmental Modelling & Software 22(12), 1705-1719.

Molnar, P. and Burlando, P. (2005) Preservation of rainfall properties in stochastic disaggregation by a simple random cascade model. Atmospheric Research 77(1-4 SPEC. ISS.), 137-151.

van der Linden, P. and Mitchell, J.F.B. (eds.) (2009) ENSEMBLES: Climate Changes and its Impacts: Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK. 160pp.

Nakicenovic, N. and Swart, R. (2000) Special report on emissions scenarios. Intergovernmental Panel on Climate Change Working Group, Policy, Cambridge University Press, Cambridge, UK.

Rodriguez-Iturbe, I., Cox, D.R. and Isham, V. (1987) Some models of rainfall based on stochastic point processes., pp. 283-298, Proceedings of the Royal Society of London, Series A.

Fatichi, S., Ivanov, V.Y. and Caporali, E. (2011) AWE-GEN Advanced Weather Generator. Technical Reference, version 1.0.

Rossman, L.A. (2010) Storm Water Management Model, User's Manual, EPA, United States Environmental Protection Agency.

Rupp, D.E., Keim, R.F., Ossiander, M., Brugnach, M. and Selker, J.S. (2009) Time scale and intensity dependency in multiplicative cascades for temporal rainfall disaggregation. Water Resour. Res. 45(7), W07409.