Modeling climate change impacts on combined sewer overflow using synthetic precipitation time series

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ABSTRACT

In the presented study climate change impacts on combined sewer overflows (CSOs) in Baden-Württemberg, Southern Germany, were assessed based on continuous long-term rainfall–runoff simulations. As input data, synthetic rainfall time series were used. The applied precipitation generator NiedSim-Klima accounts for climate change effects on precipitation patterns. Time series for the past (1961–1990) and future (2041–2050) were generated for various locations. Comparing the simulated CSO activity of both periods we observe significantly higher overflow frequencies for the future. Changes in overflow volume and overflow duration depend on the type of overflow structure. Both values will increase at simple CSO structures that merely divide the flow, whereas they will decrease when the CSO structure is combined with a storage tank. However, there is a wide variation between the results of different precipitation time series (representative for different locations).

Key words | climate change, combined sewer overflow, rainfall generator

INTRODUCTION

In Southern Germany urban areas are mainly drained by combined sewer systems (CSSs). In such systems a substantial pollution load is discharged into the aquatic environment during overflow events at CSO structures (Welker 2004; Irmer 2006). As climate change leads to changes in precipitation patterns, effects on CSO activity are also expected. There are numerous research projects that deal with climate change effects on the frequency and the intensity of precipitation events (e.g. Fowler & Kilsby 2003; Huntington 2006; Kuo et al. 2011) and the impact on storm water runoff (e.g. Ashley et al. 2005; Grum et al. 2006; Semadeni-Davies et al. 2008; Schmitt & Scheid 2009).

For Central Europe the yearly sum of precipitation has significantly increased in the last decades and a shift in the seasonal cycle has been observed leading to more rain in winter and dryer summers (DGM 2007; Beck & Bárdossy 2010). Nevertheless, the observed trend signals are scale dependent. Even though the summer becomes drier the short-term rainfall intensities can increase due to stronger convection (Trenberth 1999).

The frequency of extreme precipitation events will increase. Stauffer et al. (2010) and Siekmann & Pinnekamp (2011) conclude that precipitation intensities will increase, meaning that a precipitation event that lasts 60 min and has a return period of 6 years today will have a return period of 3 years in the future.

The projects mentioned above deal mostly with extreme events. Less investigated are the climate change impacts on precipitation events with lower intensity and higher frequency (several times a year). In temperate climates these events are the main contributors to the yearly CSO volume. For the Hamburg (Germany) sewer system, Kuchenbecker et al. (2010) investigated climate change impacts on CSO characteristics. They conclude that there will be a significant climate-induced increase in the overflow volume of approximately 50% until 2100, based upon the reference year 2000.

The study presented in this paper aims to assess future changes in CSO activity for the area of Baden-Wuerttemberg, Southern Germany. This is done by comparing the output of long-term urban drainage simulations of the past and future. The precipitation data are generated by the stochastic precipitation generator NiedSim-Klima (Beck & Bárdossy 2010).
METHODOLOGY

NiedSim-Klima

NiedSim-Klima is based on the stochastic precipitation simulator NiedSim that is able to generate precipitation time series in a high temporal resolution from 1958 until 2003 for any location in Baden-Wuerttemberg, Germany (Bárdossy 1998; Bárdossy et al. 2000). For NiedSim-Klima it has been modified to account for climate change. The methodology is described in Beck (2013) and Beck & Bárdossy (2010).

NiedSim-Klima does not use precipitation data from climate models. Instead, it uses forecasts of air pressure at sea level and mean air temperature of the model ECHAM5 for an indirect estimation. Based on mean sea-level pressure fields, a classification of atmospheric circulation pattern (CP) is done. The empirical precipitation distribution for each CP is calculated based on historical observations. Assuming the precipitation distribution for each CP stays the same in the future, the precipitation probability and the probability of intensive precipitation (>1 mm/h) can be calculated.

Many CPs have a low precipitation probability for high mean air temperature but at the same time a high probability for intensive precipitation. Therefore, the CP classes are subdivided according to the mean temperature.

The CP-classification is used for the time-series generation in the following way. Using the predicted mean sea-level pressure fields and the predicted temperature from the climate model, a time series of the CP–temperature combination is created. According to the CP–temperature class, the precipitation probability and the probability of intensive precipitation are estimated for every day. Based on these probabilities, rainfall values are drawn for every hour. The hourly precipitation values between 0 and 1 mm/h are drawn from a Beta-distribution and the values above 1 mm/h from a Weibull-distribution.

The precipitation time series created in this way is optimized using additional historical parameters such as the autocorrelation on different aggregations (e.g. daily sums) and with different time-lags. One other important characteristic is called ‘scaling’. It is expressed in the dependence of the mean, standard deviation and skewness of rainfall sums on the summation interval (5–1,440 min). It could be shown from precipitation observations that there is a tendency towards higher intensities in shorter intervals. The fraction of the daily precipitation sum that falls within a shorter time interval (e.g. 1 h) is increasing and thus the scaling properties are about to change. It is assumed that this change will continue in the future (Beck & Bárdossy 2010). It is, therefore, considered in the optimization of the synthetic precipitation time series.

Precipitation time series at seven locations (labeled with the numbers 2–8 in the figures) in Baden-Wuerttemberg have been generated for the time periods 1961–1990 (NSK1990) and 2041–2050 (NSK2050). They lie in regions with different hydrological patterns (yearly sum of precipitation ranges from 630 to 1,051 mm/yr) and at different altitudes (between 112 and 847 metres above sea level). The locations correspond to physical stations where measured precipitation time series are available in 5 min resolution for at least 10 years with only short data gaps.

Urban drainage model and model parameters

Using the generated precipitation, long-term simulations have been executed to determine possible changes in the overflow characteristic due to climate change. For the simulations a standardized virtual CSS was used as can be seen in Figure 1. This system is designed as a standard network for comparative simulation studies in Germany and was used in several previous studies (Leinweber 2002; Welker 2004). In order to have comparable results this CSS was used for all stations.

The catchment represents a provincial town with 9,900 residents, two industrial polluters, and a total impervious area (A1tot) of 102.5 ha.

There are two CSO structures, where the continuation flow is limited to 14.4 l/(s·haAi) (R10) and 12.1 l/(s·haAi) (R20). Excessive flows are directly discharged to the receiving water. The CSO tanks B10 and B20 limit the flow to 1.23 l/(s·haAi). When this flow rate is exceeded, runoff is retained in the storage tank for subsequent treatment in the wastewater treatment plant. An overflow occurs when the tanks are full. Tank volume was calculated according to German technical standards (ATV-A 128E 1992). The volume was adjusted to the local annual precipitation generated for the past. This resulted in an area specific volume between 9.9 and 18.7 m³/haAi.

The long-term simulation has been conducted with the hydrological software KOSIM (Harms & Kenter 1987). Sub-catchments are represented by a linear reservoir cascade (τ = 3, k = calculated using an overland flow time of 4 min). Flow routing is based on the Kalinin–Miljukov method. CSOs are modeled as flow dividers with no storage.
RESULTS AND DISCUSSION

Comparison of measured and synthetic precipitation data

The synthetic precipitation data for the past (reference time period) have been compared with measured precipitation data at stations 2–8. As can be seen in Figure 2 the generated precipitation exceeds the measured precipitation by approximately 15%.

To analyze deviations on smaller time scales the rainfall time series were aggregated to hourly and daily mean intensities and relative frequencies of intensities were calculated. To count as a wet aggregation interval a threshold of 0.1 mm/60 min and 1 mm/1,440 min has been applied.

Figure 2 shows for stations 2–8 the differences in relative frequencies of measured and synthetic data for the aggregation interval of 60 min (class width: 0.2 mm/60 min, x-axis shows the upper class boundary value). At all stations the frequency of low intensities (<0.7 mm/60 min) seems to be overestimated by the rainfall generator.

Yet, deviations between generated and measured data are not necessarily only due to the precipitation generation algorithm. One source of the deviations is the missing values in the measured time series.

Climate change impacts on precipitation characteristics

Comparing synthetic rainfall for the past and the future at all stations, only slight changes in the annual precipitation, with no definite trend, are visible (see Figure 1). Again changes are more pronounced on smaller time scales.

Figure 4 shows changes in the relative frequency of hourly and daily mean precipitation intensities between rainfall generated for the past (NSK 1990) and for the future (NSK 2050) for stations 2–8. As can be seen in Figure 4 (left), the change in the frequency distribution for the aggregation interval of 60 min is more pronounced. For intensities <0.7 mm/60 min there is a decrease of up...
to 12% until 2050. For intensities >0.7 mm/60 min there is a small increase of approximately 2%. For the aggregation interval of 1,440 min the changes are different (see Figure 4, right). There is a decrease of up to 30% for the lower intensities (<3 mm/1,440 min) and an increase of up to 25% for intensities between 3 and 11 mm/1,440 min.

Figure 5 shows the dependence of the rainfall sum (in 5–1,440 min) on the summation interval (1,440 min). For most stations the daily precipitation will fall in a shorter time (except for the two stations 6 and 7). In 1961–1990 the daily precipitation that fell in less than 180 min was approximately 40–60%. Until 2050 this will increase to 55–95% (a change of up to 45%) depending on the observed location.

From Figure 4 and Figure 5 it can be seen that there are great differences between the stations but the general direction of the trend is consistent. A greater proportion of the precipitation will fall in a shorter time and with higher intensities. The projections are not sufficiently accurate to predict the development of a specific point. Yet, in sum, the data indicate the range of possible developments.

**Climate change impacts of overflow characteristics**

The synthetic precipitation time series were used to determine the CSO activity of the standardized CSS by long-term simulations. The most important results are summarized in Table 1 showing the differences (minimum, median, maximum) in the parameters (i) inflow volume ($V_{in}$), (ii) overflow volume ($V_{over}$), (iii) overflow frequency ($n_{over}$), and (iv) overflow duration ($t_{over}$) between NSK1990 and NSK2050. Overflow frequency is defined by the German regulation as calendar days with at least one overflow event.

As can be seen in Table 1 the inflow volume into the CSO structures decreases by 0–4% until NSK2050, while the annual rainfall increases slightly (see Figure 2). This can be explained by the shift of precipitation to shorter and more events. This leads to increasing losses by evaporation and infiltration. Therefore, there will be less surface runoff flowing into the CSS.

Even though the inflow volume changes only slightly, the changes in overflow characteristics are significant. In the past (NSK1990), 75–80% of the total overflow volume is emitted via the CSO tanks (CSOT 10 and 20). Until 2050 this volume will decrease significantly. Even more pronounced is the reduction of overflow durations (from 50–140 h/a in NSK1990 to values of 40–100 h/a in NSK2050).

In contrast to volume and duration, the frequency of overflow events increases drastically at both CSO tanks for all but station 6. For half of the stations the frequency increases by more than 100% until NSK2050.

At CSO structures without storage the overflow frequency increases in a similar magnitude. In contrast to CSO tanks, the overflow volume of the CSOs increases...
until 2050 (median: 9% for CSO 10 and 8% for CSO 30). The overflow duration changes between –4 and 9%.

To explain the changes in event-specific overflow patterns, Figure 6 shows the difference in the cumulative, normalized (based on the overflow volume in NSK1990) frequency distribution of the overflow volume for CSOT 10 between NSK1990 and NSK2050 for stations 2–8. All stations, except station 6, show a very similar behavior varying in magnitude and shape. For station 8, for example, it is apparent that small overflow events (<1,500 m³) increase and the rest decrease. In NSK2050 approximately 60% of the total overflow volume is made up of overflow events <1,500 m³ whereas in NSK1990 it was only approximately 45%. Further, it can be seen that the total overflow volume will drop up to 30% based on the overflow volume in NSK1990.

The changes in the overflow duration are very similar. In NSK2050 there is an increase of up to 30% in short overflow events (1–2 h) and a decrease of the same magnitude for longer events.

In summary, the total annual overflow volume will decrease and be made up of a greater proportion of shorter overflow events with smaller overflow volumes. This is due to an increase in short, intensive precipitation events and the fact that the daily precipitation will fall in a shorter time. These short precipitation events with high intensities can be retained in the CSO tanks leading to a decrease in the overflow volume. As CSOs do not have storage allocated in the model, the continuation flow of the CSOs is exceeded more frequently, which leads to an immediate overflow.

### SOURCES OF UNCERTAINTY

For a complete uncertainty analysis the variability of the whole forecast chain has to be analyzed, from the global circulation model (GCM) to the sewage model KOSIM. Such an analysis could be conducted for example by a Monte-Carlo type approach (Fu et al. 2011) or in a Bayesian framework. Since it would go beyond the scope of this study, the uncertainty estimation will be limited to qualitative considerations.

#### Estimation of future climate conditions

This study relies on the prediction of future climate conditions, which is associated with a high number of sources of uncertainty. Due to the coarse spatial and temporal resolution, GCMs cannot represent all characteristics of precipitation. Convective precipitation events, which are important for this study because they provoke the highest short-term intensities, are only modeled by conceptual parameters. Therefore, future precipitation is estimated indirectly by combining the GCM data with other sources of information.

This study uses the results of only one GCM. However, model intercomparison reveals that there is significant variability between the predictions of different GCMs (Aiguo 2006). In a recent study, Deser et al. (2012) state that the internal variability of repeated runs of the same GCM is of a comparable range, as are the differences between the models. So, even if one restricts a study to the use of one single scenario, several different GCM runs would be required, which, in general, are not available.

All those facts would suggest little trust in the presented results. However, the main trend signals are supported by other findings. A shortcoming of the applied ECHAM5 is that it cannot reproduce the CP sequence very well. The predicted change, however, towards more high-pressure CPs in

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### Table 1 | Minimum, median, and maximum of the changes between NSK1990 and NSK2050 in inflow volume ($V_{in}$), overflow volume ($V_{over}$), overflow frequency ($n_{over}$), and overflow duration ($t_{over}$) for all investigated locations

<table>
<thead>
<tr>
<th>NSK1990 to NSK2050 [%]</th>
<th>$V_{in}$</th>
<th>$V_{over}$</th>
<th>$n_{over}$</th>
<th>$t_{over}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSOT 10</td>
<td>Min</td>
<td>–3</td>
<td>–26</td>
<td>–1</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>–1</td>
<td>–17</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0</td>
<td>–1</td>
<td>216</td>
</tr>
<tr>
<td>CSOT 20</td>
<td>Min</td>
<td>–3</td>
<td>–16</td>
<td>–2</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>–1</td>
<td>–11</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0</td>
<td>–1</td>
<td>240</td>
</tr>
<tr>
<td>CSO 10</td>
<td>Min</td>
<td>–5</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>–1</td>
<td>9</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0</td>
<td>27</td>
<td>283</td>
</tr>
<tr>
<td>CSO 30</td>
<td>Min</td>
<td>–4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>–1</td>
<td>8</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0</td>
<td>25</td>
<td>269</td>
</tr>
</tbody>
</table>
summer time, is confirmed by observed time series of sea-level pressure fields (Beck 2013). Moreover, even if the GCMs vary considerably in terms of precipitation prediction, they all agree on rising daily mean temperatures. The temperature sensitivity of precipitation, leading to shorter but more intensive precipitation events, is supported by trends in observed time series (Lenderink & van Meijgaard 2008; Beck 2013), regional climate models (Lenderink & van Meijgaard 2008), as well as physical considerations (Trenberth 1999). Therefore, the trend towards shorter and more intensive precipitation events can be considered reliable.

The effects of climate change on precipitation patterns are spatially heterogeneous for Baden-Wuerttemberg, Germany (36,000 km²), and show great deviations. The difference between the results of the seven modeled locations reflects the high variability in the expected trend signals. Nevertheless, the changes have the same general direction.

**Estimation of the sewage system response**

In this study a virtual CSS has been used with set parameters. So from this perspective there are no uncertainties associated with the model parameters. Nevertheless, in real systems the boundary conditions and model parameters are not always known, are only estimations, or there are uncertainties associated when measuring them (e.g. impermeable area, runoff coefficients). A sensitivity analysis in this study revealed, for example, that a 20% change of the impermeable area resulted in a change of the mean annual overflow volume of the same magnitude as the change induced by climate change.

KOSIM is a hydrological model assuming linear flow conditions. Thus retention in the CSS is underestimated and overflow from overflow structures is overestimated. As the virtual CSS used in this study has an average slope, the influence of the linear flow conditions is not as relevant, as it would be in gently sloped CSS. Further, in this study relative comparisons of the overflow pattern between the past and future are of interest, instead of absolute values. Therefore, the model uncertainties are of a lesser relevance, assuming they apply to the past and future in the same way.

Considering the possibility of underestimating the variability of precipitation events (intensity, duration, and sequence) as well as the uncertainties associated with the hydrological model and the model parameters, it is possible that the found trend in overflow pattern might be different for real CSSs. Nevertheless, as the precipitation trend signals seem reliable it can be concluded that the found trends in overflow pattern are likely trends for CSSs in Baden-Wuerttemberg.

**CONCLUSIONS AND OUTLOOK**

The study presented assessed future changes in CSO activity for the area of Baden-Wuerttemberg, Southern Germany. This has been done by comparing the output of long-term urban drainage simulations of the past and future.

It was found that for CSO tanks there will be less overflow volume, even though the annual precipitation does not change very much, but an increase in the frequency of overflow events. For CSOs without storage there will be an increase in overflow volume and frequency. Overall, the annual overflow volume will decrease and overflow events will be made up of smaller volumes reducing the mean impact on the receiving water bodies.

How the overflow patterns are affected by the changes in the precipitation pattern is mainly defined by the available storage capacity in the CSS. The study is based on an ideal CSS where all CSO structures are designed according to actual guidelines. In real systems the storage volumes, however, are not distributed homogeneously or designed according to current standards. Therefore, in the further course of this project the aim is to use ‘real’ sewer systems to account for heterogeneity but also to address the associated uncertainties.

This is also important when comparing studies from different regions or countries as CSOs are generally designed differently (e.g. storage, continuation flow). When transferring the results of this study these properties of the drainage system have to be considered.

To investigate the influence of uncertainties in the precipitation generation on the overflow pattern it is planned to execute repeated simulations for the same locations to estimate the internal variability of NiedSim-Klima and the hydraulic sewage system model.

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