Analysing urban floods and combined sewer overflows in a changing climate

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ABSTRACT

Climate change is expected to lead to an increased frequency and intensity of extreme precipitation events. For urban drainage, the primary adverse effects are more frequent and severe sewer overloading and flooding in urban areas, and higher discharges through combined sewer overflows (CSO). For assessing the possible effects of climate change, urban drainage models are run with climate-change-adjusted input data. However, current climate models are run on a spatial–temporal scale that is too coarse to resolve processes relevant to urban drainage modelling, in particular convective precipitation events.

In the work reported here the delta-change method was used to develop a high-resolution time series of precipitation for the period 2071–2100 based on a recently produced climate model precipitation time series for Oslo. The present and future performance of the sewer networks was determined using MOUSE software. The simulations indicated future increases in annual CSO discharge of 33% when comparing years of maximum annual runoff. There is also an 83% increase in annual CSO discharge when comparing years of maximum annual precipitation. In addition, there are increases in the flooding of manholes and increased levels of backwater in pipes, which translates into more flooding of basements.

Key words | adaption, climate change, combined sewer overflow (CSO), delta-change method, stormwater, urban drainage

INTRODUCTION

Control of flooding in urban areas is an important consideration because of the potential for damage to property. With the increasing density of urban areas, along with the attendant infrastructure, the costs of flood damage will also increase. This factor is especially so in areas where many of the buildings have basements, as these are particularly susceptible to flood damage. Information from a major insurance company in Norway indicates an increase in compensation payments for flood damage, and that the poor condition of water and sewerage networks are one of the main reasons for this damage (Lindholm & Holmskau 2005).

The effects of urbanization on storm water runoff include reduced infiltration, increased volumes of runoff, and higher and earlier peak flow rates. These result from the increased percentage of impervious surfaces, as well as from changes in efficiency associated with artificial channels, curbing, gutters and storm drainage collection systems which increase the velocity of the flow and magnitude of the flood peaks (Mays 2005).

The increased rainfall intensity already caused by climate change has also led to problems with stormwater handling in cities (Lindholm et al. 2006; Nie et al. 2009). Heavy rainfall events of short duration increase the risk of pluvial floods causing damage (Haugen et al. 2008). In addition, during prolonged precipitation events, the ground becomes saturated, leading to a faster runoff response and thereby increasing the risk of flooding. The stormwater systems currently in use have not been designed to accommodate increased volumes of runoff. Climate
models indicate that future climate changes will most likely be more severe than changes that have already taken place (Drange et al. 2007). In addition to an increase in heavy rainfall, the average sea level is also expected to rise (Drange et al. 2007) along with the maximum sea level during spring tides (La Casce & Debernard 2007). An increase in sea level will result in reduced hydraulic capacity of the stormwater system, leading to higher levels of backwater and increases in combined sewer overflows (CSO) discharge.

Several case studies conducted in Norway have analysed the effects on stormwater networks of increased precipitation resulting from climate change. Most studies have relied on upscaling existing intensity–duration–frequency curves (IDF curves) or pluviographs by multiplication with ‘climate change factors’ (more or less guessed).

The effect of climate change on flooding in the City of Fredrikstad in Norway was analysed by Hardang (2007) using the Danish Institute of Hydraulics modelling software MOUSE. He found that an increase of only 15% in the rainfall intensity of storms with a 20 year return period would increase the number of flood-damaged buildings by 86%. The same result was found for rain storms with a 50 year return period.

The effect of climate change on flooding in the City of Lillestrom in Norway was analysed by Kringstad (2009), also using the MOUSE model. The rainfall intensity of a storm with a 3 year return period was increased by 30% to simulate the effect of climate change. The results indicated that approximately 80% more buildings will be damaged by flooding compared with present climate conditions.

When conducting impact assessments with hydrologic/hydraulic models, the ideal situation would be to apply precipitation output from climate models as direct input in urban runoff models. However, there is still a major discrepancy between the data needs of urban runoff models and the data output from climate models. Several authors (Schilling 1991; Berne et al. 2004; Aronica et al. 2005) have studied the rainfall data needs of urban hydrology, and the general recommendations are that a temporal resolution of 1–5 min and spatial resolution of 1–5 km² is preferred; the spatial-temporal resolution of current climate models is far coarser than this one. The following problem therefore arises: How can the projected rainfall patterns resulting from climate change be represented in urban drainage models for the purpose of making climate change impact assessments?

Denault et al. (2006) used linear regression analysis to detect statistically significant trends in the annual maximum intensity series for rainfall events of different durations. The trends were then extrapolated into the future to obtain new estimates of IDF curves. This approach makes two major assumptions: (1) that the observed trends are, in fact, linear (can be tested statistically) and (2) that the trends will continue into the future.

He et al. (2006) proposed a method in which the output from a global climate model (GCM) was used to calculate the change (from present climate to future climate) in the mean and variance of the annual maximum 24 h duration rainfall. The new estimates of the mean and variance were then related to the parameters of the Gumbel distribution through the method of moments, providing estimates of the future return periods associated with 24 h duration rainfall events of different magnitudes. Then, in the most crucial part of the analysis, the following empirical equation for IDF curves was used:

\[ i = \frac{dT^e}{(b + t_d)^c} \]

where \( i \) is the rainfall intensity, \( t_d \) is the event duration and \( T \) is the return period; \( b, c, d \) and \( e \) are parameters. For a given location, parameters \( b, c, d \) and \( e \) completely describe the IDF curves (valid for all return periods). In the study, historically measured rainfall time series were used first to determine the values of all these four parameters using curve-fitting techniques. Then, holding \( b \) and \( c \) constant, they used the values obtained from the Gumbel distribution to estimate new, future values of \( d \) and \( e \). The crucial aspect here is that, when all four parameters are determined, the equation allows for interpolation to any rainfall duration, even though the analysis was based only on the 24 h duration maximum values. This situation was made possible by utilizing the empirically observed properties of the equation parameters.
Guo (2006) used a similar approach to detect changes in the IDF curves in the Chicago area in the 20th century. Grum et al. (2006) presents a methodology for using the output (more specifically, the projected change from the control climate to the scenario climate) from a regional climate model (RCM) to modify several historically observed time series, thereby arriving at an estimate of the future change in point rainfall extreme statistics. The novelty of the study is that the areal extent of the RCM’s output is taken into consideration by applying the projected RCM change, not to a single measured time series, but rather a weighted average (Thiessen polygons) of 16 time series that are geographically close. The study only considered precipitation of 1 h duration, as this time was the resolution of the RCM that was used. The method is an example of the delta-change method that will be presented below.

Mailhot et al. (2007) used data from the Canadian RCM and regional frequency analysis to estimate future changes in the IDF curves at both station and grid-box scale. However, the shortest rainfall duration that was considered was two hours, and this period is generally too long for urban drainage applications.

As opposed to the methods mentioned above that mostly focus on developing new IDF curves, a different approach is to generate new time series that are supposed to be representative of future precipitation patterns. A class of methods known as delta-change methods can be identified within this approach. These are methods that make use of climate model output and have been used extensively to prepare input for hydrological models (Hay et al. 2000). The fundamental assumption is that the climate model’s projection of the relative change between the control climate and the scenario climate is more reliable than the absolute values it produces for the scenario climate. The change that is projected by the climate model (in the form of a delta-change factor (DCF) or a delta change difference) is applied to a historically observed time series to arrive at a new time series that is adjusted to account for climate change. Usually the method also involves assumptions that the coarse output from climate models can be applied to a measured time series that is obtained on a finer temporal and spatial scale.

Semadeni-Davies et al. (2008a,b) used the delta-change method on a 6 h basis to assess the climate change impact on urban drainage in Helsingborg, Sweden. Recently, a new version of the delta-change method was proposed by Olsson et al. (2009) in which the delta-change factors are related to rainfall intensity, providing a potentially more realistic version of the method. This refined method was used in the work presented in this paper.

Finally, statistical techniques exist to disaggregate rainfall time series with low resolution to rainfall time series with higher resolution (Burckhardt-Gammeter & Fankhauser 1998; Hingray & Ben Haha 2005; Arnbjerg-Nielsen 2006). This approach requires an assumption about the statistical relationship between rainfall events of different durations. For application to scenario time series produced by climate models, an additional assumption is needed; that the present relationships between different rainfall durations continue to be true in a changed climate. An approach related to the disaggregation techniques is the use of stochastic rainfall generators; computer programs that generate artificial rainfall time series on the basis of model parameters related to the local climate. One such generator, TSRSim, has been used in the UK for climate change impact assessments (Arnbjerg-Nielsen 2006).

**METHODS**

There are two main approaches when modelling urban drainage systems, whether it is present or future performance that is to be assessed:

1. Running the model with design rainfall events (single events), with the event volume usually obtained from IDF curves and a time distribution from one of the available methods for developing hyetographs. Sometimes the single event is extracted from a measured time series instead of extracting it from an IDF curve. The advantage of the single-event approach is that it is not computer-intensive and provides a quick check of whether the system is performing as it is designed to do.

2. Running the model with long-term, continuous, historically observed time series. The advantage of this method is that it gives a broader picture of system performance than just running single events and it is possible to perform statistical calculations to describe
system performance. Also, as a hydrological model will keep track of the state of different storages at all times (e.g., degree of soil water saturation, snow cover, etc.) the runoff response to a rainfall input will depend on the initial catchment conditions, which allows for more realistic results. The downside is that this approach is very computer-intensive and time-consuming.

Corresponding to these modelling approaches, the two main approaches for estimating future rainfall are described in the introduction. In short these are:

1. Estimating the change in single events, design rainfall events.
2. Generating time series that are supposed to be representative of the future rainfall pattern.

Delta-change approach for adapting RCM output to urban hydrologic modelling

Previous attempts to apply the delta-change method in urban hydrology have been reported (Semadeni-Davies et al. 2008a,b). These studies have used a simple approach, in which DCFs are based on coarse-resolution output from RCMs. With the availability of higher resolution output from RCMs, both in time and space, the delta-change method can be refined, and such a refinement was proposed by Olsson et al. (2009). The authors used output from the Swedish Rossby RCM with a time resolution of 30 min and horizontal spatial resolution of 50 km to create a distribution of DCFs where each factor is related to the rainfall intensity level. When such a DCF distribution is applied to a measured precipitation time series, different intensities will undergo different changes. The end result is a realization of a possible future precipitation pattern, with a resolution that satisfies the needs of urban hydrology.

This recently proposed version of the delta-change method was applied in the project reported in this paper, with some minor changes. In Figure 1 an overview of the calculation procedure is given. An RCM time series for the period 2071–2100 with a temporal resolution of one hour (internal computational time step is 4 min) and horizontal spatial resolution of 25 km was used as input. The RCM time series was developed with the HIRHAM model by the Norwegian Meteorological Institute, using Intergovernmental Panel on Climate Change (IPCC) emissions scenario B2 (IPCC 2000). Two measured precipitation time series, to which the DCF factors were applied, were used for hydraulic impact assessment in this work. The first time series (1968–2007) was taken from the tipping-bucket recording pluviometer at Blindern (University of Oslo) with a volume resolution of 0.2 and 0.1 mm and time recording precision of 1 min. The second time series (1985–2007) was taken from the tipping-bucket recording pluviometer at Lambertseter (south-east Oslo) with a volume resolution of 0.1 mm and time recording precision of 1 min.

The analysis was started by grouping all the RCM data according to season. This analysis was done because the pattern of change in the future climate is expected to be dissimilar for the different seasons. The next step was to further divide each 50 year period into three 10 year periods.
This approach served two purposes: as the RCM data was produced from just a single model run, there was a possibility that the resulting precipitation pattern would be systematically different from the average pattern that would result if the model had been run several times. Dividing the time series into three 10 year periods gave three different realizations of the future precipitation that are considered equally probable and, as such, were a ‘replacement’ for multiple runs of the RCM model. At the same time, the amount of statistical scattering in the final DCF distribution was reduced. After dividing the data into 10 year periods, the original two (control and scenario climates) RCM series were split into a total of 24 subseries, each characterized by belonging to either the present or future climate, to a certain season and to a certain 10 year period.

Percentiles were calculated for each of these 24 subseries (the $i$th percentile is the value for which $i\%$ of the observations are less than or equal to). The percentiles were calculated with a resolution of 0.1 (1,000 percentiles) to make sure that important patterns did not escape the analysis. In effect, these percentile distributions are (empirical) cumulative probability distributions for hourly rainfall intensities. A change in the percentile distribution between the control climate and the scenario climate thus represents a change in the probability distribution for rainfall intensities. For example, an increase from the control to the scenario in the 90th percentile means that the 10% most intense rainfall hours have become even more intense in the scenario climate. By dividing percentiles from the scenario climate by the corresponding percentiles from the control climate, a factor for each percentile was obtained that quantifies the change in the probability distribution, the so-called DCF.

For each season, every percentile of each 10 year period in the scenario climate was divided by the corresponding percentile of every control climate 10 year period, giving a total of nine DCF distributions that were averaged to produce a single DCF distribution. This averaging procedure was, however, not enough to eliminate some erratic fluctuations in the DCF for the highest intensities. To smooth the DCF distribution for the highest intensities, the DCF for the highest 10% were averaged over integer percentiles. This method may have had the effect of reducing the 90th–100th percentiles to some extent, but gave a more robust estimate, as discussed by Olsson et al. (2009).

**Application of the delta-change factors to a measured time series**

As the RCM time series has a resolution of one hour, the application of the DCFs to a measured time series should also be done on an hourly basis. Thus, the measured time series were first aggregated into an hourly time series. Secondly, percentiles for this hourly time series were calculated, as for the RCM time series, using all the hourly values. After calculating the percentiles, each hourly value in the aggregated measured time series had to be coupled with its corresponding percentile. For example, if the 90th percentile was 4.4 mm and the 90.1th percentile was 4.6 mm, an hourly value of 4.5 mm would be coupled with the 90.1th percentile (being smaller or equal to 4.6 mm but larger than 4.4 mm). When the correct percentile had been established, the DCF corresponding to this percentile was applied to the precipitation value in question. For example, if the DCF for the 90.1th percentile was 1.1, the hourly value of 4.5 mm would be multiplied by 1.1 to become 4.95 mm. As the original volume resolution of the measured series was 0.2 or 0.1 mm, the range of different hourly values in the aggregated series was limited, and it was observed that many of the percentiles were equal to each other. This observation led to the problem that, rather than being coupled with a single percentile, many of the hourly values were coupled with several percentiles each. This factor was taken care of by applying the average of all the corresponding DCFs instead of selecting just a single one.

Having applied a DCF to all the hourly values, the hourly series was then disaggregated into the resolution of the original observed series. This method was done by going through the original unmodified observation series and, for each observation, identifying the hour it belonged to and applying the corresponding DCF to this observation. Hence, all observations that belonged to the same hour were multiplied by the same DCF.

There are some complicating aspects to the above procedure. In calculating the DCFs, the question arises as to what should be done with the lowest intensities in the RCM time series. The percentage of dry hours in the RCM series is around 50%, so using all the hourly values would result in half of the DCFs being undefined (because of division by zero) or zero, which is clearly not an option.
Another possibility could be to calculate percentiles on the basis of only those hours when the precipitation is non-zero. This method was tested and resulted in DCF distributions that showed significant scatter for both low and high intensities, to the degree that they were not usable. Another argument against this choice is that, as the ultimate goal is to apply the DCF to a measured point precipitation series, most of the low hourly values in the area-averaged RCM series would correspond to zero precipitation in a point, and should thus be omitted from the analysis. A third option, discussed by Olsson et al. (2009), would be to use a fixed cut-off value, for example 0.2 mm, and consider only those values larger than this one. Such a cutoff is, however, difficult to define with confidence and, equally problematically, would result in the lowest DCF converging to ‘1’. The strategy that was adopted by Olsson et al. (2009) was to use only a fixed number of RCM values, and the number of values was chosen in such a way that the average intensity of the RCM control time series corresponded to the average intensity of the measured time series. This method of selection resulted in truncating the RCM time series at the 85th percentile, keeping only the 15% highest values. However, in the present study, it was found that the number of values included had a dramatic influence on the general magnitude of the DCF distributions. Thus, the choice of how many values to include in the analysis should be based on solid grounds.

In this work, a strategy related to that of Olsson et al. (2009), but slightly modified, was adopted: The total relative change in precipitation volume, season by season, should be the same for the original vs. modified measured time series as it is for the RCM control vs. scenario series. For example, if the average summer precipitation decreases by a factor of 0.85 for the RCM scenario climate as compared with the RCM control climate, then this change in average precipitation should be the same for the modified measured time series when compared with its original counterpart.

The volume change criterion was met by individually adjusting the number of RCM values to include in the analysis for each season. After having applied the DCFs to all the measured hourly values, the volume change for the modified series was calculated for each season. If the volume change for a season was not within 1 percentage point of the volume change calculated for the RCM data, then the number of values to include in the DCF derivation for that season would be adjusted and a new DCF distribution would be calculated. This calculation would be done for all the seasons until all the measured volume changes satisfied the criterion of being within 1 percentage point of the corresponding RCM volume changes.

By truncating the RCM time series and keeping only a fixed number of the highest values, an approximation of the precipitation averaged over the area in the RCM to the required point precipitation was obtained. This factor is because, as already mentioned, most of the low values in the RCM series would correspond to zero precipitation in a point. Secondly, by letting the volume change criterion determine how many values to actually include in the analysis, it is hoped that the algorithm will choose this number in such a way that the truncated RCM control time series attains an intensity distribution that is similar to the corresponding measured time series. The point here is that, if the intensity distributions of the truncated RCM control series and the measured series are similar, the percentage volume change will also be similar (even if the truncated RCM control series and measured distributions are displaced vertically). Thus, this method represents a best approximation of the RCM area precipitation to point precipitation.

Verification of the applicability of this approach to the datasets mentioned is extremely difficult. To test the hypothesis that it is possible to approximate point precipitation by truncating a precipitation series representing area averages, one would need a region with a sufficiently dense network of pluviometers, allowing the construction of an average area precipitation series that could be compared with point measurements.

RESULTS AND DISCUSSION

Delta-change factors

In Figures 2 and 3, the DCF distributions for Oslo-Blindern and Oslo-Lambertseter are shown, respectively. The results share the same overall pattern as the DCF distributions found by Olsson et al. (2009). Both in this work and in the work by Olsson et al. (2009) all seasons have DCF distributions that are below unity for the lowest intensities and
increasing DCF factors with increasing intensity, but they cross the line of unity at different values. The DCFs in the summer season are generally lower than the factors for the other seasons. This situation can partly be explained by the fact that the percentage change in the precipitation volume for the summer season is less than 1, around 0.85. The highest intensities will be subjected to DCFs between 1.2 and 1.4, which is significant. The lowest intensities in the summer season are multiplied by a factor of approximately 0.3.

Validity of the delta-change approach

Climate change research involves trying to predict the future, and it must always be remembered that this approach is a formidable task that involves uncertainties that are difficult to assess quantitatively.

The major uncertainties related to this work, broadly speaking, can be listed as follows:

- Lack of understanding of the climate system and the inability of current climate models to describe in sufficient details the processes that are understood.
- Only a single run with a single RCM was used to produce the precipitation time series in this work, and the boundary conditions for each RCM run came from a single run with a single GCM. Thus the precipitation time series represents only one possible realization of the future precipitation pattern and it is not certain that this pattern agrees with what would result as the average if several models and/or model runs were applied.
- Only one of several plausible emissions scenarios was used to produce the time series.
- The RCM precipitation time series were extracted from a single grid point. This factor is unfortunate as grid points represent the fundamental calculation unit of the climate model and grid point data are therefore subject to uncertainty.
- The delta-change procedure applied involves several strong assumptions:
  - Future changes in area-averaged precipitation will be similar to future changes in point precipitation.
  - Future changes in short-duration precipitation will be governed by changes in hourly precipitation.
  - The percentage dry hours will remain the same in the future as it is today.
  - The technique of how to determine how many values from the RCM time series to include in the analysis is plausible.

However, there are some arguments that the results obtained in this study can be considered somewhat conservative:

- The B2 scenario is a moderate emissions scenario and it can be assumed that climate change prognoses produced with this scenario are less extreme with regards to precipitation.
- It has been suggested that climate change may produce more localized precipitation generating mechanisms,
and short-duration point precipitation extremes may increase more than the area-averaged, longer-duration extremes that are predicted by climate models.

Concerning the refined delta-change method applied here, as in all delta-change approaches, it is difficult to assess to what degree the associated assumptions are valid. Of even more concern is the ad hoc approach used to determine how many RCM values to include in the calculations of the DCF distributions. Hence, the method suggested by Olsson et al. (2009) may be a step towards more realistic representations of future precipitation time series, but the added finesse of the new approach also serves to obscure the validity of the results. In the face of such uncertainty, practitioners may benefit from performing simpler sensitivity analyses to various levels of climate change (e.g., using various multiples of existing IDF curves) rather than relying on advanced, single-scenario time series such as the one developed here.

Predictions of hydraulic impact by application of the modified time series in a small residential catchment

In order to obtain an idea of the impact of climate change on the performance of an urban drainage network, the original measured precipitation time series and DCF-modified precipitation time series for Oslo-Lambertseter were both used as input data in a hydraulic model for a small residential catchment area at Abildsø in south-east Oslo. The catchment was chosen for modelling as there have been some problems with basement flooding in the area, and an already calibrated network model was available. The catchment is also small enough to accommodate the massive time series used as input and the Oslo-Lambertseter meteorological station is situated close by.

The model covers a catchment area of 26 ha with an average imperviousness of 5.8% and it contains about 70 nodes and 3 km of pipelines (diameters from 200 mm to 300 mm). There are no overflow weirs. The entire area is served by a combined sewer system and the dry-weather flow (household water consumption) is set to 240 l/p/day.

The building regulations of the City of Oslo specify 0.9 m as the minimum distance from pipe top to basement floor. Water levels above 0.9 m are considered critical to basement flooding. The results from the hydraulic model were used in a simple frequency analysis, using the Weibull plotting formula, to develop the graphs shown in Figure 4. They relate the number of manholes (out of a total of 69 in the network) for which the water level in a flooding event exceeds the critical level to the return period for that particular flooding event. As can be seen, return periods seem to be decreasing with a maximum factor of 0.5. The return periods calculated here should be interpreted with some caution as this is a small network and the data are discrete. It should also be noted that, in this system, there are few new nodes that become flooded in the future, but for a given return period, more of the nodes that are flooded today become flooded in the future. This fact will, in general, depend entirely on how surplus capacity is distributed throughout the system.

Impacts on flooding and CSO-discharge in a sub-catchment in the City of Oslo related to the city river Akerselva

The City of Oslo has decided to keep the CSO discharge to a minimum in order to facilitate recreational use of its water bodies. The city river Akerselva has become increasingly popular as a recreational area after extensive efforts by the city authorities to restore and thereafter maintain the quality of the once-heavily-polluted river. There are currently bathing areas and possibilities for other recreational
activities including hiking trails, fishing and canoe paddling. Therefore floods leading to deterioration in water quality or the aesthetics of the river should be avoided, today as well as in the future. To assess whether the City of Oslo will have to intensify its rehabilitation program in the future, the city's already established urban runoff model (MOUSE) was run with the delta-change-modified time series for Oslo-Blindern as input data.

The pipe network in the catchment comprises 1,188 manholes, seven weirs, two pumps and 1,233 pipes. In order to save computation time and hard drive space, it was found necessary to limit the analysis to only a few years of the modified time series. It was decided to identify a mean and extreme year with respect to runoff and an extreme year with respect to precipitation. A simplified model, thought to be sufficiently representative of the full-scale model, was set up.

The original unmodified precipitation time series was run through the simplified model for one year at a time. The volume of CSO overflow for each year, and thereafter the mean CSO overflow for all years, was determined. The year that had an overflow closest to the mean of all the years was determined to be the mean year (1979), while the year with the largest volume of overflow was determined to be the extreme year (1980). The year with most rainfall was 1988.

The area of the catchment is 376 ha and consists of mixed office and residential buildings. The current level of both CSO discharge and flooding in the sewer network was determined by running the unmodified precipitation time series for both the mean and extreme years in the full-scale MOUSE network model. The future level of CSO discharge and flooding in the sewer network was then determined by running the modified precipitation time series for the same years, representing what would presumably be a mean and extreme year in the period 2071–2100.

In the mean year (1979), there was no overflow computed, but in both the extreme years with respect to runoff (1980) and rainfall (1988), there was overflow registered (Table 1).

Following the increase in precipitation in the future scenario, there is also a corresponding increase in the discharge from the CSO for single events (Table 2). The results in Table 2 were generated by running the model with single events obtained from new IDF curves developed from the modified time series. It may seem strange that the percentage increase of CSO, due to climate change, is larger for a 1 in 5 year and a 1 in 10 year storm compared with a storm with a return period of 20 year. The main explanation for this finding is that the setting of the weir capacity in the CSO outlet is the same for all simulations, making the relative increase in the volume of water exceeding the CSO capacity higher for the 5 and 10 year return period than for the 20 year return period.

**Flooding of nodes**

At present there are five nodes in the network that are prone to flooding (meaning that water could rise to/above ground level) and these are affected to various degrees by the increase in runoff generated. The number of flooded nodes nearly doubles in the future scenario, with nine nodes being prone to flooding following precipitation events with a 20 year return period.

**Backwater in pipes**

Similarly, due to the increase in the runoff generated, there is a corresponding increase in the number of pipes in which the backwater levels are higher than the recommended 90 cm above the top of the pipe (Figure 5). All basement floors in buildings should be at least 90 cm above the top.
of the municipal pipes, according to the municipal guidelines.

**Reducing CSO discharge and flooding of basements**

The predicted hydraulic response due to climate change will have a negative impact on the aquatic environment as it will lead to an increased volume of sewage discharge via the overflow weirs, particularly during the summer season. This volume will have a dramatic and adverse effect on the swimming activities in the river Akerselva and severely change the recreational value of the river. The negative impacts include increased health risk due to increasing number of *Escherichia coli* bacteria and objectionable aspects of the water such as visible sewage particles and floating matter, reduced transparency and odour. An increased nutrient load, particularly phosphorus, is a major problem for river water ecology, as phosphorus enrichment can promote excessive growth of aquatic plants (eutrophication), and undesirable changes in the structure and function of the ecosystem. An increased phosphorus load during the low flow summer season is more critical than at other times of the year as it coincides with conditions (higher water residence times, abundant light levels and high water temperatures) that promote rapid algae growth (Mainstone & Parr 2002; Jarvie et al. 2006).

Given the modeled response of the catchment to the predicted changes in climate, it will become necessary to implement measures that will contribute to attenuating peak discharges and reducing the volume of CSO and, at the same time, contribute to reducing backwater levels and flooding of manholes.

The proposed goal of the City of Oslo is to have no more than one CSO event every 5 year and this goal would be hard to achieve in the future change climate scenario, according to the results presented here, without intervention.

**Evaluation of possible countermeasures**

The following is a short discussion (non-exhaustive) of possible measures that increase the capacity of the sewer network or reduce the inflow to it. Many of the countermeasures will be difficult to implement in the catchment studied because the area is long-established and is mostly privately owned. The property situation in the area leaves very little free space for measures that needs space on the surface.

- **Disconnection of roof downpipes.** As this is a residential area, roof downpipes can be disconnected and the water infiltrated on the house owners’ own property. This measure is feasible and very cost-effective.
- **Installation of an underground in-line detention volume.** An in-line detention volume can be built as a pipe with a large diameter. This measure is feasible but more expensive than disconnection of roof downpipes.
- **Retention ponds.** Ponds improve the cityscape aesthetics and reduce inflow to the sewer network. However, ponds are difficult to implement in the study area due to the limited public property available.
- **Use of green infrastructure.** The city will consider possibilities for increased use of green areas for infiltration of storm runoff, swales, green roofs, etc., even though it will be difficult to impose costs for these measures on private house owners.
- **Separation of sewer flows.** Separation of combined sewer systems into a new separate sewer system is a measure that could be achieved during the process of replacing old sewer pipes. Stormwater will then be channelled to the nearby Akerselva River. This method is expensive and very time-consuming to implement, but can be sufficient to keep pace with expected changes in the climate.

![Figure 5](https://iwaponline.com/jwcc/article-pdf/2/4/260/375281/260.pdf)
• **Replacement of pipes.** Given the old age of much of Oslo’s sewer network, an intensive program to replace pipes is under way. When a conduit with insufficient capacity to cope with the effects of climate change needs to be renewed, a replacement with a larger pipe will be considered.

• **Decrease hydraulic loss in manholes.** There is room for improving the flow dynamics by the use of manholes with better hydraulic design. This method can increase capacity by 10–15% (Lindholm & Holmskau 2005), and should be investigated in field studies. The hydraulic performance of the 1,188 manholes is not known for the time being, so this measure must be analysed when data on this problem are available.

For the reasons explained above, disconnection of roof drainage and installation of an in-line detention volume were the only measures considered feasible in the near future. The effect of these measures was simulated in this project. A good functioning set of measures was found to be to install a detention volume of 500 m³ (in the pipe that was the main cause of the CSO), and to disconnect 50% of the roof downpipes. The optimal outlet discharge from the detention basin was 130 l/s as a constant discharge. This achieves a good reduction in the CSO discharge for precipitation events of up to a 20 year return period both in the present day and the future scenario. The reduction is 98–100% in the present and 90–100% in the future scenario, depending on the return period.

In addition to reduced CSO discharge, the combination of the two measures also resulted in a reduction in the number of manholes and pipes that are prone to flooding and high backwater levels, respectively. However, the reduction is attributed mostly to the disconnection of the downpipes.

**CONCLUSIONS**

A refined delta-change method that was recently proposed in the literature was applied, but some methodological difficulties were encountered that had to be resolved with an *ad hoc* method which introduced additional uncertainty into the other assumptions made. However, arguments can be made that the results obtained here constitute a conservative estimate of the possible effects of climate change. Generating long-term rainfall time series that are representative for the end of this century is an extremely difficult task and will have a high degree of uncertainty. However, the delta-change method is, so far, one of the best available methods to simulate flood effects in a sewerage network in a changed climate. The increase in CSO volume predicted by the model for the investigated sub-catchment of Oslo is substantial. The model predicts an increased overflow in both the extreme years, with respect to runoff and rainfall, of 33.3% in the year with maximum runoff and 82.9% in the year with maximum precipitation compared with the current situation.

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**REFERENCES**


Optil én meter havstigning langs Norskrysten innen år 2100 (in Norwegian).  


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