Simulating future trends in urban stormwater quality for changing climate, urban land use and environmental controls
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ABSTRACT
The effects of climatic changes, progressing urbanization and improved environmental controls on the simulated urban stormwater quality in a northern Sweden community were studied. Future scenarios accounting for those changes were developed and their effects simulated with the Storm Water Management Model (SWMM). It was observed that the simulated stormwater quality was highly sensitive to the scenarios, mimicking progressing urbanization with varying catchment imperviousness and area. Thus, land use change was identified as one of the most influential factors and in some scenarios, urban growth caused changes in runoff quantity and quality exceeding those caused by a changing climate. Adaptation measures, including the reduction of directly connected impervious surfaces (DCIS) through the integration of more green spaces into the urban landscape, or disconnection of DCIS were effective in reducing runoff volume and pollutant loads. Furthermore, pollutant source control measures, including material substitution, were effective in reducing pollutant loads and significantly improving stormwater quality.

Key words | climate change, computer simulation, future scenarios, influential factors, urban stormwater quality

INTRODUCTION
The impacts of urbanization on surface waters have been historically managed by building drainage infrastructure, providing multiple benefits in the form of flood protection, land-use convenience through avoiding water ponding, and protection of receiving waters against the pollution conveyed by runoff. In recent decades, this approach has been further expanded by including the maintenance of local water balance, beneficial uses of blue/green areas and subpotable use of stormwater among the goals of urban drainage systems (UDSs). From the hydrological point of view, these systems have been designed on the basis of historical rainfall data, assuming the stationarity of precipitation data and air temperatures. However, the evidence of the last two decades indicates that this assumption may no longer be valid in view of the large degree of climate variability attributed to anthropogenic causes leading to climate change. Thus, there is a need to assess the vulnerability of existing UDSs in a changing climate and to develop risk management measures focusing on adaptation measures.

The vulnerability of UDSs is particularly critical with respect to flooding, and much of the earlier research has focused on such issues (Willems et al. 2012). Towards this end, the climate change scenarios have been derived from the scaled-down results of global circulation models and used in assessing the functionality of the existing UDSs with respect to flow conveyance and storage. This research resulted in a plethora of reports and papers typically indicating larger runoff flow rates and volumes in the future. However, so far such efforts have not resulted in the recommendation of universally accepted methods or approaches for selecting the global circulation models (GCM) models for climate projections, downscaling methods providing the data needed in fine scales appropriate for urban areas, and drawing robust practical conclusions from these results with respect to adaptation.
Much less attention has been paid to the potential impacts of climate change on urban stormwater quality, which even though closely related to stormwater quantity, represents a different issue with less acute impacts than, for example, flooding. Thus, the problem here could be formulated as: what is the vulnerability of the existing UDSs, with stormwater quality measures and structures, to a changing climate; and how could one maintain (or improve) the performance of the existing systems in a changing climate? When addressing this issue, one needs to consider two driving forces, changing climate and progressing urbanization, and consider the ongoing and future changes in stormwater management as a part of adaptation measures.

Stormwater quality research in a changing climate has so far focused on the accumulation and wash-off of pollutants from catchment surfaces, which depend on pollutant sources and rainfall characteristics (He et al. 2011; Sharma et al. 2011; Borris et al. 2012). Changes in the rainfall regime do affect the quality of stormwater (described, for example, by total suspended solids), as noted by the aforementioned authors. Similarly, progressing urbanization impacts on catchment characteristics, causing higher rates and volumes of runoff, as well as greater accumulation of pollutants due to increased intensity of land use (e.g., increased intensity of traffic). Thus, the potential effects of these driving forces, described by a higher degree of urbanization and greater sources of pollutants, need to be considered. The outcomes of these forces can be mitigated by environmental controls, which include pollution source controls (Marsalek & Viklander 2011) as well as other stormwater best management practices (BMPs), which can be viewed as adaptation measures for mitigating the impacts of a changing climate on stormwater quality. In this regard, it should be recognized that, besides the potentially worsened stormwater quality (primarily caused by more efficient wash-off), the performance of BMPs may be also reduced because of higher flows and volumes of stormwater to be treated in the future.

For northern Sweden, an increasing trend in hourly rainfall maxima is projected for the future, with significant changes particularly likely during spring and autumn (Moghadas et al. 2011). Consequently, higher runoff flows carrying higher pollutant loads are expected, especially for low-to-medium intensity rain events that were found to be sensitive to climate changes (Borris et al. 2012). Hence, it is necessary to assess the likely changes in stormwater quality and the feasibility of designing adaptation measures preserving or improving the performance of existing UDSs with respect to the protection of water quality.

The analysis of future stormwater quality needs to be based on computer simulations, recognizing that the most advanced current urban runoff models can simulate the generation of urban runoff, with an acceptable level of certainty, for broadly varying conditions (Zoppou 2001). Furthermore, these models mimic fairly well the processes governing the quality of stormwater and, therefore, can be used as practical tools for examining changes in water quality due to climatic changes and changing pollutant sources (Tsirintzis & Hamid 1998). For addressing various combinations of changes in the climate, urban area characteristics, and BMPs, different future scenarios can be devised and simulated.

The objective of this paper is to examine future trends in simulated stormwater quality in a northern Sweden community by examining future scenarios, which account for: (a) climatic changes projected for the study area for the period when the catchment is snow free (i.e. from April to October), (b) increased pollutant generation due to progressing urbanization and intensification of urban land-use activities, and (c) ongoing and future efforts in controlling sources of the selected pollutants (total suspended solids (TSS) and two metals).

**METHODS**

The stormwater quality was examined by analyzing simulation results obtained for seven scenarios combining variations in three influential factors: (a) climate, (b) progressing urbanization (characterized by the total area and its land use), and (c) selected pollution control measures. Descriptions of scenarios follow.

**Future scenarios**

Future scenarios were defined by Nakicenovic & Swart (2000) as images of how the future might unfold, which can assist in the understanding of possible future developments of complex systems. To develop meaningful scenarios, the system studied needs to be described in a structured way. For stormwater quality, this has to be done for different constituents of interest, which were represented in this study by three examples: TSS, Cu (copper) and Zn (zinc). When describing stormwater quality processes, different physical, regulatory, social, economic, environmental and technical dimensions need to be taken into account, as illustrated in Figure 1.
According to Figure 1, three general types of changes may occur in the future and affect stormwater quality: (a) changing atmospheric inputs (i.e. both precipitation and deposition), (b) changing catchment sources (e.g. more vehicular traffic due to increasing intensity of land-use and the change in catchment surfaces (e.g., more impervious surfaces due to progressing urbanization), and (c) changing control measures (e.g. improved source controls).

Since the focus of this preliminary study phase is on TSS and heavy metals, scenarios affecting those constituents are of particular interest. In urban areas, traffic and the corrosion of metal surfaces are known to be the main sources of heavy metals in stormwater runoff (Davis et al. 2001; Fuchs et al. 2006). Fuchs et al. (2006) evaluated these sources and their relative contributions. Based on their study, it is assumed that copper is released in nearly equal amounts by traffic and metal surfaces. For zinc this is different, since metal surfaces contribute more than traffic. Therefore in the corresponding scenarios it is assumed that the contribution of metal surfaces is twice the contribution of traffic. In total, a reference scenario reflecting the current situation and six future scenarios have been developed.

Scenario 0: Represents the current situation (described in the sections on hydrological parameter estimation and calibration and parameter estimation for quality processes representing the current scenario (S0)) and serving as a reference for comparison with the other scenarios.

Scenario 1: A business-as-usual scenario, in which only the climatic input was changed.

Scenario 2: Assumes redevelopment of the study area and a greater uptake of adaptation measures, including the integration of more green spaces into the urban landscape. Consequently, the area of directly connected impervious surfaces (DCIS) is reduced.

Scenario 3: Increasing fuel prices and public education result in changed driving habits and fewer kilometres driven. This results in a lower production of particulates (TSS) due to traffic and a lower release of heavy metals. A greater reduction in copper concentrations, compared to those of zinc, can be expected, since traffic is only a minor contributor of zinc.

Scenario 4: Use of alternative materials in brake pads due to restrictions on copper. The current copper content in brake pads is relatively high and contributes greatly to copper loads in urban stormwater. While some jurisdictions, including the State of Washington, legislated for great reductions in the copper content of brake pads (not more than 0.5% by 2025) (Stormwater 2010), in Sweden no such regulation has been introduced yet and a high reduction potential exists.

Scenario 5: Assumes an increasing population, resulting in a more densely built-up urban area. By 2050, the Swedish population is expected to grow by 15% (Statistics Sweden 2011) and this may result in more impervious areas, which may contribute to more surface runoff and faster accumulations of solids on catchment surfaces, further contributing to higher heavy metal releases. It is assumed that the contributions by traffic and metal surfaces would increase in the same manner.

Scenario 6: Assumes an increasing population (as in Scenario 5), which causes peripheral growth of the affected urban area (urban sprawl). Urban dwellers move away from the city centre to the suburbs, or to outlying rural areas. This increases dependency on car transportation, which is reflected in the increased number of cars per household and the distances travelled (Behan et al. 2008). Consequently, the pollutant emissions due to traffic are likely to increase, resulting in higher solids build-up rates and increasing metal concentrations. It was assumed that the larger urban area has the same imperviousness as the present catchment. Table 1 summarizes the future scenarios.

Study site

A suburb of the city of Skellefteå in northern Sweden, characterized by a mixed urban land use, was chosen as a
test catchment, because of the earlier studies done there (Borris et al. 2013), which contributed to the setting up of an urban drainage model for the catchment and the collection of good physiographic and hydrometeorological data, including a rainfall record with high temporal resolution and flow measurements in the sewer system.

**Model description**

The Storm Water Management Model (SWMM) was chosen as the simulation engine. In SWMM, the computation of surface runoff is based on the theory of a non-linear reservoir, and the hydrologic abstractions considered include surface depression storage and infiltration on pervious surfaces. Using the kinematic wave approach, a runoff hydrograph is computed for each subcatchment, considering the physical properties of the subcatchment. Pollutant build-up is simulated during dry weather and is followed by pollutant wash-off during rain events. Different pollutants can be included and some may be adsorbed on the other constituents (solids). In the latter case, potency factors are used to compute such pollutants as a fraction of TSS (Huber & Dickinson 1988).

**Model setup**

As described in Borris et al. (2013), the test catchment of 235 ha was divided into 51 subcatchments, which represent a fairly detailed discretization.

**Hydrological parameter estimation and calibration**

The hydrological calibration and validation of the model was done in an earlier study (Borris et al. 2013) and yielded the following calibrated parameter values: catchment imperviousness: 35%; surface roughness (n) for impervious and pervious areas: 0.014 and 0.08, respectively; Horton maximum and minimum infiltration rates: 25 and 5 mm/h, respectively; infiltration decay coefficient: 5 h⁻¹; and, depression storage depths on impervious and pervious areas: 1–2.5 and 2.5–5.5 mm, respectively.

### Parameter estimation for quality processes representing the current scenario (S0)

TSS build-up, B, and wash-off, W, are described in SWMM by Equations (1) and (2):

\[
B = b_1 \left(1 - e^{-b_2 t}\right) \quad (1)
\]

where \(B = \) build-up of solids (TSS), \(b_1 = \) maximum build-up possible, \(b_2 = \) build-up rate constant, and \(t = \) elapsed time.

\[
W = w_1 q^{w_2} B \quad (2)
\]

where \(W = \) wash-off load of solids (TSS), \(w_1 = \) wash-off coefficient, \(q = \) runoff rate and \(w_2 = \) wash-off exponent.

The parameters in Equations (1) and (2) were chosen on the basis of literature data (Egodawatta et al. 2007; Li & Yue 2011) and adjusted to match Swedish conditions.

For the chosen build-up rate of 0.3, 80% of the maximum build-up is reached in 5 days. The maximum build-up mass was set to 35 kg of TSS/ha (Viklander 1997) and held constant, because wash-off patterns were independent of the maximum build-up and the fraction removed by each rain event remains the same.

The wash-off exponent showed only a minor sensitivity for the range of values reported in the literature and was set equal to 1.15. To get a best estimate of practical values of parameters in Equation (2), the wash-off rates were

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>Future*</td>
<td>Future</td>
<td>Future</td>
<td>Future</td>
<td>Future</td>
<td>Future</td>
</tr>
<tr>
<td>Population</td>
<td>Current</td>
<td>Current</td>
<td>Current</td>
<td>Current</td>
<td>Increased</td>
<td>Increased</td>
</tr>
<tr>
<td>Land development</td>
<td>Current</td>
<td>LIDb</td>
<td>Current</td>
<td>Current</td>
<td>Current area, more impervious</td>
<td>Larger area, urban sprawl</td>
</tr>
<tr>
<td>Traffic &amp; Buildings</td>
<td>Current</td>
<td>Current</td>
<td>Less km driven</td>
<td>Current</td>
<td>Increase</td>
<td>More km driven</td>
</tr>
<tr>
<td>Newly legislated source controls</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Less Cu in brake pads</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

*aMore rainfall, higher rainfall intensities.
bLID = low impact development.

**Table 1** Future scenarios
adjusted to yield standard event mean concentration (EMC) values of TSS representing Swedish urban conditions, which were described by Larm (1997) as about 100 mg TSS/l. This adjustment was achieved by applying a wash-off coefficient of 0.04.

The potency factors were also based on prior studies analyzing heavy metal concentrations in sediment build-up on different urban surfaces (Duong & Lee 2011) and on runoff quality characteristics recommended by Larm (1997) for different urban land uses in Sweden. Consequently, the potency factors for Cu and Zn were chosen as 0.4 and 0.2, respectively, and the corresponding mean concentrations were 40 and 200 μg/l.

Implementation of the future scenarios

The potential changes described in the section on Future scenarios were simulated for the six future scenarios by altering the model inputs and parameters, namely the climatic input, the impervious fraction, the catchment area, the build-up rate constant (b1) for TSS and the potency factors for the heavy metals studied. For imperviousness, catchment area, and build-up rate, three parameter values were tested to consider a range of likely values and to address the uncertainty involved. These are derived as follows: (a) imperviousness: S2, 0.85, 0.9 and 0.95 times the S0 value (35); S5, 1.05, 1.10, and 1.15 times the S0 value (35); (b) catchment area: S6, 1.05, 1.10, and 1.15 times the S0 value (235); and, (c) build-up rate: S3, 0.85, 0.9 and 0.95 times the S0 value (0.3). For the potency factors single changes were tested, since strictly linear responses can be expected. Table 2 summarizes the parameters and their variation in the model for the future scenarios.

Historical climate data and climate change scenarios

A 15-year rainfall record was used as a sample of the current climate. Only liquid precipitation in the form of rain was studied; snowfall was considered outside the scope of this study. To reflect climate change, future climate projections were used and the historical rainfall record was rescaled to serve as an input to the stormwater runoff simulations. Among the future projections, a medium severity scenario AIB was used, as defined in Nakicenovic & Swart (2000). The future projections span 2011 to 2100, but for this study, only the projections for the middle of the 21st century (2041–2070) were selected, since this period was considered to be reaching as far into the future as could be handled with some confidence. The rainfall records were rescaled using the delta change method described in Olsson et al. (2012).

Model runs

Wet weather periods were selected from the available rainfall record (April–October) and continuous model runs were performed for the current and the six future scenarios. For each model run, the runoff volume and loads of TSS and heavy metals were noted. The percentage changes for the future scenarios compared to the current scenario (S0) were then calculated for all three stormwater quality constituents studied.

RESULTS AND DISCUSSION

For the modelled periods, the rainfall depth increased on average by 9% for the future scenarios, compared to the current scenario. In Table 3 the runoff volumes simulated for the different scenarios and the constituent loads are shown as average values for the parameter ranges tested. Figure 2 shows the percentage changes compared to Scenario 0. The error bars indicate the min and max values for the parameter ranges tested.

It can be observed that the runoff volume shows a high sensitivity to scenarios considering a progressing
urbanization with changing imperviousness and the catchment area (Scenarios 2, 5 and 6). The runoff volume is almost linearly dependent on the area and imperviousness. Through a reduction of the impervious surface by 10% (Scenario 2) the influence of climate change could be counterbalanced with a reduction of the runoff volume by 8% compared to Scenario 1. In contrast, Scenarios 5 and 6 show a significant increase in runoff, by about 20%. It can be noted that a 10% higher imperviousness produces runoff volumes comparable to those from a 10% larger area. This indicates that pervious areas have only a minor influence on the runoff volume and impervious areas are the main contributors, for the catchment and rain series studied here.

For scenarios with no changes in the quality parameters (Scenarios 1 and 2), the changes in the TSS load followed the changes in runoff volume, since runoff quantity is the main driver for quality. For Scenario 2 the TSS load could therefore decrease significantly and that is explained by reduced runoff flows. The change in runoff is higher than the change of wash-off, and this can be explained by transport limited conditions. The Scenario 1 results indicate that the change in TSS is slightly smaller than the change in runoff, and this can be explained by the occurrence of supply limited conditions, indicating that there are not enough pollutants on the catchment surface to meet the transport capacity of the runoff flow. The same effect can be seen clearly in the results for Scenarios 5 and 6. Even though the build-up rate of TSS has been increased, the change in TSS is still smaller than, or equal to, the changes in the runoff volume. However, it can be noted that considerably higher amounts of TSS were produced for those scenarios, when almost 20% more of TSS were as transported.

Concerning runoff volumes, it can be stated that progressing urbanization is an important factor, which affects the TSS load significantly. Scenario 3 shows only a minor change in the TSS load. The build-up rate for TSS was decreased by 10% because of less traffic, which results in about 1% lower TSS load. Based on these data, the build-up rate can be identified as a parameter of minor importance with respect to stormwater quality, as also noted for scenarios 5 and 6.

For Scenarios 1 and 2, the metal load strictly followed the changes observed for TSS, since the potency factors were not changed here. For the remaining four scenarios, high sensitivities to changes in model parameters can be seen. With reduced traffic (Scenario 3) the metal loads were reduced considerably compared to scenario 1 (only climatic changes) and the simulated loads were comparable to those obtained for the current scenario (S0); for copper, even lower loads were noted. The use of alternative materials in brake linings, as assumed in Scenario 4, highly reduced the copper load, by −18%, compared to the

Table 3 | Runoff volumes and percentage changes in constituent loads

<table>
<thead>
<tr>
<th>Scenario</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff [m³]</td>
<td>202</td>
<td>221</td>
<td>204</td>
<td>221</td>
<td>221</td>
<td>242</td>
<td>243</td>
</tr>
<tr>
<td>TSS load [t]</td>
<td>22.2</td>
<td>24.3</td>
<td>22.6</td>
<td>24</td>
<td>24.3</td>
<td>26.5</td>
<td>26.8</td>
</tr>
<tr>
<td>Cu Load [kg]</td>
<td>8.9</td>
<td>9.7</td>
<td>9.1</td>
<td>8.6</td>
<td>7.3</td>
<td>12.2</td>
<td>11.8</td>
</tr>
<tr>
<td>Zn load [kg]</td>
<td>44.4</td>
<td>48.5</td>
<td>45.4</td>
<td>45.6</td>
<td>48.5</td>
<td>61.1</td>
<td>56.3</td>
</tr>
</tbody>
</table>

Figure 2 | Percentage changes for the future scenarios.
current scenario. Therefore such pollutant source control measures can be effective for improving stormwater quality. Based on these results, a general finding can be formulated that pollutant source controls and less traffic have a strong potential for reducing heavy metal loads in stormwater and thereby counterbalance the effects of the climate change simulated here. This can be further corroborated by some prior studies reporting that the quality of runoff is associated with traffic intensity and suggesting that higher traffic intensities tend to produce higher constituent loads, including TSS and heavy metals (Viklander 1997; Kayhanian et al. 2007), and vice versa. Furthermore, past success in source controls shows that the resulting benefits can be highly significant. Phasing lead (Pb) out of gasoline is a good example of that; Marsalek & Viklander (2011) estimated that this measure contributed to removing about 97% of Pb from freeway runoff.

Progressing urbanization and increasing releases of heavy metals (Scenarios 5 and 6) produced high pollutant loads, which were in some cases almost 40% higher than the reference load (S0). This suggests in particular that combined effects of changes in urban development (increasing urban area and its imperviousness) and higher releases of heavy metals due to more intensive land-use, increase heavy metal loads significantly. The imperviousness of the catchment is therefore not only a very important parameter regarding stormwater quantity (Jacobson 2011), but also stormwater quality. The latter finding was also noted in the studies reporting that loads of various pollutants were strongly correlated with the magnitude of directly connected impervious areas (Hatt et al. 2004).

The scenarios tested indicate that pollutant loads may vary significantly in the future, since high sensitivities of stormwater quality simulations to changes in several influential factors were shown. However, the scenarios and numerical results have to be viewed with caution since they involve huge uncertainties. More scenarios for the forces driving future changes and different climatic regions, including additional test catchments, should be tested to support the results presented here. So far, only single values for the model parameters were used to describe stormwater quality, namely those describing the build-up and wash-off. Simulations of ranges of parameter values would allow exploration of the nature of changes in the objective function values, concentration and loads, and to increase the reliability of the results. Furthermore, the feasibility of incorporating pollutant source-based approaches in stormwater quality modelling should be considered, as well as an expanded list of pollutants to increase the analysis comprehensiveness.

CONCLUSIONS

The effects of future changes on the simulated stormwater quality in northern Sweden were addressed for the snow-free part of the year. Toward this end, the effects of changes in the climate, urban development, intensity of land use activities and pollutant control measures have been tested. Within the limitations of this simulation setup, the following tentative conclusions may be drawn.

In regions where rainfall will increase due to climatic changes, as exemplified here for northern Sweden, more pollutants will be transported. In addition, progressing urbanization, due to increasing population, may contribute to increasing urban areas and their imperviousness, and may significantly influence the quantity and quality of stormwater. This is therefore identified as one of the most important factors; in some instances, rapid urban growth will produce greater runoff changes than those attributed to a changing climate. Adaptation measures, like the reduction of DCIS through the integration of more green spaces into urban landscape was identified as an effective measure serving to reduce runoff volume, peaks and pollutant loads. Similarly, pollutant source controls, like limiting copper content in brake pads, appear to be effective tools in reducing pollutant loads and significantly improving stormwater quality.

REFERENCES


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