Continuous simulations of urban stormwater runoff and total suspended solids loads: influence of varying climatic inputs and catchment imperviousness

Matthias Borris, Anna-Maria Gustafsson, Jiri Marsalek and Maria Viklander

ABSTRACT

Potential implications of climate change for future stormwater management were addressed by undertaking continuous simulations of runoff and total suspended solids (TSS) loads for three urban catchments, with imperviousness varying from 23 to 63%, which were exposed to five rainfall regimes during the snow-free part of the year: the current climate and four climate change scenarios projecting higher rainfalls. Simulated runoff volumes increased in all the future scenarios, particularly in the sub-arctic climate and the fixed uplift scenario (plus20) indicating appreciable rainfall increases. Simulated runoff volumes increased depending on the projected increases in rainfall and increasing runoff contributions from pervious areas when more intense future rainfalls exceeded hydrologic abstractions. The increased runoff volumes then contributed higher TSS loads, which were highly variable for the rainfall regimes tested. In cold climate regions, residues of solids from winter road maintenance may contribute to high initial accumulations of TSS on the catchment surface and high washed off loads. In general, the study suggests that intermediate design-life stormwater management facilities require flexible design allowing for future step-wise adaptation by gradually increasing design capacities and modifying treatment trains.

Key words | catchment imperviousness, climate change, computer simulations, TSS loads, urban stormwater quality

INTRODUCTION

Studies of climate change impacts on urban drainage have so far focused mostly on a single issue, the management of flood risks arising from exceedance of design hydraulic loading (Berggren et al. 2011; Willems et al. 2012). Yet the current practice demonstrates that urban drainage systems are planned, designed and adapted to perform other tasks of urban water management as well, including the protection of water quality in receiving waters (MOE 2003). This latter task is achieved by implementing modern stormwater management measures, which are frequently referred to in the literature as Best Management Practices (BMPs) or Low Impact Development measures serving to prevent or mitigate the urbanization impacts on stormwater generation and its quality (Marsalek 2013). Thus, from the environmental protection point of view, it is of interest to examine how well the urban drainage systems will cope with future changes in pollutant loads carried by stormwater (Borris et al. 2015), and the changes in pollutant removal by hydraulically overloaded BMPs.

Investigations of future urban stormwater quantity and quality need to be based on computer simulations reflecting future rainfall and catchment physiographic data. The selection of simulation models for such a purpose is important and raises the question of robustness of stormwater simulations. In this connection, Elliott & Trowsdale (2007) and Zoppou (2001) noted that the current advanced urban
runoff models can simulate stormwater quantity with a high level of certainty, and even the stormwater quality models simulate fairly well the processes governing stormwater quality and can therefore be used as practical tools for examining the changes in urban stormwater quality due to climatic changes (Tsihrintzis & Hamid 1998; Vaze & Chiew 2003). Simulations of changes in urban stormwater quality due to rainfall regime changes were conducted, among others, by He et al. (2011), Sharma et al. (2011), Mahbub et al. (2011) and Borris et al. (2013), who all concluded that increased rainfall intensities did affect the simulated quality of stormwater. Such a quality was described by various constituents, with total suspended solids (TSS) being most common. The use of TSS as a stormwater quality indicator is justified by their impacts on receiving waters ecology, including interference with photosynthesis resulting from reduced sunlight penetration; blanketing gravel substrates where fish spawn, rear their young, and where algal and invertebrate food sources live; filling up of pools where fish feed, take refuge from predators and rest; abrasion of gills and other sensitive tissues of aquatic organisms; reduced visibility for catching food and avoiding predators; and, transport of hydrophobic contaminants (Horner et al. 1994). Consequently, a number of environmental agencies in Canada and the USA use TSS as the critical constituent in stormwater quality control (e.g. the Province of Ontario (MOE 2003) and the State of Connecticut (CDEP 2004)), and similar action has been proposed, for example in Switzerland (Rossi et al. 2003, 2006, 2013).

A common trait of the studies by He et al. (2011), Sharma et al. (2011), Mahbub et al. (2011) and Borris et al. (2013) was the investigation of the effects of climatic changes on pollutant transport only by discrete rain event simulations. Using different models, He et al. (2011) and Mahbub et al. (2011) observed that increased runoff contributed to increased wash-off of catchments, and therefore increased concentrations and loads of washed off constituents in stormwater. Catchment imperviousness influenced not only runoff generation, but also the accumulation and consequent wash-off of pollutants (Hatt et al. 2004). Sharma et al. (2011) investigated the effects of increased rainfall intensity on pollutant build-up and wash-off processes under an assumption that the pollutant wash-off was proportional to rainfall intensity; thus, neglecting the cases when wash-off was limited by pollutant supply limitations. Borris et al. (2013) allowed for supply limitations and noted another cause of changes in stormwater quality – resulting from changes in the runoff contributing area. Increased rainfall depths and intensities allowed contributions of pervious areas, which under the old rainfall regime either produced less runoff or no runoff at all. Thus, rain events of intermediate intensity are particularly sensitive to climate changes, and may produce significantly higher pollutant loads in a changed climate. Since those rain events contribute a high percentage of the annual rainfall (Roesner et al. 2001), it is also likely that annual pollutant loads may change significantly.

A common limitation of the above studies arises from the nature of discrete event simulations, in which the initial catchment conditions, including soil moisture and pollutant accumulation on the catchment surface, may be misrepresented. To mitigate such a limitation, this study was undertaken with the overall aim of examining, by means of continuous simulations, the climate change scenario effects on the urban stormwater quality in three urban catchments of various imperviousness, assuming the current (existing) pollutant sources and design practices (e.g. impervious fractions). The study focused on TSS concentrations and loads in stormwater runoff simulated for climatic series with increased rainfall intensities and temperatures reflecting future climate projections in the sub-arctic and temperate climate regions.

**METHODS**

Continuous simulations of stormwater runoff and TSS loads in three test catchments were carried out for two recent rainfall series and the projected future climate scenarios, and analyzed with respect to the quality of urban runoff from these catchments in a changing climate. The catchments were selected to represent urban developments with various degrees of imperviousness (23–63%), and the climate scenarios represented both downscaled results of a regional circulation model (FC1, FC2 and FC3), as well as a recommendation of the Swedish Water Agency, which assumes a constant climate factor (CF) of 1.2 for future rainfall depths (hence referred to as scenario plus20). This CF
value is comparable to those abstracted by Willems et al. (2012) from studies carried out in Canada, Denmark and Sweden, for durations and return periods typical for design of minor drainage systems (return periods 2–10 years, durations 1–3 hours). A potential influence of high TSS accumulations at the end of the melting period, resulting from winter road maintenance, was also considered in additional model runs with high TSS accumulations at the beginning of simulations.

**Catchments studied**

Three test catchments of greatly varying imperviousness were selected for this study, namely a residential suburb of Kalmar, which is located on Baltic coast in the south of Sweden (56° 40' 02” N/16° 17’ 51” E), a residential catchment in Skellefteå in the north of Sweden (64° 45’ 0” N/20° 57’ 0” E), and a highly-developed western subarea of the Skellefteå catchment, with high imperviousness. Further details follow.

**Kalmar residential catchment (KRC)**

The KRC is a residential suburb of the City of Kalmar (36,400 inhabitants in 2010) situated by the Baltic Sea in the south-east region of Sweden with a temperate climate. The catchment area is 140 ha, of which 32.3 ha are directly connected impervious surfaces yielding a relatively low imperviousness of 23%. The area comprises residential properties, with a typical lot size of 1,000 m². Surface drainage of the catchment is provided by lawns, impervious areas and swales sloping towards sewer inlets. Subsurface drainage is provided by separate concrete storm sewers, ranging in diameter from 0.15 to 1.0 m. In an earlier study conducted by Danish Hydraulic Institute (DHI) (Strander & Andréasson 2004) for the municipality of Kalmar, flow meters were installed at multiple points in the sewer system and used to measure runoff flows. Furthermore, a rainfall record of 13 years’ duration (October 1991–October 2004) was also available for this catchment. Such rainfall and runoff flow measurements were used in this study. The annual precipitation in Kalmar is 484 mm, based on the 1960–1991 climate normal. The main reasons for including the KRC catchment in the current study were the geographical catchment location (representing low-density residential developments and temperate climate conditions), availability of rainfall/runoff data of suitable properties, and availability of the catchment and sewer system discretization for rainfall/runoff modelling.

**Skellefteå residential catchment (SRC)**

The SRC was used in an earlier study by Borris et al. (2013) and consequently its description below is abbreviated. It is a residential part of the City of Skellefteå (32,800 inhabitants in 2010) comprising 235 ha, of which 82 ha are directly connected impervious surfaces, thus yielding an intermediate imperviousness of 35%. The catchment is served by separate storm sewers ranging in diameter from 0.225 to 1.8 m. Similarly as in KRC, in an earlier study conducted by DHI (Lindblom & Hernebring 2007) runoff flows were measured at a number of points in the sewer system. Furthermore, a rainfall record of almost 14 years’ duration (September 1996–July 2010) was available for this catchment. The mean annual precipitation for Skellefteå is 589 mm, based on the 1960–1991 climate normal. The main reasons for including the SRC catchment in the current study were the geographical catchment location (representing an intermediate-density residential developments and sub-arctic climate conditions), availability of rainfall/runoff data of suitable properties, and availability of the catchment and sewer system discretization for rainfall/runoff modelling.

**Skellefteå highly impervious catchment (SHIC)**

The SHIC is a highly-impervious (I = 63%) 34 ha subarea of the SRC catchment, with impervious surfaces attributed to roofs, streets, sidewalks and parking lots. The catchment is served by concrete storm sewers ranging in diameter from 0.5 to 1.8 m. Other conditions are similar to those listed for SRC. The main reason for including the SHIC in the current study was the high imperviousness of the catchment; secondary reasons were similar to those for the SRC catchment.

**Catchment discretization**

For modelling purposes, the catchments studied were subdivided into a number of subcatchments representing the...
physical drainage system, adopting the discretization done in the earlier studies by the DHI (Persson 2011). Essentially, in the DHI approach, subcatchments were assigned to end manholes and additional manholes were added as inlet points to reflect the local drainage patterns. Using this approach, KRC, SRC and SHIC catchments were discretised into 47, 51 and 9 subcatchments, respectively, with the average subcatchment areas ranging from 3.0 to 4.6 ha.

**Historical rainfall records for the study areas and their changes projected for future climate change scenarios**

Simulations of runoff from the test catchments were conducted for two types of rainfall data: (a) historical rainfall records representing the current (reference) climate and (b) four climate change scenarios. In Kalmar, rainfall was recorded by a tipping bucket rain gauge, with a bucket capacity of 0.2 mm, during snow free periods (April–October) over 13 years (October 1991–October 2004), as reported in Berggren et al. (2011). For the same period, daily minimum and maximum temperatures were also available. In Skellefteå, rainfall was recorded by the same type of rain gauge during snow free periods (April–October) over almost 14 years (September 1996–July 2010), and daily minimum and maximum temperatures were also available.

To describe the changing climate, four future climate projections were used to re-scale historical rainfall and temperature data for further use as inputs to simulations. Those future projections included an emission scenario defined in the Intergovernmental Panel on Climate Change (IPCC) report as a medium emissions scenario (A1B), which reflects a more integrated world with fast economic and technical development and stabilizing world population (Nakicenovic & Svart 2000) and projects an intermediate increase in global temperatures. The implementation of future climatic projections for A1B was carried out by the Swedish Meteorological and Hydrological Institute (SMHI) using the global circulation model ECHAM (Roeckner & others 1992) and performing downscaling for the study area by the regional climate model RCA 3 (Kjellström 2005). The future projections reached until the year 2100 and were divided into three different time periods: near-future climate (2011–2040) further referred to as FC1, intermediate-future climate FC2 (2041–2070) and far-future climate FC3 (2071–2100). All three scenarios, FC1–FC3, were used to examine the sensitivity of stormwater quality simulations to various climatic changes. Using the procedure described in Olsson et al. (2012), rainfall records were rescaled with a delta change method for different time periods. In this method, various magnitudes of rainfall intensity are rescaled differently (i.e. using variable CFs) and produce higher maximum rainfall intensities, while the total rainfall depths may decrease. The method also changes the seasonal inter-event periods, which in the cases studied contributed to dryer summers and more rainfall during the rest of the year. Some basic statistics of the rainfall records and their future scenarios are presented in the Results section. Temperatures were rescaled in a similar way, with different increases assigned to different temperature levels, but constant increases for temperatures above 0 °C.

Finally, the Swedish Water Association scenario plus20 (Hernebring & Svensson 2011) was also implemented for both rainfall records by increasing the recorded rainfall intensities by 20%, without making any other changes to the rainfall records.

**Storm Water Management Model (SWMM): calibration and analysis of simulation results**

All rainfall/runoff simulations for the catchments studied were carried out with the SWMM, respectively its surface runoff module, which computes rainfall excess and simulates overland flow using a non-linear reservoir. Runoff hydrographs are computed for individual subcatchments and routed through the sewer network using a modified kinematic wave approach. Runoff quality processes include linear or non-linear build-up of dust and dirt (solids), or other constituents during dry weather, and such accumulations can be reduced by decay or street sweeping. In wet weather, pollutants are fully or partly washed-off (Huber & Dickinson 1988). Detailed descriptions of the SWMM model can be found elsewhere (Rossman 2009).

**SWMM hydrological calibration and runoff quality parameter value choices**

The selection of model process parameters was guided by default values from the model manual (Huber & Dickinson 1988) and model calibration, in which the parameter values
were adjusted to reach acceptable agreement between the measured and simulated runoff hydrographs. As used in this study, the following SWMM model parameters were considered in hydrological calibration: the width of overland flow, impervious fraction, surface roughness (described by Manning coefficients, for impervious and pervious surfaces, respectively), depression storage depths (for impervious and pervious surfaces, respectively), and Horton infiltration parameters.

Individual subcatchments were approximated by rectangles, of which longitudinal axis represented the sewer drain collecting lateral overland flow. Thus, the total width of overland flow W, which is a SWMM input parameter, is twice the longitudinal dimension of the rectangle and the length of overland flow is the subcatchment area divided by 2W. This procedure implies that the parameter W could be considered as a calibration parameter, but in this study it was taken as a measured descriptor of the catchment properties. Subcatchment runoff entered the sewer system through sewer inlets which were the closest ones to the subcatchment area centroids.

Simulated runoff volumes and peaks were calibrated in two steps, by adjusting the catchment imperviousness and surface depression storage. The initial value of imperviousness was determined from catchment data (accounting for directly connected roads and roofs). Subsequently, catchment runoff was simulated for small rain events, producing runoff only from impervious areas, and the imperviousness was adjusted to obtain agreement between the simulated and observed runoff flows. Next, all rain events were used in calibration of the depression storage depth, which was the only remaining parameter affecting simulation results. For the rest of the parameters, default values from the SWMM manual were adopted (Huber & Dickinson 1988). This procedure agrees with the findings of Krebs et al. (2013), who applied genetic parameter optimization to SWMM calibration and found that the depression storage was the key calibration parameter, with all the others showing no or only a minor influence on simulation results. The SHIC catchment is a part of the Skellefteå catchment, and, therefore, it did not require separate calibration. Finally, catchment characteristics, SWMM hydrological parameters (default values) and the calibrated parameters (impervious fraction and surface depression storage depths) are shown in Table 1. In verification runs, the goodness of fit was assessed by linear regression (Tsihrintzis & Hamid 1998) with satisfactory results.

Calibration data in Kalmar comprised 2 months (July–August 2004) of runoff flow measurements at three nodes of the Kalmar sewer system, as well as the corresponding rainfall. This period contained 17 events with a total rainfall depth of 182 mm and was divided into two parts: the first part containing nine rain events (about 56% of the total rainfall) was used for calibration and the second part with eight events (44% of the total rainfall) was used for verifications.

In Skellefteå, calibration data comprised 6 weeks (during July and August 2007) of rainfall and runoff flow measurements at five nodes in the sewer system. This period contained 14 rain events with a total rainfall depth of 210 mm and was also divided into two parts: the calibration part included eight events (58% of the total rainfall) and the verification part contained six events (42% of the total rainfall). Further information on these rainfall/runoff measurements can be found elsewhere (Lindblom & Hernebring 2007).

In both cases, calibration and verification data covered a relatively short period of the year, which might lead to some

### Table 1 | Physiographic and hydrological characteristics of the catchments studied

<table>
<thead>
<tr>
<th></th>
<th>KRC</th>
<th>SRC</th>
<th>SHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contributing area (ha)</td>
<td>140</td>
<td>235</td>
<td>34</td>
</tr>
<tr>
<td>Impervious fraction (ha)</td>
<td>32.3 (23%)²</td>
<td>82 (35%)³</td>
<td>21.3 (62.6%)³</td>
</tr>
<tr>
<td>Subcatchments</td>
<td>47</td>
<td>51</td>
<td>9</td>
</tr>
<tr>
<td>Surface roughness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impervious n</td>
<td>0.018</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>Pervious n</td>
<td>0.10</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Horton infiltration parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum infiltration rate</td>
<td>25 mm/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum infiltration rate</td>
<td>5 mm/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decay coefficient</td>
<td>5 h⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depression storage depth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pervious</td>
<td>2.5–5.5 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impervious</td>
<td>1–2.5 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

²The value shown was adjusted by calibration.
³The value determined from the catchment map.
uncertainties while running the model during other periods of the year.

Besides hydrological calibration, the operation of the SWMM model also required estimation of parameters controlling runoff quality processes. The procedure applied followed that of Borris et al. (2013) and was largely based on the earlier research on pollutant (TSS) build-up and wash-off (Vaze & Chiew 2002, 2005b; Egodawatta & Goo- netilleke 2006; Egodawatta et al. 2007; Brodie & Egodawatta 2011; Li & Yue 2011). The parameters requiring estimation pertain to the equations of build-up and wash-off, which are expressed in the SWMM model as follows:

**Build-up:**

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

(1)

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

**Wash-off:**

\[ W = w_1 q^w_2 B \]  

(2)

where \( W \) = wash-off load of solids (TSS), \( w_1 \) = wash-off coefficient, \( q \) = runoff flow rate, \( w_2 \) = wash-off exponent, and \( B \) = build-up of solids defined by Equation (1).

Recognizing the difficulties with estimating the parameters in Equations (1) and (2), and that these parameters cannot be calibrated for future conditions, ranges of build-up and wash-off parameters were adopted. In the case of build-up, both fast and slow build-up rates were tested. For fast rates, 80% of the maximum build-up was reached in less than 2 days, but for the slow rate, the same build-up took 5.5 days to reach. In routine runs, the maximum build-up mass, representing the initial condition in continuous simulations, was held constant and set to 35 kg of TSS/ha, which produces a standard TSS event-mean-concentration (EMC) value of 100 mg/L, recommended for example for Sweden (Larm 1997) and the USA (US EPA 1985). To test the influence of the initial TSS build up, a second value of 200 kg of TSS/ha (Viklander 1998) was used in a special run. This high value reflects northern climate conditions, in which high applications of sand and grit in winter road maintenance may result in great accumulations of solids on urban streets and roads during the winter months.

Various wash-off rates can be obtained by varying the wash-off coefficient \((w_1)\) in Equation (2). The literature indicates that the wash-off exponent \(w_2\) varies only slightly (Egodawatta et al. 2007) and, accordingly, it was set equal to 1.15. Furthermore, the wash-off rates were adjusted to yield standard EMC values of TSS as 100 mg TSS/L, yielding a wash-off coefficient of 0.04. Taking this value as the best estimate, two more wash-off coefficients were defined as low practical and high practical values, respectively. The low practical value \((w_1 = 0.013)\) yielded TSS EMC of 33 mg/L; the high practical value \((w_1 = 0.12)\) yielded TSS EMC of 300 mg/L. Thus, these values allowed TSS EMC variation within an order of magnitude.

For testing the sensitivity of stormwater TSS simulations to build-up and wash-off parameters, six pairs of different parameter values were chosen and applied in simulations (see Table 2), and will be referred to in the following sections.

**Model runs and their analysis**

Continuous model runs were performed for snow-free seasons of the year, spanning from April to October of each record year. In the Kalmar rainfall record, this resulted in 12 simulation periods, containing on average 68% of the annual precipitation, and in the Skellefteå record, the comparable values were 13 simulation periods and 59% of the annual precipitation. Both climate samples and the corresponding climate scenarios were simulated for all the three test catchments, thus allowing examining results in both

<table>
<thead>
<tr>
<th>Parameter values</th>
<th>Build-up</th>
<th>Wash-off</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Notation</strong></td>
<td><strong>Rate of build-up</strong></td>
<td><strong>Rate of wash-off</strong></td>
</tr>
<tr>
<td>BSWL</td>
<td>Slow</td>
<td>Low</td>
</tr>
<tr>
<td>BSWI</td>
<td>Slow</td>
<td>Intermediate</td>
</tr>
<tr>
<td>BSWH</td>
<td>Slow</td>
<td>High</td>
</tr>
<tr>
<td>BFWL</td>
<td>Fast</td>
<td>Low</td>
</tr>
<tr>
<td>BFWI</td>
<td>Fast</td>
<td>Intermediate</td>
</tr>
<tr>
<td>BFWH</td>
<td>Fast</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 2: Stormwater quality simulation build-up and wash-off parameter pairs
climates, temperate and sub-arctic, for three values of catchment imperiousness. When simulating runoff from catchments with climate scenarios from the other location, such catchments can be viewed as hypothetical test catchments. Notation for simulation runs is shown in Table 3. For each model run, the rainfall depths, runoff volumes and TSS wash-off loads were recorded.

TSS wash-off loads simulated for various climate scenarios were analyzed for variance, in order to determine the statistical significance of differences in simulation results for five different climate inputs. This analysis was carried out for all three test catchments as well as for all six parameter pairs listed in Table 2, and the results were graphically displayed in the form of box plots. Additionally a paired t-test was performed comparing each simulation for the TC scenario with its corresponding simulation for the future scenarios. When comparing different recorded or simulated parameters (rainfall, runoff and TSS wash-off loads) for different scenarios, deviations of the average parameter values (i.e. for the whole simulated periods) from the reference values (for the current climate (TC)) were also expressed in percent of the reference values and displayed graphically.

Finally, additional model runs were performed to demonstrate the influence of increased accumulation of TSS on road surfaces at the start of simulation periods (April 1; typically representing the end of the melting period). In those runs, the initial pollutant build-up was increased from 35 to 200 kg/ha after Viklander (1998), which corresponded to the mass of TSS per curb metre of 0.8 kg, at the end of the winter season. This build-up was then taken as the initial condition in continuous simulations of TSS wash-off.

RESULTS

The presentation of results starts with model calibration and verification, followed by analysis of changes in precipitation, runoff and TSS loads for an average snow-free period.

Model calibration and verification

As the first step of calibration, catchment directly-connected imperviousness values were adjusted as needed. Generally only small adjustments were made, since the initial estimates produced good results. In the case of KRC, the adjusted value was 23%, and for SRC, a calibrated value of 35% was adopted from an earlier study (Borris et al. 2013). Finally, for SHIC, such calibration was not possible (it is a ‘nested’ subcatchment of SRC, located at the downstream end of SRC) and the value determined from maps (63%) was adopted. The depression storage depths for impervious surfaces were set to 1 mm for all the catchments. The pervious depression storage depth was set to 5.5 mm for KRC and 5 mm for SRC, respectively. Examples of verification runs and the goodness of fit achieved for one node in the Kalmar sewer system, located close to the catchment outlet, are shown in Figure 1.

The other two nodes in KRC showed comparable results, but are not shown here for brevity. A similar goodness of fit was reported for SRC by Borris et al. (2013).

Changes in precipitation and runoff

Descriptive statistics of precipitation data for two climate samples, temperate (Kalmar) and sub-arctic (Skellefteå) and the corresponding four future scenarios, limited to the runoff simulation during the snow-free period, are summarized in Table 4.

Several observations of interest can be made concerning the data in Table 4: (a) precipitation during the snow-free period (mostly rainfall) greatly varies, particularly in the case of the sub-arctic climate (Skellefteå), where the maximum values almost double the record average, (b) the minimum precipitation somewhat decreases in the temperate climate (Kalmar), but slightly increases in Skellefteå,

Table 3 | Model runs and the notation used

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Climate sample</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KRC</td>
<td>Temperate</td>
<td>KRC(T)</td>
</tr>
<tr>
<td>KRC</td>
<td>Sub-arctic</td>
<td>KRC(S)</td>
</tr>
<tr>
<td>SRC</td>
<td>Sub-arctic</td>
<td>SRC(S)</td>
</tr>
<tr>
<td>SRC</td>
<td>Temperate</td>
<td>SRC(T)</td>
</tr>
<tr>
<td>SHIC</td>
<td>Sub-arctic</td>
<td>SHIC(S)</td>
</tr>
<tr>
<td>SHIC</td>
<td>Temperate</td>
<td>SHIC(T)</td>
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</tbody>
</table>
compared to TC, and (c) standard deviations increase for future scenarios. Plus20 scenario values are equal to the TC data multiplied by the CF of 1.2 and are shown here just for completeness.

Besides seasonal precipitation statistics, the distribution of precipitation according to the event depth is also of interest. Thus, the distributions of total precipitation into six classes, according to the event precipitation depth (2–5, 5.1–10, 10.1–20, 20.1–30, 30.1–40, and >40 mm), were determined and are shown in Figure 2 for TC, FC3 and Plus 20.

Both climate samples have different distributions of precipitation events with certain rainfall depths. In the temperate (Kalmar) TC climate sample, small events with depths between 2 and 5 mm, represent a much higher percentage of the total precipitation (24.6%) than in the sub-arctic (Skellefteå) TC climate sample (14.6%), and a similar tendency was noted for FC3 as well (20.4 and 12.4%, respectively). In future climate scenarios, the number of these smallest events declined in the temperate climate sample, but increased in the sub-arctic climate sample. The largest events (>40 mm) displayed a reversed trend, contributing a higher percentage of the total precipitation in future scenarios. Thus, climate change projections indicate a redistribution of precipitation events in the direction towards greater-depth events in the future.

Changes in precipitation resulted in changes in runoff simulated for various climate change scenarios:

<table>
<thead>
<tr>
<th>Statistics for rainfall depths of the temperate (KRC) and sub-arctic (SRC) climate samples and future scenarios for snow-free periods (April–October)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperate (Kalmar) Climate sample</strong>^a</td>
</tr>
<tr>
<td>TC</td>
</tr>
<tr>
<td>Average (mm)</td>
</tr>
<tr>
<td>Standard deviation (mm)</td>
</tr>
<tr>
<td>Max (mm)</td>
</tr>
<tr>
<td>Min (mm)</td>
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</tbody>
</table>

^a N = 12 (=length of the record in years).  
^b N = 13 (=length of the record in years).
with somewhat different responses in the two climate samples studied. Whereas for the sub-arctic climate sample (Skellefteå) the percentage changes in runoff follow the changes in precipitation with minor differences, a different response can be observed for the temperate climate sample (Figure 3), in the temperate climate sample and a low imperviousness catchment (KRC), the change in runoff, attributed to increased contributions of pervious areas, exceeded that in precipitation, and reached a maximum difference of about 9% for FC3.

Changes in simulated TSS loads

Using the calibrated SWMM model, simulations of TSS loads were produced and plotted in Figure 4, where TSS loads for TC (current climate) and the four earlier defined future climate scenarios are exemplified by box plots for slow build-up and intermediate wash-off (BsWt). The dot points above the whiskers represent outliers. Similar plots were produced for the remaining five pairs of build-up and wash-off parameters and displayed similar trends as in the figure below, but are not shown here for brevity.
Examination of data in Figure 3 indicates fair variation in TSS loads and some presence of outliers (dot symbols). Based on the analysis of variance, no significant difference could be found between the current and future climate scenarios at a 95% confidence interval for individual cases, even when comparing the results for TC with those for plus20. This was the case for all the catchments and parameter pairs. The paired t-test showed somewhat different results. For all the three test catchments, the test showed statistically significant differences between TC and plus20 at a 95% confidence interval. For low-imperviousness catchment (KRC) only, and BSWH and FC1, no statistically significant differences were found, whereas for the intermediate and high imperviousness catchments (SRC and SHIC) this was the case even for FC2 and FC3, for both parameter pairs containing high wash-off rates (i.e. BSWH and BFWH) and the BSW1 parameter pair. Furthermore, it should be noted that the mean values of all simulations of the TSS loads increased for the future scenarios compared to the current scenario for
all the three test catchments in Kalmar and Skellefteå catchments.

To reduce variation in TSS loads simulated for the three catchments of broadly varying size and generalize the results, the simulated TSS loads were normalized by dividing the catchment loads by the corresponding impervious area, and focusing on two types of climate (temperate and sub-arctic) and three climate scenarios: today’s climate, FC3 and plus20. An example of such results is presented in Table 5, for \( B_3W_L \).

The data in Table 5 provide a useful summary of simulation results, obtained for the chosen build-up and wash-off parameters (\( B_3W_L \)). Catchment imperviousness contributes to lower normalized loads; this is caused by contributions of runoff and TSS loads by the pervious parts of the catchment in today’s climate and even more so in the two future climates (FC3 and plus20). The sub-arctic climate indicated somewhat higher standardized loads, but this difference was not statistically significant. Finally, the highest loads were noted for the two future scenarios tested, FC3 and plus20, with the latter one producing the maximum values (statistically significant compared to TC, but not when compared to FC3).

It was also of interest to examine relative changes in basic simulation inputs (precipitation) and outputs (runoff and TSS loads for three rates of wash-off) for various climate scenarios (FC1–3, plus20) and compare them to those for TC. Such results were produced for the three catchments studied (low to high imperviousness, KRC, SRC, and SHIC, respectively) and the current temperate and sub-arctic climate samples, as shown in Figure 4 for slow build-up. Analogous simulations were produced for fast build-up as well, but the results were practically identical to those in Figure 4 and consequently are not shown here. Note that whenever one of the catchments is used with climatic inputs from the other location, it effectively represents a hypothetical catchment created for that climatic location. The main reason for such numerical experiments was to examine whether varying catchment imperviousness would produce some new insight into the catchment response with respect to TSS simulations.

A number of observations concerning the tendencies in data in Figure 4 can be made. In general, climate change scenarios produced higher average precipitation, by 2–20% and higher runoff, by 4–29%, compared to the current climate. Thus, a generally non-linear response of runoff simulations to climatic changes can be noted. Furthermore, a visual comparison of the graphs in Figure 4 indicates that the two climate samples, temperate and sub-arctic, produced different simulation results. For the temperate climate sample (Kalmar in southern Sweden), minimal changes (<5%) in FC1, FC2 and FC3 runoff volumes can be noted, and the plus20 scenario produced distinctly higher values for precipitation, runoff, and TSS loads. It can be also stated that the runoff results for FC1–FC3 are within the uncertainty of the hydrological calibration (selected for runoff volumes as ±10%). The sub-arctic climate (Skellefteå) produced a different response. The values of TSS loads, precipitation and runoff were increasing from FC1–FC3, and the plus20 scenario represented another step in this series, with a marginal increase in runoff and TSS loads compared to FC3. In this case only the scenarios FC1 and FC2 produced results within the uncertainty of hydrological calibration; FC3 and plus20 scenarios showed larger changes.

A comparison of the two climate samples, temperate and sub-arctic, shows that the precipitation increases for the future scenarios FC1, FC2 and FC3 differ significantly; for the temperate climate sample (Kalmar) a precipitation depth increase of 3% is projected for FC3, whereas the comparable value for the sub-arctic climate (Skellefteå) is 17.5%.

Furthermore, significant differences between the results for the different wash-off rates can be observed. Percentage changes are generally lower for high wash-off rates. When

<table>
<thead>
<tr>
<th>Type of climate</th>
<th>Catchment imperviousness</th>
<th>Normalized TSS loads (kg/impervious ha/season)</th>
<th>TC</th>
<th>FC3</th>
<th>Plus20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperate</td>
<td>Low (23%)(^a)</td>
<td>305</td>
<td>334</td>
<td>388</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intermediate (35%)(^b)</td>
<td>282</td>
<td>299</td>
<td>348</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High (63%)(^c)</td>
<td>268</td>
<td>278</td>
<td>324</td>
<td></td>
</tr>
<tr>
<td>Sub-arctic</td>
<td>Low (23%)(^a)</td>
<td>339</td>
<td>404</td>
<td>432</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intermediate (35%)(^b)</td>
<td>311</td>
<td>359</td>
<td>376</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High (63%)(^c)</td>
<td>288</td>
<td>325</td>
<td>342</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)KRC (Kalmar).
\(^b\)SRC (Skellefteå, whole catchment).
\(^c\)SHIC (Skellefteå, high-imperviousness subcatchment).
comparing different build-up rates, slightly higher percentage changes are observed for fast-build-up.

Examining the results for the three catchments studied, it can be noted that the highest changes occur for the least impervious catchment (KRC) and the lowest for the most impervious catchment (SHIC), regardless of the climate sample applied.

In the case of TSS loadings from urban catchments, there is another important issue concerning the initial build-up of solids on the catchment surface at the end of the winter period. Such a build-up represents an initial condition for the continuous runoff simulations (performed in this study) and it is particularly important for cold climate regions, where large quantities of anti-skid materials (sand and grit) are applied during winter road maintenance. This material is further pulverized by vehicle tires and its particle size distribution and chemical composition may change during the winter period. To demonstrate this effect, two initial build-up values were considered, 35 and 200 kg/ha, where the first one corresponds to the mean TSS concentrations in stormwater of 100 mg/L and the latter value is based on literature data (Viklander 1998). Both initial values were applied in a numerical experiment carried out for a 5.8 ha subcatchment of SHIC, assuming BSW1 and the current sub-arctic climate (Skellefteå, TC). A cumulative wash-off of TSS from the catchment is plotted for those two initial conditions in Figure 5, together with the difference (delta) between both simulated load curves. It can be noted that the effect of the high initial build-up persisted for about 100 days (i.e. throughout the spring season) and produced a load increase of about 650 kg, over this period.

DISCUSSION

The discussion comprises of two parts: runoff and TSS modelling results and their implications for future urban stormwater management.

Modelling results

The TSS loads simulated for both Kalmar and Skellefteå catchments and the five climate scenarios did not differ statistically from each other, based on the analysis of variance. This was explained by huge variance in rainfall inputs, and consequently in the simulated TSS wash-off loads, for various simulation periods. Contrarily, the paired t-test showed significant differences in TSS loads between TC and the four future scenarios, with some exceptions. This would imply that the mean loads for the different scenarios differed significantly, with a general trend of mean loads increasing in the future scenarios. Thus, further discussion addresses tendencies in simulated TSS loads, resulting from different test catchment characteristics, climatic inputs, and TSS build-up and wash-off parameters.

Comparing the three test catchments, different responses to climatic changes were observed. The non-linear response in runoff generation is given by increasing runoff contributing areas in future scenarios, with some pervious parts starting to generate runoff when exposed to higher rainfall depths and intensities (Borris et al. 2013). Probability of this condition occurring is higher in less impervious catchments and the largest relative increase in runoff volume was noted in the least impervious catchment (I = 23%, KRC). This further indicates the importance of pervious catchment elements in studies of climate change impacts on runoff generation. Furthermore, percentage changes in TSS loads were higher for areas with low imperviousness (Figure 4), as a result of expanding runoff contributing areas in future climates. Absolute TSS loads varied depending on the catchment area and imperviousness, in accordance with the reported effects of impervious surfaces on both stormwater quantity and quality (Hatt et al. 2004; Jacobson 2011).
Climate change scenarios produced different tendencies for the two locations studied, indicating more future precipitation (rainfall) and higher year-to-year variations in the subarctic region (Skellefteå, located 900 km north of Kalmar), but only small changes in the temperate climate location (Kalmar). Even though these results may be affected by relatively short precipitation records applied in this study, they agree with the findings of Moghadas et al. (2011) indicating higher future precipitation increases in northern Sweden, compared to the temperate climate region of southern Sweden.

For both climate samples, the results of the downscaled scenarios, in the form of runoff volumes and TSS loads, were below those corresponding to the plus20 scenario recommended by the Swedish Water Agency. However, the comparison of the two climate samples and their future scenarios may be influenced by limiting the simulation period to the snow-free period from April to October; the climatic changes for the full year may be higher, because climate scenarios generally project increased precipitation during winter months (Moghadas et al. 2011). In any case, FC3 projections were closer to those for the plus20 scenario in the sub-arctic location (Skellefteå) than in the temperate climate region of Kalmar. The preceding comparisons suggest that the plus20 scenario is realistic and readily implementable by Swedish municipalities.

Besides differences in seasonal precipitation, differences in total precipitation distribution into events with various rainfall depths are also important and are displayed in Figure 2. In the temperate climate (Kalmar), a higher percentage of total precipitation is contributed by smaller events than in the sub-arctic region (Skellefteå). This distribution of rain events then contributes to increased volumes of runoff, and since stormwater quantity is the main driver for stormwater quality, it has an important effect on changes in TSS loads as well. In the Kalmar climate, relatively small changes in total precipitation led to significant changes in TSS loads; for example, a 3% increase in precipitation caused a 13% increase in the TSS load for the B3W_L parameter pair and FC3.

Concerning the number of rain events during the simulation period, differences can be observed between the two climate samples. According to the projections used here for the temperate climate region of southern Sweden (FC3), small rain events do become even smaller and larger rain events are likely to become more intense, particularly in summer. Consequently, percentage changes in TSS loads can be negative as noted for the highly impervious test catchment (SH1C and temperate climate). In the subarctic region (Skellefteå), changes in storm event rainfalls are distributed more evenly. Another interesting finding can be made by comparing FC3 with plus20 for the Skellefteå climate. Whereas the projected changes in precipitation are almost the same (+17.5% for FC3; +20% for plus20), the resulting changes in runoff volume and consequently the changes in wash-off loads show greater differences. This is most obvious for the low-imperviousness (23%; KRC) simulated in the sub-arctic (Skellefteå) climate. For FC3 the resulting change in runoff is about +20% and for plus20 about +30%. This again documents the great importance of addressing the distribution of the individual events with respect to their characteristics (i.e. depth and intensity) in future scenarios.

Considering the uncertainties in selecting the wash-off and build-up rates for TSS simulations, six combinations of such rates were tested and produced varying results. High wash-off rates induce relatively frequent and thorough scour and cleaning of the catchment surface; thus, for parameter pairs B3W_L and B3W_H (high wash-off rates), practically no changes in wash-off loads can be detected in computer simulations. The differences between slow and fast pollutant build-up can be explained by the influence of TSS supply-limited conditions. For high wash-off rates, the available TSS mass on the surface is exhausted quickly. A further increase in runoff, therefore leads to ‘supply limited conditions’ and relatively small changes in TSS loads. In addition the available TSS mass is lower for successive rain events, if TSS build-up is not fast enough to reach the maximum amount during the dry weather period. Contrarily, there is an increased probability of encountering transport limited conditions for low wash-off rates and fast build up. The percentage changes for B3W_L and B3W_H parameter pairs followed the trend of changes in runoff, whereas the results for parameter pairs containing higher wash-off rates (B3W_H and B3W_H) showed always smaller changes than those for runoff, meaning that supply limited conditions took place. In regions with high use of sand and grit in winter road maintenance (Viklander 1998), the
selection of appropriate initial conditions with respect to TSS accumulations on the catchment is important. High initial values have a most profound effect on TSS simulations, producing much higher TSS loads than the routine runs.

**Implications for future stormwater management**

While the presented modelling results indicate increased runoff and export of TSS from the catchments studied in future climate scenarios, there are two underlying questions concerning the implications of such increases for environmental protection of the receiving waters against stormwater discharges: (a) likelihood of environmental effects and (b) consequences for planning stormwater management. An assessment of ecological risks caused by future stormwater discharge is beyond the scope of this paper and possibly the current level of knowledge in this field (Marsalek 2013), as each particular case is described by the type of urban area, production and quality of TSS in the catchment, level of controls, and receiving water properties (sensitivity, type and size, aquatic habitat features, biodiversity), both now and in the future, and will require locally devised solutions. However, it is possible to identify the influential parameters affecting the discharge/impact processes and promising approaches to stormwater management planning.

Concerning the former issue, two fundamental points were made already in the introduction: TSS exert broad impacts on receiving waters quality and their aquatic habitats and, consequently, control of TSS in urban stormwater has been adopted by a number of jurisdictions (MOE 2005; CDEP 2004) in their stormwater management programs. Control objectives in these programs can be defined by concentration limits on TSS discharges, or by prescribed average removal of TSS from stormwater, and in both cases, such limits depend on the quality of receiving waters. A great deal of ambiguity is introduced into this process by the fact that the existing guidelines (or in some cases standards) for acceptable TSS concentrations in receiving waters broadly vary, as noted in an US EPA overview (US EPA 2005) indicating that 50% of jurisdictions had no numeric standard for TSS, 25% had standards comparing discharge concentrations to background, 20% used an absolute threshold, and the rest used other approaches (e.g. a narrative standard). Furthermore, some standards or references (e.g. Rossi et al. 2006, 2013) define the limiting concentrations as being dependent on discharge duration. Thus, the assessments of receiving waters are site-specific and no generalization of the obtained results is possible.

The latter approach, based on prescribed removals of TSS from stormwater, is more flexible in allowing further discussion of implications of increased runoff volumes and TSS loads for adaptation planning. For good quality receiving waters, average TSS removals of 80% are applied (MOE 2005; CDEP 2004) and can be readily achieved with traditional BMPs, like stormwater ponds and sand filters (TSS removals 82–90%), or more recent bioretention facilities and permeable pavements (TSS removals 80–86%, Urbonas & Olson 2010). Because the performance of these BMPs also depends on runoff flows and volumes, future adaptation planning requires consideration of increases in both runoff flows and TSS loads; without accommodating higher runoff flows, the performance of BMPs may drop below the required level of 80% and such facilities would no longer meet the prescribed performance criterion. Thus, the planning of new stormwater management measures may require accounting for climate changes by increasing the design capacity, with respect to both, runoff flows/volumes, and pollutant fluxes/loads.

The planning horizon for stormwater management measures differs from that for the conveyance infrastructure. While the design life of concrete sewers may be as long as 100 years, the corresponding periods for the earlier listed BMPs vary from 15 to 35 years (Urbonas & Olson 2010). This has significant implications for urban drainage planning: sewers need to be designed for far-future climates (e.g. FC5 or plus20), but BMPs can be planned in a stepwise progression of 15–35 year intervals.

Where municipalities do not have access to the downscaled climate change scenarios, they may follow interim recommendations based on constant precipitation uplifts, as demonstrated here by the recommendations of the Swedish Water Agency (i.e. the plus20 scenario) for Swedish municipalities, and also recommended elsewhere (Willems et al. 2012). This scenario mimicked fairly well the climate conditions in northern Sweden, but somewhat overestimated the changes in southern Sweden (Kalmar). Recognizing large uncertainties in climate projections, and
the benefits of environmental overdesign (better flow reductions and/or pollutant removals), the plus20 scenario is not unreasonable. Where local managers are concerned about the additional costs of designing for plus20, they may consider acquiring a downscaled GCM scenario, or allow for the implementation of additional stormwater management adaptation measures in the catchment in the future (Waters et al. 2003).

Examination of data in Figure 4 indicates that for all six cases displayed (i.e. three imperviousness and two climates), TSS loads increased either as much or less, than runoff volumes. Thus, one can expect higher loads of TSS to be discharged into receiving waters, but not at higher average concentrations. Typically, these increases in loads (and runoff) ranged from 1.09–1.21 and 1.12–1.32 for FC3 and plus20 scenarios, respectively, in the sub-arctic climate, and 0.99–1.12 and 1.14–1.30 for FC3 and plus20 scenarios, respectively, in the temperate climate. Thus, the plus20 scenario indicated higher TSS load increases in all the cases, compared to FC3, and such differences were particularly marked in the temperate climate. The issue remains how to deal with these additional TSS loads, and whether such measures can be generalized. Maintaining the current level of protection of receiving waters (typically stipulated as an average removal of 80% of TSS from stormwater) will require gradual adaptation of the existing stormwater management systems to the ongoing changes. It is worthwhile to note that Urbonas & Olson (2010) estimated rehabilitation cycles for common stormwater BMPs as ranging from 15–35 years, with the short cycle corresponding to bioretention and the long cycles corresponding to stormwater management ponds. Thus, these cycles represent opportunities for adaptation steps, with each step serving to accommodate additional 5–10% of runoff volume and TSS load, depending on the choice of future climate scenario and BMP measures.

Information gained from considerations of the increased initial pollutant build-up after winter (Viklander 1998) shows the importance of catchment cleaning after the winter to remove large solids residues from winter road maintenance in cold climate regions. Such cleaning has to take place before the first large storm comes and washes surface solids into the sewers. Simulations of TSS wash-off from catchments with high initial solids build-up demonstrated that most of the additional build-up was washed off by a few rain events, which occurred early in the simulated period. Furthermore, it can be noted that the total load washed-off almost doubled in simulation runs with the increased initial pollutant build-up. Hence, these results indicate that the period of transition from the winter to spring can be of great importance for stormwater quality and the maintenance of storm sewers and stormwater management facilities (e.g. stormwater ponds). Finally, it should be recognized that future stormwater management will also be affected by other factors than just climatic changes. Such factors include changes in pollutant sources as well as in environmental practices (e.g. street cleaning).

CONCLUSIONS

Continuous simulations of stormwater TSS loads for three catchments, six pairs of TSS build-up and wash-off parameters, and rainfall inputs from two current climate records, as well as the four projected future climate scenarios, during snow-free periods (April–October), demonstrated that changes due to perturbation in the climatic inputs cause high variability of simulation results. Consequently, no statistically significant differences between the current and future loads of TSS were found based on the analysis of variance. However, simulation results suggest that average TSS loads washed off from urban catchments similar to those studied are likely to increase in the future, because of the projected climatic changes. A constant precipitation uplift (+20%) climate change scenario recommended by the Swedish Water Agency for Swedish municipalities (plus20 scenario) seems realistic for northern Sweden (sub-arctic climate), but may overestimate the changes produced by downscaled scenarios for southern Sweden, where in Kalmar, the downscaled climate change scenarios did not differ much from the current conditions. However, on an annual basis covering winter conditions as well, higher changes in precipitation and TSS wash-off can be expected.

Comparisons of responses of three different catchments for two climate samples and downscaled future scenarios showed that a variety of factors influenced the simulation results. Catchment hydrological responses were affected by the imperviousness; the catchment with a low
imperviousness (Kalmar, 23%) produced higher percentage changes in runoff volumes and TSS loads, when compared to catchments with higher imperviousness (35 and 63%, respectively). The relative changes were explained by increasing runoff contributing area, resulting from pervious elements runoff contributions for higher rainfall, but unit area runoff volumes and TSS loads increased with increasing imperviousness. Furthermore, significant differences between the two climate samples (temperate and sub-arctic) were observed. Because of different distributions of the rain events of various depths, runoff volumes and consequently TSS loads were affected differently in the future climate scenarios. A high proportion of small rain events (<5 mm) was noted in the temperate climate sample and caused a difference between changes in total precipitation and the corresponding runoff volume. Since stormwater quantity is the main driver for quality, changes in runoff affected the TSS loads as well. Therefore, relatively small changes in precipitation input caused high changes in TSS loads. Those patterns could be observed independently of the build-up and wash-off parameter pairs describing stormwater quality processes. Finally, the catchment initial conditions at the end of the winter period with respect to TSS accumulations caused by winter road maintenance can have a great impact on annual TSS (and associated pollutant) loads and should be controlled by timely catchment cleaning.

Relatively short design lives of stormwater BMPs (15–35 years) allow the planning of stormwater management in future climates in a step-wise progression of 15–35 years, with each step increasing the stormwater management capacity by less than 5–10%. Compared to the concrete infrastructure, with a design life of 100 years and the need to plan for far future climate scenarios, the adaptation process for stormwater BMPs offers more flexibility with respect to the selection and updating of climate change scenarios and the financing of gradual BMP adaptation.

REFERENCES


Kjellström, E. 2005 A 140-Year Simulation of European Climate with the New Version of the Rossby Centre Regional Atmospheric Climate Model (RCA3). SMHI, Norrköping.

Krebs, G., Kokkonen, T., Valtanen, M., Koivusalo, H. & Setälä, H. 2015 A high resolution application of a stormwater

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Persson, O. 2011 Personal communication.

Roeckner, E. 1996 *The Atmospheric General Circulation Model ECHAM-4: Model Description and Simulation of Present-Day Climate*. Max-Planck-Institute for Meteorology, Hamburg.


Urbonas, B. & Olson, C. C. 2010 *Assessment of Stormwater BMP Cost Effectiveness*. A draft manuscript available from Urban Watersheds Research Institute, Denver, CO.


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