

Simulating future trends in urban stormwater quality for changing climate, urban land use and environmental controls

Simulation des évolutions futures de la qualité des eaux pluviales urbaines en fonction du changement climatique, de l'urbanisation et des contrôles environnementaux

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RÉSUMÉ

Les effets du changement climatique, de l'urbanisation croissante et de l'amélioration des contrôles de l'environnement sur la qualité des eaux pluviales simulées dans une communauté de la Suède du Nord ont été étudiés. De futurs scénarios rendant compte de ces changements ont été développés et leurs effets simulés avec le Modèle de Gestion des Eaux Pluviales (MGEP). Il a été observé que la qualité des eaux pluviales simulées était hautement sensible aux scénarios mimant une urbanisation croissante avec une imperméabilité variable et au bassin versant. Le changement d'occupation des sols a donc été identifié comme un des facteurs les plus influents et dans certains scénarios, la croissance urbaine a provoqué des changements dans la quantité et la qualité du ruissellement, supérieurs à ceux provoqués par un changement climatique. Des mesures d'adaptation, comprenant la réduction des surfaces imperméables directement connectées à travers l'intégration d'espaces verts supplémentaires dans le paysage urbain, ou la déconnexion de ces surfaces, ont été efficaces dans la réduction du volume de ruissellement et des charges polluantes. De plus, les mesures de contrôle des sources de polluants, comprenant le remplacement de matériau (ex. : limiter la teneur en cuivre des plaquettes de frein) ont été efficaces dans la réduction des charges polluantes et ont considérablement amélioré la qualité des eaux pluviales.

ABSTRACT

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 imperviousness and the catchment 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 (e.g., limiting copper content in brake pads) were effective in reducing pollutant loads and significantly improving stormwater quality.

KEYWORDS

Climate change, Computer simulation, Influential factors, Future scenarios, Urban stormwater quality

1 INTRODUCTION

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 by avoiding water ponding, and protection of receiving waters against the pollution conveyed by urban 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, commonly 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 climate variability attributed to anthropogenic causes leading to climate change. Thus, there is a need to assess the vulnerability of the existing UDSs in a changing climate and develop risk management measures focusing on adaptation measures.

The vulnerability of UDSs is particularly critical with respect to the flooding issues, and indeed, 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, but so far such efforts have not resulted in recommendations of universally accepted methods or approaches for selecting the 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. Some studies even indicate extreme increases in runoff flows (He et al., 2011), which could not be managed for the current level of service (i.e., safety and convenience), because of costs. Other approaches are more cautionary, as e.g. advocated by the U.S. federal interagency report (2009) recommending a four-step strategy: (a) track change impacts, (b) anticipate changes with respect to climatic data, (c) anticipate change by selecting appropriate decision making methods, and (d) respond by adaptation.

Much less attention has been paid to 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 e.g. flooding. Thus, the problem here could be formulated as what is the vulnerability of the existing urban drainage systems, with stormwater quality measures and structures, to a changing climate and how one could maintain (or improve) the performance of the existing systems in a changing climate. One of the weaknesses of the research on stormwater quantity is the fact that this work often addresses just the aspects of changes in climatic inputs to UDSs in the future, but neglects other factors, including progressing urbanization and changes in environmental practices. To avoid the same problem in the assessment of stormwater quality, one needs to consider two basic driving forces, changing climate and progressing urbanization, and consider the ongoing and future changes in stormwater management and pollutant source controls 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 (Sharma et al. 2011, Borris et al. 2012, He et al. 2011). Changes in the rainfall regime do affect the quality of stormwater (described e.g. by total suspended solids), as noted by the aforementioned authors. Similarly, the 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 such measures as pollution source controls (Marsalek and Viklander, 2011) as well as best practices for stormwater management, which can be viewed as climate change adaptation measures for mitigating the impacts of a changing climate on worsening of the stormwater quality. In this connection it needs to be recognized that beside 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 (Marsalek et al. 2008).

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, Hernebring and Svensson 2011). Consequently, higher runoff flows carrying higher pollutant loads are expected, especially for low-to-medium intensity rain events which were found to be sensitive to climate changes

(Borris et al. 2012). Such risks can be mitigated by best management practices (BMPs) improving stormwater quality by source controls, limiting the availability of pollutants for wash-off, and by treatment. Hence, it is required to assess the likely changes in stormwater quality and the feasibility of designing adaptation measures preserving or improving the performance of the 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 current most advanced urban runoff models are capable of simulating the generation of urban stormwater runoff, with a high 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 (Tsihrintzis and Hamid 1998, Vaze and Chiew 2003a). 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 the future trends in the 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 intensifying urban land-use activities, and (c) the ongoing and future efforts in controlling sources of the selected pollutants (TSS and two metals).

2 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.

2.1 Future Scenarios

In Nakicenovic (2000) scenarios are defined as images of how the future might unfold and they are meant to assist in the understanding of possible future developments of complex systems. In order to develop meaningful scenarios, the studied system should be described in a structured way and along this description scenarios can be developed. Related to the urban stormwater quality this has to be done for different constituents of interest, which were represented in this study by three constituents: TSS (total suspended solids), Cu (copper) and Zn (zinc). In the description of urban stormwater quality, different physical, regulatory, social, economic, environmental and technical dimensions need to be taken into account, as illustrated in Figs. 1 and 2. In Figure 1 general factors and their interrelationships are shown.

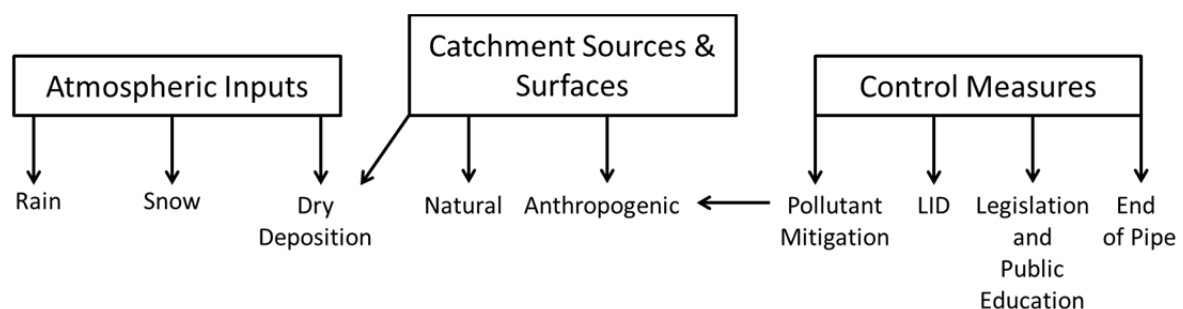


Figure 1. General factors influencing stormwater quality

A detailed hierarchic structure for man-made sources and surfaces is shown in Fig. 2.

Even though this description is far from complete, it is helpful for developing future scenarios. According to Fig. 1 three general types of changes may occur in the future and consequently 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).

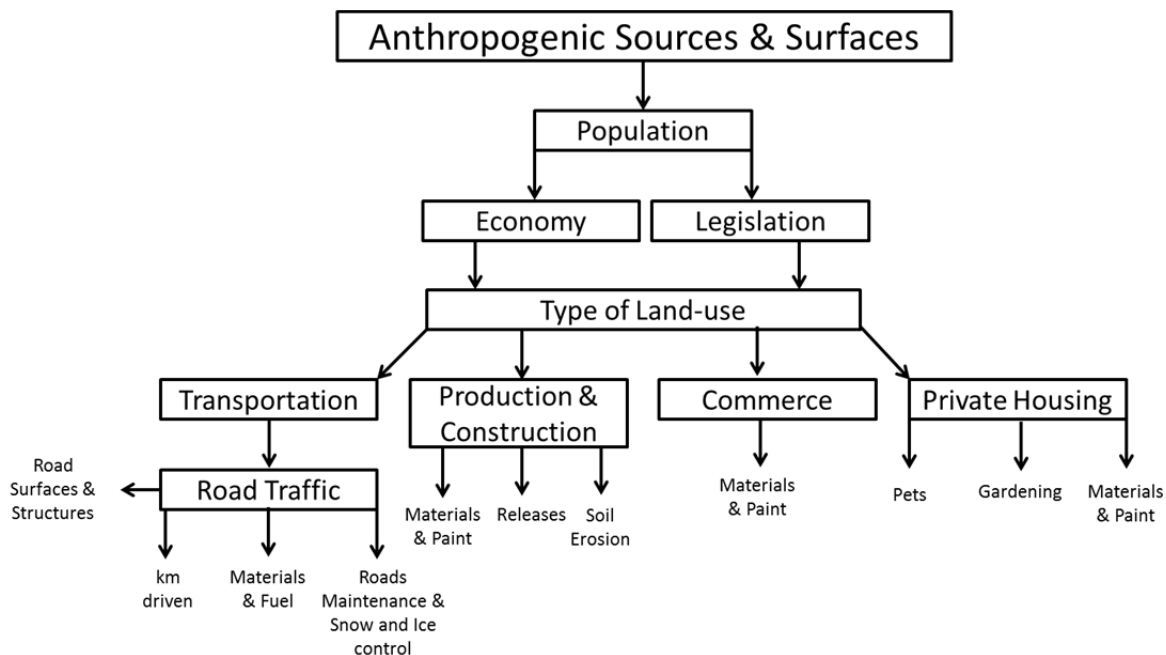


Figure 2. Hierarchic structure of man-made pollutant sources in stormwater

Since the focus of this preliminary study phase is on TSS and the heavy metals, scenarios affecting those constituents are particularly of interest. In urban areas traffic and the corrosion of metal surfaces are known to be the main sources of heavy metals in stormwater runoff (Fuchs et al. 2006, Hillenbrand et al. 2003, Davis et al. 2001). 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 later in sections 2.4.1 and 2.4.2) and will serve as a reference scenario 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 improvement of adaptation measures resulting in landscape changes, namely in the integration of more green spaces into the urban landscape. Consequently, the area of directly connected impervious surfaces is reduced.

Scenario 3: Increasing fuel prices and public education result in changed driving habits and a fewer kilometres driven. This results in a lower production of particulates (TSS) due to traffic (e.g. less abrasion of pavements and tire wear) 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. Currently, copper content in brake pads may be relatively high and contribute greatly to copper loads in urban stormwater (Hillenbrand et al. 2003). While some jurisdictions, including the State of Washington legislated great reductions in copper content of brake pads (not more than 5% and 0.5% by 2021 and 2025, respectively) (Stormwater 2010), in Sweden no such regulation has been introduced yet and a high reduction potential can be expected.

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% (from 9.3 million today to 10.7 million by 2050) (Statistics Sweden 2011). This densification may result in an increasing catchment imperviousness, 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 a peripheral growth of the affected urban area, also known as urban sprawl. In this scenario, urban dwellers are moving away from the city centre to the suburbs, or even to the outlying rural areas. Such a type of urban development increases the dependency on car transportation, which is reflected in the increased number of cars per household and the distances travelled (km driven) (Van Metre et al. 2000, Behan et al. 2008). Furthermore, some of the additional km driven fall outside of the city studied, thereby increasing the ecological footprint of the city. 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.

Scenario	1	2	3	4	5	6
Climate	future ¹	future	future	future	future	future
Population	current	current	current	current	increased	increased
Land development	current	LID ²	current	current	current area, more impervious	larger area, urban sprawl
Traffic & Buildings	current	current	less km driven	current	increase	more km driven
Newly legislated source controls	none	none	none	less Cu in brake pads	none	none

¹ More rainfall, higher rainfall intensities, ² LID = Low Impact Development

2.2 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 setting of an urban drainage model for the catchment and the provision of good physiographic and hydrometeorological data, including a rainfall record with high temporal resolution and flow measurements at several sewer system nodes.

2.3 Model Description

The Storm Water Management Model (SWMM) was chosen as the simulation engine, recognizing that other well-established models should produce comparable results. In SWMM, the computation of surface runoff is based on the theory of non-linear reservoir, and the hydrologic abstractions considered include surface depression storage and infiltration on pervious surfaces. Runoff from impervious areas occurs when rainfall exceeds the depression storage depth. Runoff from pervious areas occurs when rainfall exceeds the infiltration rate and the depression storage is full. Using the kinematic wave approach, a runoff hydrograph is computed for each subcatchment considering the physical properties of the subcatchment, including the area, length of overland flow, ground-slope, imperviousness and surface roughness. 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 other constituents (solids). In the latter case, potency factors are used to compute such pollutants as a fraction of TSS (Huber and Dickinson 1988).

2.4 Model Setup

Based on the stormwater drainage system and the local topography the test catchment was delineated with a contributing area of 235 ha. For catchment discretization, subcatchments were assigned to end manholes and some intermediate manholes, as practiced by the Danish Hydraulic Institute (DHI) (Persson, O., personal communication, October 2011). Consequently, the catchment area was divided into 51 subcatchments, which represent a fairly detailed discretization.

2.4.1 Hydrological Parameter Estimation and calibration

The hydrological calibration of the model was adopted from the prior studies (Borris et al. 2013) and the calibrated parameter values can be summarized as follows: 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.

2.4.2 Parameter Estimation for quality processes representing the current scenario (S0)

A set of parameters for TSS build-up and wash-off can be defined on the basis of the earlier studies published in the literature (Vaze and Chiew 2003b, Egodawatta et al. 2007, Li and Yue 2011, Brodie and Egodawatta 2011, e.g. Vaze and Chiew 2002, Egodawatta and Goonetilleke 2006). Equations (1) and (2) were used to describe the build-up and wash-off:

$$\text{Build-up: } B = b_1(1 - e^{-b_2 \cdot t}) \quad (1)$$

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

With the chosen build-up rate constant of 0.3, 80% of the maximum build-up is reached in 5 days. The maximum build-up mass was held constant and set to 35 kg of TSS/ha. Testing different maximum build-up masses was not needed, since wash-off patterns were independent of the maximum build-up; the fraction removed by a single rain event remains the same, so the produced results can be directly scaled up.

$$\text{Wash-off: } W = w_1 q^{w_2} B \quad (2)$$

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

The wash-off exponent showed only a minor sensitivity for the range of values reported in the literature and was set to 1.15. To get a best estimate of practical values of parameters in eq. (2), the wash-off rates were adjusted to yield standard 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 can be also based on prior studies analyzing heavy metal concentrations in sediment build-up on different urban surfaces (Duong and Lee 2011) and on runoff quality characteristics listed in general databases. Larm (1997) recommended heavy metal concentrations in stormwater for different urban land uses in Sweden. Table 2 shows the potency factors for the two metals studied and the resulting mean concentrations. Recognizing great variations in observations, these values were chosen as representing a mixed urban land use.

Table 2. Potency factors and modelled mean concentrations

	Copper	Zinc
Potency Factor	0.4	2
Mean Concentration [$\mu\text{g/l}$]	40	200

2.4.3 Implementation of the future scenarios

Potential changes as described in section 2.1 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 (b_1) for TSS and the potency factors for the heavy metals studied. For the imperviousness, the catchment area, and the buildup rate, three parameter values were tested to consider a range of likely values and address the involved uncertainty. Those 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 3 summarizes the parameters and their variation in the model for the future scenarios.

2.4.4 Historical climate data and climate change scenarios

A historical rainfall record can serve as a sample of the current climate. Only liquid precipitation in the form of rain was studied; snowfall was considered outside of the scope of this study. The available rainfall data were recorded over a period of 15 years (1996 – 2010) using a tipping bucket rain gauge, with a bucket volume corresponding to 0.2 mm of rainfall. To reflect climate change, future climate projections were used and the historical rainfall records were rescaled to serve as an input to the stormwater runoff simulations. Among the future projections, a medium severity scenario was used, namely the AIB scenario, defined in Nakicenovic (2000). The future projections span from 2011 until the year of 2100, but for this study, only the projections for the middle of the 21st century (2041 –

2070) were selected, since this period was considered reaching as far into the future, as could be handled with some confidence. The rainfall records were rescaled using the delta change method as described in Olsson et al. (2012).

Table 3. Implementation of the current scenario in SWMM simulations and alterations for future scenarios

Scenario	0	1	2	3	4	5	6
Climatic input	current	future	future	future	future	future	future
Imperviousness (%)	35	35	29.8; 31.5; 33.3	35	35	36.8; 38.5; 40.3	35
Area (ha)	235	235	235	235	235	235	246.8; 258.5; 270.3
Build-up rate	0.3	0.3	0.3	0.255; 0.27; 0.285	0.3	0.3+15%	0.3+10%
Potency Factor Cu	0.4	0.4	0.4	0.4-10%	0.4 - 25%	0.4+15%	0.4+10%
Potency Factor Zn	2	2	2	2-5%	2	2+15%	2+5%

2.5 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.

3 RESULTS & DISCUSSION

For the modelled periods the rainfall depth increased on average by 9% for the future scenarios, compared to the current scenario. In Table 4 the runoff volumes simulated for the different scenarios and the constituent loads are shown as average values for the parameter ranges tested.

Table 4. Runoff volumes and percentage changes in constituent loads

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

Figure 3 shows the percentage changes compared to Scenario 0. The error bars indicate the min and max values for the parameter ranges tested.

Generally 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 & 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 & 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 & 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, which happens when there is 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 & 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 transported.

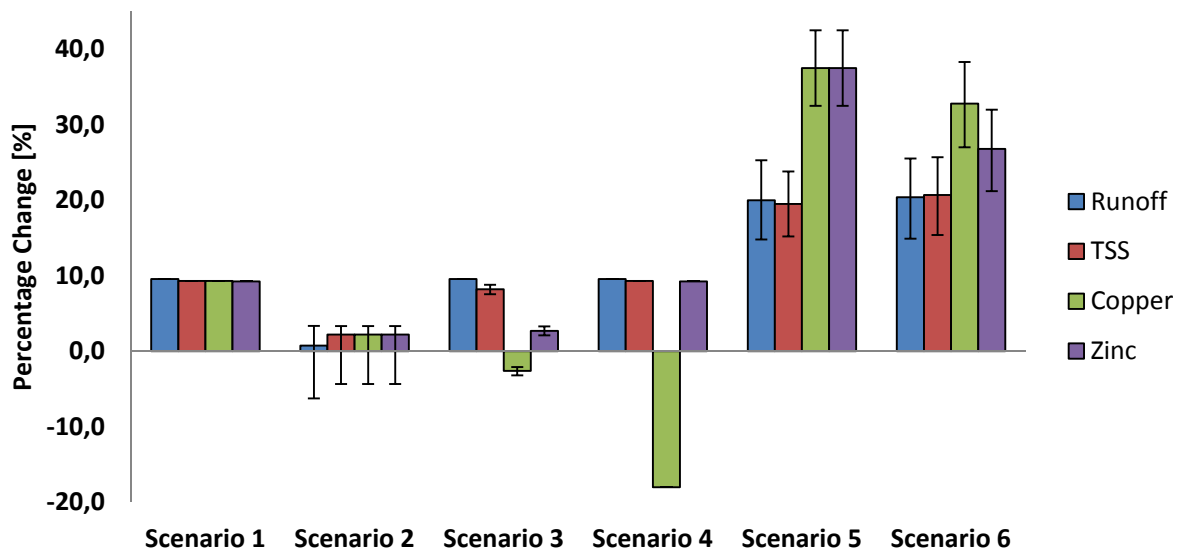


Figure 3. Percentage changes for the future scenarios

As noted for runoff volumes, it can be stated that a 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 followed strictly 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 current scenario. Therefore such pollutant source control measures can be effective tools for improving stormwater quality. Based on these results, a general finding can be formulated that less traffic and pollutant source control measures 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 out of gasoline is a good example of that; Marsalek and 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 & 6) produced high pollutant loads, which were in some cases almost 40% higher than the reference load (S0). This suggests that especially combined effects of changes in the urban development (increasing the urban area and its imperviousness) and higher releases of heavy metals due to more intensive land-use increase the 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 a connection between the level of directly connected impervious areas and the quality of runoff. For example, Hatt (2004) concluded that loads of various pollutants were strongly correlated with the magnitude of directly connected impervious areas.

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 to

explore 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.

4 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 a 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 directly connected impervious surfaces 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 reducing pollutant loads and significantly improving stormwater quality.

LIST OF REFERENCES

- BEHAN, K., MAOH, H. and KANAROGLOU, P., 2008. Smart Growth Strategies, Transportation and Urban Sprawl: Simulated Futures for Hamilton, Ontario. *Canadian Geographer* 52 (3): 291-308.
- BORRIS, M., VIKLANDER, M., GUSTAFSSON, A. and MARSALEK, J., 2012a. Using urban runoff simulations for addressing climate change impacts on urban runoff quality in a Swedish town. *Proceedings of the Ninth International Conference on Urban Drainage Modelling: 4-6 September 2012*. Belgrade, Serbia.
- BORRIS, M., VIKLANDER, M., GUSTAFSSON, A., MARSALEK, J., 2013. Modelling the effects of changes in rainfall event characteristics on TSS loads in urban runoff. *Hydrological Processes*, DOI 10.1002/hyp.9729.
- BRODIE, I.M. and EGODAWATTA, P., 2011. Relationships between Rainfall Intensity, Duration and Suspended Particle Washoff from an Urban Road Surface. *Hydrology Research* 42 (4): 239-249.
- DAVIS, A.P., SHOKOUHIAN, M. and NI, S., 2001. Loading Estimates of Lead, Copper, Cadmium, and Zinc in Urban Runoff from Specific Sources. *Chemosphere* 44 (5): 997-1009.
- DUONG, T.T.T. and LEE, B.K., 2011. Determining Contamination Level of Heavy Metals in Road Dust from Busy Traffic Areas with Different Characteristics. *Journal of Environmental Management* 92 (3): 554-562.
- EGODAWATTA, P., THOMAS, E. and GOONETILLEKE, A., 2007. Mathematical Interpretation of Pollutant Wash Off from Urban Road Surfaces using Simulated Rainfall. *Water Research* 41 (13): 3025-3031.
- EGODAWATTA, P. and GOONETILLEKE, A., 2006. Characteristics of pollution build-up on residential road surfaces. *Proceeding of the International conference on hydroscience and engineering*. Drexel University, Philadelphia.
- FUCHS, S., SCHERER, U. and HILLENBRAND, T., 2006. Sources and pathways of heavy metals in urban areas *Proceedings of IWA World Water Congress and Exhibition, 10.-14. Sept.* Beijing.
- HATT, B.E., FLETCHER, T.D., WALSH, C.J. and TAYLOR, S.L., 2004. The Influence of Urban Density and Drainage Infrastructure on the Concentrations and Loads of Pollutants in Small Streams. *Environmental Management* 34 (1): 112-124.
- HE, J., VALEO, C., CHU, A. and NEUMANN, N.F., 2011. Stormwater Quantity and Quality Response to Climate Change using Artificial Neural Networks. *Hydrological Processes* 25 (8): 1298-1312.
- HERNEBRING, C. and SVENSSON, G., 2011. *Nederbördsdata Vid Dimensionering Och Analys Av Avloppssystem; Precipitation Data for the Design and Analysis of Drainage Systems*. Stockholm: Svensk Vatten.
- HILLENBRAND, T., et al., 2003. *Discharges of Copper, Zinc and Lead to Water and Soil - Analysis of the Emission Pathways and Possible Emission Reduction Measures*. Berlin: Federal Environmental Agency Germany.
- HUBER, W.C. and DICKINSON, R., 1988. *Stormwater Management Model. Version 4, Part A. User's Manual*. Washington D.C.: U.S. Environmental Research Agency. Office of Research and Development.
- JACOBSON, C.R., 2011. Identification and Quantification of the Hydrological Impacts of Imperviousness in Urban Catchments: A Review. *Journal of Environmental Management* 92 (6): 1438-1448.

- KAYHANIAN, M., SUVERKROPP, C., RUBY, A. and TSAY, K., 2007. Characterization and Prediction of Highway Runoff Constituent Event Mean Concentration. *Journal of Environmental Management* 85 (2): 279-295.
- LARM, T., 1997. *Standard Concentrations of Pollutants and Nutrients in Stormwater*. Stockholm: Streets and Real Estate Administration in the City of Stockholm.
- LI, H. and YUE, L., 2011. Research on Method of Confirming Typical SWMM Water Quality Parameters. *Advanced Materials Research* 243-249 5308-5313.
- MARSALEK, J. and VIKLANDER, M. (2011). Controlling Contaminants in Urban Stormwater: Linking Environmental Science and Policy. In: LUNDQVIST, J., 2011. *On the Water Front: Selections from the 2010 World Water Week in Stockholm*. Stockholm International Water Institute (SIWI), Stockholm.
- MARSALEK, J., JIMENEZ-CISNEROS, B., KARAMOUZ, M., MALMQUIST, P.-A., GOLDENFUM, J. and CHOCAT, B., 2008. *Urban Water Cycle Processes and Interaction*. UNESCO and Taylor & Francis: Paris and Leiden, The Netherlands.
- MOGHADAS, S., BERGGREN, K., GUSTAFSSON, A. and VIKLANDER, M., 2011. Regional and Seasonal Variations in Future Climate - Is Green Roof One Solution? *Proceedings of the 12th International Conference on Urban Drainage*. Porto Alegre/Brazil.
- NAKICENOVIC, N., et al., 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Washington State: Pacific Northwest National Laboratory, Richland, Environmental Molecular Sciences Laboratory.
- OLSSON, J., GIDHAGEN, L., GAMERITH, V., GRUBER, G., HOPPE, H. and KUTSCHERA, P., 2012. Downscaling of Short-Term Precipitation from Regional Climate Models for Sustainable Urban Planning. *Sustainability* 4 (5): 866-887.
- PERSSON, O., personal communication, October 2011.
- SHARMA, A., et al., 2011. Effect of climate change on stormwater characteristics and treatment efficiencies of stormwater retention ponds *Proceedings of the 12th International Conference on Urban Drainage*. Porto Alegre/Brazil.
- STATISTICS SWEDEN., 2011. *Sveriges Framtida Befolkning 2011-2060 ;the Future Population of Sweden 2012-2060*. Stockholm: Statistics Sweden.
- STORMWATER, 2010. Regulating copper in brake pads. March 28, 2010 [viewed October 12, 2012]. Available from: <http://www.stormh2o.com/SW/Forum/598.aspx>.
- TSIHRINTZIS, V.A. and HAMID, R., 1998. Runoff Quality Prediction from Small Urban Catchments using SWMM. *Hydrological Processes* 12 (2): 311-329.
- USGS, US ARMY CORPS OF ENGINEERS, U.S DEPARTMENT OF THE INTERIOR and NOAA, 2009. Climate change and water resources management: A federal perspective. Reston, VA.
- VAN METRE, P.C., MAHLER, B.J. and FURLONG, E.T., 2000. Urban Sprawl Leaves its PAH Signature. *Environmental Science and Technology* 34 (19): 4064-4070.
- VAZE, J. and CHIEW, F.H.S., 2003a. Comparative Evaluation of Urban Storm Water Quality Models. *Water Resources Research* 39 (10): SWC51-SWC510.
- VAZE, J. and CHIEW, F.H.S., 2003b. Study of Pollutant Washoff from Small Impervious Experimental Plots. *Water Resources Research* 39 (6): HWC31-HWC310.
- VAZE, J. and CHIEW, F.H.S., 2002. Experimental Study of Pollutant Accumulation on an Urban Road Surface. *Urban Water* 4 (4): 379-389.
- VIKLANDER, M., 1997. Snow quality in urban areas. Ph.D. Thesis. LTU, Lulea, Sweden.
- WILLEMS, P., OLSSON, J., ARNBJERG-NIELSEN, K., BEECHAMS, S., PAHIRANA, A., BUELOW GREGersen, I., MADSEN, H. and NGUYEN, V. T. V., 2012. *Impacts of Climate Change on Rainfall Extremes and Urban Drainage Systems*. IWA Publishing: London, New York.
- ZOPPOU, C., 2001. Review of Urban Storm Water Models. *Environmental Modelling & Software* 16 (3): 195-231.