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Source-Based Modeling Of Urban Stormwater Quality Response to the Selected Scenarios Combining Future Changes in Climate and Socio-Economic Factors

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Abstract The assessment of future trends in urban stormwater quality should be most helpful for ensuring the effectiveness of the existing stormwater quality infrastructure in the future and mitigating the associated impacts on receiving waters. Combined effects of expected changes in climate and socio-economic factors on stormwater quality were examined in two urban test catchments by applying a source-based computer model (WinSLAMM) for TSS and three heavy metals (copper, lead, and zinc) for various future scenarios. Generally, both catchments showed similar responses to the future scenarios and pollutant loads were generally more sensitive to changes in socio-economic factors (i.e., increasing traffic intensities, growth and intensification of the individual land-uses) than in the climate. Specifically, for the selected Intermediate socio-economic scenario and two climate change scenarios (RSP = 2.6 and 8.5), the TSS loads from both catchments increased by about 10 % on average, but when applying the Intermediate climate change scenario (RCP = 4.5) for two SSPs, the Sustainability and Security scenarios (SSP1 and SSP3), the TSS loads increased on average by 70 %. Furthermore, it was observed that well-designed and maintained stormwater treatment facilities targeting local pollution hotspots exhibited the potential to significantly improve stormwater quality, however, at potentially high costs. In fact, it was possible to reduce pollutant loads from both catchments under the future Sustainability scenario (on average, e.g., TSS were reduced by 20 %), compared to the current conditions. The methodology developed in this study was found useful for planning climate change adaptation strategies in the context of local conditions.

Keywords Source-based modeling · Stormwater quality · Future scenarios · Climate change · Socio–economic factors

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Introduction

It is a broadly accepted fact that a number of future changes in physical (e.g., glaciers and permafrost soils), biological (terrestrial and marine ecosystems) and human-managed systems (e.g., livelihoods, food production and economics) may be attributed to climatic changes (Barros et al. 2014). Consequently, one can refer to those changes as climate change impacts and there is a huge interest in assessing such impacts, in order to develop adaptation and/or mitigation strategies. Such assessments are usually based on future scenarios, which reflect conceivable future developments. The goal of applying scenarios is not to predict the future, but rather to discover the underlying uncertainties, in order to make informed decisions of a robust nature under a wide range of possible futures (Schwartz 1996). Berkhout et al. (2002) further state that those scenarios should account for both future changes in climate as well as changes in socio–economic factors, since only by combining those two groups of influential factors it is possible to evaluate the impact of climate change on future societies. Towards this end, Van Vuuren et al. (2012) suggested developing scenarios for climate change impact assessment around a matrix consisting of radiative forcing levels (and the associated climate signal) and socio-economic conditions. The application of this framework across all disciplines would facilitate the development of a more consistent and comparable research on climate change impacts (Van Vuuren et al. 2012).

Berkhout et al. (2002) pointed out that changes in socio-economic systems are often not sufficiently incorporated in climate change impact assessment studies, and their argument can be supported by examples from urban stormwater management, where many of the earlier studies focused just on increased risks of flooding due to future climatic changes, without considering changes driven by socio-economic factors (Waters et al. 2003; Berggren et al. 2011; Jung et al. 2015). A relatively small number of studies in that field highlighted the importance of taking socio–economic factors into account, by for example addressing changes in land-use and the capacity of drainage systems (Semadeni-Davies et al. 2008; Lafontaine et al. 2015).

Recently, also the importance of assessing future climate change impacts on stormwater quality was suggested, in order to ensure the effectiveness of the existing stormwater quality infrastructure in future climates (He et al. 2011; Sharma et al. 2011; Borris et al. 2013; Borris et al. 2014b; Wu and Malmström 2015). The need for such assessments follows from the fact that urban stormwater is recognized as an environmentally significant source of conventional as well as priority pollutants (US EPA 1983; Björklund et al. 2009; Zgheib et al. 2012), and adversely impacts water quality in many receiving environments (Marsalek et al. 2008). Pollutant accumulation on catchment surfaces during dry periods and wash-off during wet weather depend on climate characteristics (e.g., rainfall intensity) (Vaze and Chiew 2003b), as well as on pollutant sources (Davis et al. 2001; Gobel et al. 2007; Petrucci et al. 2014). The type and strength of pollutant sources, as well as the catchment characteristics, depend on land-use and intensity of related activities (Gobel et al. 2007). At the same time, there are ongoing efforts to control pollutant discharge with stormwater runoff into the receiving waters through environmental management as source controls and many other management interventions referred to as stormwater best management practices (BMPs) or low impact development (LIDs) measures (Elliott and Trowsdale 2007). Hence, more realistic scenarios should recognize that in the future, the stormwater pollution generation is likely to change not only because of climate change, e.g., changing rainfall characteristics, but also because of progressing urbanization, contributing to changes in the current land-use patterns and pollutant sources, and because of environmental controls.

Recognizing that stormwater quality strongly depends on stormwater quantity (Marsalek et al. 2008), the approach to stormwater quality changes in the future climate focused on quantity impacts and socio-economic factors were barely addressed in studies of future trends in stormwater quality. So far, such studies focused on climate change impacts on stormwater quantity and the resulting implications for stormwater quality (He et al. 2011; Sharma et al. 2011; Borris et al. 2014b; Wu and Malmström 2015), with few exceptions. In a large watershed, El-Khoury et al. (2015) studied combined effects of changes in climate and land-use on nutrient loads, and identified both as important with respect to water quality and quantity variables. For an urban catchment, Borris et al. (2013), beside climatic changes, also considered changes in land-use and environmental management, and identified the latter changes as highly important, within some limitations of their study. Among such limitations, one could list at least two: (a) the chosen modeling approach, with stormwater quality parameters lumped for the whole catchment, without the possibility of tracking major pollutant sources, and (b) considering only one catchment, without actual stormwater quality data. Hence, only limited conclusions could be drawn from that study. Thus, there are opportunities for further advancement of knowledge on combined effects of changes in climate and socio-economic factors on stormwater quality.

The objective of the presented work is to examine the combined effects of potential changes in climate and socio-economic factors on stormwater quality in two urban catchments, on the basis of simulations with a source-based computer model. Furthermore, the sensitivity of stormwater quality changes to variations in climate and socio-economic factors was also addressed, and the use of two catchments, one centrally located and the other one in suburbs, allowed examination of different methods of adaptation applicable in different locations within the urban area. Thus, the methodology developed in this study can be used for planning climate change adaptation strategies in the context of local conditions.

Methods

Four scenarios were simulated for two mixed land-use urban catchments; a base scenario reflecting the current conditions and three future scenarios mimicking different future developments of climate change and socio–economic factors.

Study Sites

The two study sites were located in Östersund, a Swedish city with about 45,000 inhabitants. The first catchment in central Östersund is characterized by high imperviousness and mostly commercial and institutional land-uses, and is further referred to as the "central" catchment. The second catchment is a low imperviousness mixed land-use catchment in a suburb of Östersund, further referred to as the "suburban" catchment. The main reason for choosing these catchments was the availability of stormwater quantity and quality data. Furthermore, the catchments differed significantly in size, layout and the mix of land-uses, which allowed testing responses of different catchments to possible future changes. Table 1 summarizes the characteristics of the two catchments.

Rainfall was recorded by a tipping bucket (0.2 mm resolution) located about 900 m from the central catchment and about 2 km from the suburban catchment. The record contains 87 individual events with a total rainfall depth of 755 mm, in the 2012 and 2013 snow-free periods combined. The minimum/maximum rainfall depths of those events were 2 and 40 mm, respectively. Precipitation in the form of snow was not recorded. Based on the 30-year average (1961–1990), Östersund receives annually 350 ± 72 mm of precipitation as rain during those months. Therefore, the rainfall record implied slightly wetter conditions, than indicated by the climate normal.

Base Scenario

In the base scenario, the model setup represents the current situation, including the areas and distribution of various land-uses. The model parameters were calibrated against field measurements performed in 2012 and 2013.

Future Scenarios

A new scenario framework for climate change research was used in order to develop future scenarios. Within this framework, a matrix of representative greenhouse gas emissions and concentration pathways (RCPs) and shared socio–economic pathways (SSPs) was developed by Van Vuuren et al. (2012). The RCPs describe the evolution of greenhouse gas concentrations in the atmosphere and the consequent changes in climate factors (e.g., temperature and precipitation). Within the SSPs, the future development of socio-economic driving forces is described for example by economic development, population growth, technology development, and environmental policies. This new framework allows for a comparison across various combinations of SSPs and RCPs extending until the end of the 21st century. The application of this framework would help develop a consistent and comparable research within and across different research communities (Van Vuuren et al. 2012). Following this general approach, three future scenarios, denoted as Sustainability, Security and Intermediate (i.e., between sustainability and security) scenarios, were developed here and supplemented by environmental strategies, which would be developed locally and as such may be somewhat independent of climate change. Note, however, that it is climate change, and the need for adaptation, which provide impetus for developing such environmental strategies.

Sustainability Scenario

This scenario was developed in accordance to the SSP1 scenario defined by Kriegler et al. (2014) and mimics a world, where the adoption of sustainable development proceeds at high pace. This includes rapid technological changes towards environmentally friendly processes and environmental protection due to awareness of environmental degradation. Generally the population is well educated and grows slowly. Carbon dioxide emissions can be reduced, fossil fuel dependency is decreasing, and consequently, climate change is somewhat controlled. Furthermore, this scenario is analogous to Östersund's plans for developing their city in the future (Östersund Municipality 2014).

It is, therefore, assumed that the study catchments develop in a way that stormwater quality is controlled by mitigation strategies. Well-designed structural stormwater BMPs/LIDs are installed, targeting pollution hotspots. Generally, the urban settlements become denser and some well-planned new settlements may develop. Due to low population growth, low urban sprawl and alternative transportation, traffic intensities are stagnating.

Security Scenario

This scenario was developed in accordance to the SSP3 scenario defined by Kriegler et al. (2014) and represents a

Table 1 Characteristics of the test catchments

Land-use	Central catchment (ha)	Suburban catchment (ha)
Roofs (connected to sewer system)	1.43 (65 %)	1.54 (8 %)
Roofs (not connected to sewer system)	n.a.	5.76 (31 %)
Streets	0.12 (6 %)	1.09 (6 %)
Parking areas	0.20 (9 %)	0.86 (5 %)
Green areas	0.25 (11 %)	7.83 (42 %)
Other unpaved areas	0.20 (9 %)	1.40 (8 %)
Total area	2.20	18.5

vision of the world, where focus is placed on energy and food security. Such a world is struggling to maintain the living standards for a strongly growing population, and economic goals are prioritized before environmental goals, which results in relatively low investments in technology development and education. The fossil fuel dependency is high and most emissions are not mitigated, which results in relatively large climatic changes.

The study catchments are growing intensively, because of the high population growth. New settlements are not well planned, which causes urban sprawl contributing to increased traffic intensities and overburdened roads. Only some conventional BMPs may be installed and become quickly undersized.

Intermediate Scenario

This scenario was developed in accordance to the SSP2 scenario defined by Kriegler et al. (2014) and reflects an intermediate pathway between the Sustainability and the Security scenarios.

Finally, the features of the Sustainability and Security scenarios are summarized in Table 2.

Stormwater Quality Model Description

The source-based stormwater quality model WinSLAMM was chosen as a simulation engine. It was developed in the late 1970s, and continuously updated and expanded (Pitt and Voorhees 1989; Pitt 2008). WinSLAMM is strongly based on actual field observations and includes a variety of source areas as well as different management options. During the model development, special emphasis was placed on small storm hydrology and particulate wash-off, since large percentages of annual pollutant loads are transported with such small storms.

Stormwater quantity is computed for individual events by the application of event runoff coefficients for each type of land-use. Furthermore, such coefficients depend on rainfall depths, with generally low coefficients for small rain events and higher coefficients for larger events.

Total suspended solids (TSS) are calculated continuously for street contributions and on the basis of events for the remaining land-use surfaces. For street surfaces, TSS loads are computed by TSS build-up and wash-off functions. During dry periods, a fast build-up occurs in the beginning, but the rate of build-up decreases over time and eventually becomes zero. During rain events, an exponential wash-off function is used and produces a first flush. Furthermore, a wash-off reduction coefficient is applied, reflecting the situation, in which particles may be dislodged, but not transported to the sewer inlet. This coefficient depends on the rainfall depth; high reductions apply to small events.

For the remaining land-uses (roofs, parking lots, green areas, etc.) particulate solids concentrations are applied for the individual land-uses to compute TSS loads on per event basis, by multiplying the respective concentrations by event runoff volume from the individual land-uses. The total TSS load is then calculated as the sum of individual land-use contributions. The particulate solids concentrations available in the model are based on TSS measurements in runoff for different rain events and land-uses.

Finally, loads of three heavy metals of concern (copper, lead, and zinc) are computed for each land-use either as a fraction of TSS (particulate metals) or as concentrations in runoff from the individual land-uses (dissolved metals). Both the fraction of heavy metals in particulates and the dissolved standard concentrations are based on runoff measurements, and are processed in a similar way as described earlier for particulate solids (Pitt and Voorhees 1989).

Model Setup, Calibration, and Validation

Using GIS-software and high-resolution local maps, the types and sizes of land parcels with different land-uses were identified, as summarized in Table 1.

Table 2 Summary of scenario features (sustainability and security)

Scenario features	Scenario	
	Sustainability	Security of energy and food
Environmental education	Prioritized	Lower priority
Transition towards sustainable development	Rapid	Slow
Environmental technology advancement	Fast	Slow
Population growth	Low	High
Type of urban (re)development	Densification of existing developments	Urban sprawl
Type of stormwater management	Proactive—LID	Conventional BMPs
Dependency on fossil fuels and CO_2 emissions	Reduced and declining	Uncontrolled
Contributions to climate change	Controlled	Uncontrolled

For calibration and validation, two sets of five monitored rainfall/runoff events were available. The calibration procedure was performed as suggested in Pitt (2008), starting from the model default values and then adjusting model parameters to obtain good fit. First stormwater quantity was calibrated by altering runoff coefficients until a good agreement was achieved. This was followed by calibration for TSS and finally for the heavy metals (copper, lead, and zinc). Recognizing that the model focuses on processes, the model calibrated for the central catchment was validated in the suburban catchment and the goodness of fit of validation runs was assessed by linear regression in the form $y_s = sy_m$ (y_s = simulated value; y_m = measured value; s = line slope), as done e.g., by Tsihrntzis and Hamid (1998). Both the regression function and the correlation coefficient were evaluated; the slope of the regression line should be close to 1 (perfect fit) and the R^2 value, which determines the goodness of fit, should also be close to 1. Since WinSLAMM calculates runoff volume on an event basis, other goodness of fit measures based on hydrographs (e.g., Nash–Sutcliffe) were not applicable.

Implementation of the Future Scenarios and Uncertainty Assessment

The projections of both the SSPs and RCPs span until the end of the 21st century. In this study, only the projections for the middle of the 21st century were selected, since this period was considered reaching as far into the future as could be handled with some confidence. Both projections for climate change (RCPs) and socio-economic changes (SSPs) involve large uncertainties. Furthermore, computer simulations by themselves are uncertain and, therefore, also contribute to the overall uncertainty of results. The above three general sources of uncertainty were assessed and pooled, in order to provide insights of possible ranges of pollutant loads within the future scenarios.

RCPs

Downscaled climate scenarios for the Östersund region were acquired from the Swedish Meteorological and Hydrological Institute (SMHI). Data were available for a low climate change scenario, further referred to as RCP 2.6, an intermediate climate change scenario (RCP 4.5), and a high climate change scenario (RCP 8.5). Within the individual RCPs, ensembles of datasets were available. For RCP 2.6, three different datasets were available, and for each RCP 4.5 and 8.5, nine datasets were available. Those datasets differed mainly by the choice of the climate models (SMHI 2015). The use of ensembles provides valuable insights into the uncertainty of climatic changes.

Besides other information, those datasets contain annual information on how much precipitation may change in the future. The data were averaged over a 30-year period in the middle of the 21st century (2035–2064). Those percentage changes were applied to the measured rainfall record by multiplying the rainfall intensities by the factor corresponding to the projected change (SMHI 2015). Table 3 summarizes the RCPs.

SSPs

According to the Östersund Masterplan, the municipality is planning to grow with respect to the number of inhabitants by about 8 % until the middle of the 21st century (Östersund Municipality 2014). This is within the range of the projections for whole Sweden by the year 2050, which are between 6.5 and 18 % (average 13 %) (Statistics Sweden 2009). Furthermore in the Östersund Masterplan (Östersund Municipality 2014), it is also stated that the land development in central parts of the city will be further intensified, in order to benefit from the existing infrastructure, including existing road and drainage infrastructures. On the other hand, some suburban areas will be expanded to offer more space for single family housing. Within the SSPs, this is reflected by an increasing area of the suburban catchment. This is however unlikely to happen in the central catchment, because of space limitations and Östersund's plans for their future development. Therefore, the catchments land-uses were assumed to show higher pollutant generation in future scenarios, due to intensification of land-uses.

In order to implement the three SSPs (Sustainability, Intermediate and Security), different parameters in the model were altered in order to mimic changes in: (1) size of the individual land-uses within the catchment (applied to the suburban catchment), (2) pollutant generation (i.e., constant concentrations values) due to land-use intensification (applied to the central catchment), (3) pollutant generation through traffic (i.e., pollutant build-up rate) caused by urban sprawl and (4) the control of stormwater pollutants through BMPs/LIDs. As those developments are highly uncertain, an ensemble of model setups was developed in order to consider the underlying uncertainty.

Table 3 Summary of the percentage change of rainfall intensities in three RCPs ensembles

	Average	Minimum	Maximum
RCP 2.6 ($N = 3$)	6.8	3.1	12.5
RCP 4.5 ($N = 9$)	11.8	4.3	18
RCP 8.5 ($N = 9$)	14.6	8.1	19

Furthermore, this procedure offers the possibility to identify the most influential factors in future stormwater quality

Land-Use Areas in the Test Catchments

Based on the future projections for population growth, it was assumed that the individual land-uses of the suburban catchment, with respect to impervious areas, may grow in a similar manner (6.5, 13, and 18 % for Sustainability, Intermediate, and Security scenarios, respectively). Additionally, the land-use distribution within the test catchments may change in the future, since either new areas develop or existing areas redevelop and this development may involve a huge uncertainty. In order to consider this, 21 model setups with random distribution of land-uses were developed for each test catchment and each SSP. The size of each land-use was allowed to vary within the range of plus/minus 20 % starting from the value for the respective SSP.

Intensification of Land-Uses

For the central catchment, densification was projected, which was reflected by an increased pollutant generation in the individual land-uses. At the same time, the size of the catchment remained constant. The pollutant generation (i.e., particulate solids concentration values and concentration values for dissolved heavy metals) of the individual land-uses (except streets) was increased by 6.5 % for the Sustainability scenario, 13 % for the Intermediate scenario and 18 % for the Security scenario. These changes were directly proportional to the increases in population. In order to consider the underlying uncertainties, the pollutant generation was varied within the range of plus/minus 20 % starting from the value for the respective SSP. This was done in 21 model setups.

Pollutant Generation Through Traffic Activities

Traffic is recognized as a major source of pollutants transported by urban stormwater (Davis et al. 2001; Fuchs et al. 2006; Gobel et al. 2007). This is the reason why special emphasis was placed on street surfaces as sources of traffic related pollution. Traffic intensities are likely to change in the future, as for example the population and their dependency on vehicular traffic changes. In growing cities, the distances traveled may also change. This effect is known as urban sprawl (Van Metre et al. 2000; Behan et al. 2008). Therefore, depending on the SSP, the pollutant generation due to vehicular traffic may change significantly in the future. Within the model setups, this was represented by altering the pollutant build–up rate on street surfaces. Consequently, the following changes in pollutant build-up rate were assumed: Sustainability: no changes; Intermediate: the rate was increased by 30 %; Security: the rate was increased by 50 %. Undoubtedly, such changes in pollutant generation are highly uncertain. This fact was treated by the randomization of land-use sizes, including streets, for the suburban catchment. In case of the central catchment this was treated by the variation of pollutant generation by ±20 % (starting from the respective value) due to land-use intensification.

BMPs/LIDs

In future scenarios, installations of BMPs/LIDs were assumed within the catchments at different levels of planning and design, and consequently, produced varying pollutant reduction capacities. Furthermore, maintenance of such facilities is a critical issue, since if not properly maintained, their performance may be significantly reduced (Al-Rubaei et al. 2014). A proper maintenance is costly and needs personnel, which is why their long-term performance may vary in the future. This fact was considered by variation of their infiltration capacity, which can be reduced, if not maintained, due to for example clogging. For all three scenarios, the initial infiltration capacity was varied between 100 % (perfect maintenance) and 0 % (total failure). Similar to the before described randomization of the distribution of land-uses, infiltration capacity was generated randomly within this range for the 21 model setups for each SSP. With the help of WinSLAMM, street surfaces were identified as pollution hotspots producing major shares of heavy metals and TSS for both test catchments. Furthermore, connected roof surfaces produced significant amounts of heavy metals. Therefore, grassed swales for streets and biofilters for roof runoff were installed here, serving as examples of commonly applied BMPs/LIDs.

Sustainability

Within the Sustainability scenario, it was assumed that grassed swales were implemented for street surfaces and biofilters for roof surfaces, respectively. Both measures were designed in order to capture about 80 % of the pollutants from the respective land-use. With respect to TSS, this is in accordance to some stormwater management manuals (Ministry of the Environment 2003).

Intermediate

Within the Intermediate scenario, it was assumed that only grassed swales were implemented for runoff from street surfaces. Those measures were designed to capture about 40 % of the generated pollutant loads from street surfaces. Consequently, reduction was assumed to be 50 % lower compared to the sustainability scenario.

Security

Within the Security scenario, a similar setup as in the Intermediate scenario was chosen (only grassed swales for street surfaces). However, those swales were poorly designed by only capturing about 10 % of the generated pollutant loads from street surfaces.

Model Uncertainty

Assessing uncertainty in urban drainage modeling is currently a research topic. There are numerous methods described in the literature, many of which are complex, poorly understood, or still under development (Dotto et al. 2012; Vezzaro and Mikkelsen 2012). Thus, there are no standard procedures for assessing model uncertainty. In the case of WinSLAMM, this problem becomes more complex, since WinSLAMM consists of both categorical parameters, as the type of land-use, and numerical parameters as runoff coefficients. This makes it difficult to apply traditional uncertainty assessment techniques and, therefore, an alternative method was applied here.

In order to assess the uncertainty of WinSLAMM model outputs, result prediction intervals were calculated from the linear regressions derived in the model validation analysis and were used to assess uncertainty for each model run. Assuming normal distribution of data in the prediction interval, such data were sampled 100 times, and the resulting 100 values, distributed normally within the prediction interval, were used in uncertainty analysis.

Model Runs and Statistical Analysis

In order to simulate the future scenarios, the RCPs were combined with the SSPs and every possible combination was simulated within the scenarios. Table 4 shows the combinations of the RCPs and SSPs which were simulated within the scenarios.

Following this matrix, 441 individual model runs were done for each scenario. For each simulation, the accumulated runoff volume, accumulated TSS load, and accumulated heavy metal loads were noted and compared with those for the base scenario. An analysis of variance (ANOVA) was done in order to ascertain whether scenario results differed significantly from each other.

Table 4 Combining RCPs and SSPs in the model runs

	Sustainability	Intermediate	Security
RCP 2.6	X	X	X
RCP 4.5	X	X	X
RCP 8.5	X	X	X

The source-based modeling approach allows determining the most important factors within the SSPs, for which a correlation analysis was done. The respective area and intensity of pollutant production of the individual land-uses as well as the infiltration capacity of the BMPs was correlated to pollutant loads. The correlation coefficient r and p level were noted and used to compare the relative importance of the individual land-uses and performance of the BMPs with respect to pollutant loads.

Table 5 summarizes the implementation of the RCP/SSP-matrix in WinSLAMM

Results and Discussion

Calibration and Validation

Figure 1 shows the evaluation of the validation runs for runoff volume, TSS, copper, zinc, and lead by linear regression. The 1:1 line represents a perfect fit. Both dashed lines show the upper and lower prediction interval.

In general, the simulated values for runoff volumes, TSS, and the heavy metals matched well the observed values. The worst fit was noted for zinc loads, which were underestimated. However, the differences between the observed and simulated values were within the range of those reported in other studies with WinSLAMM (Pitt 2008). For example, in the case of zinc, errors of up to 70 % were reported for some sites and the median error was about 40 %. It was also noted in the literature that other stormwater quality models produced comparable ranges of the goodness of fit (Tsihrintzis and Hamid 1997; Vaze and Chiew 2003a).

Calibration and validation of simulation models are typically done with separate datasets from the same catchment (Sun and Bertrand-Krajewski 2012). However, in this study, the shortage of calibration/validation data contributed to the decision to adopt, with some modifications, the Pitt (2008) procedure consisting in conducting calibration on one test catchment and validating the calibrated model performance on another catchment with generally different characteristics. Such an approach may introduce additional uncertainties into the calibration/validation procedure, mostly because of potential implications of different characteristics of the two catchments. No recommendations were found in the literature concerning the minimum number of calibration events (Liu and Han 2010), even though such a number may significantly influence the performance of calibrated models in the validation process, especially when the calibration data set is small (Sun and Bertrand-Krajewski 2012). Consequently, to avoid splitting the observed events ($N = 5$) into calibration and validation sets, all the five events were used

Table 5 Summary of the future scenarios and their implementation in WinSLAMM

Scenario	Land-use		BMPs/LID	Climate
	Central	Suburban		
Current	Used for calibration	Used for validation	No BMPs/LIDs	Current climate sample
Sustainability	Change of pollutant generation between −13.5 % and +26.5 % for all individual land-uses;	Change of size for all individual land-uses (except green areas) between –13.5 % and +26.5 %	Swales for streets and biofilters for connected roof surfaces, designed to remove 0–80 % of pollutants	RCP 2.6, 4.5, and 8.5
Intermediate	Change of pollutant generation between −7 % and +33 % for all individual land-uses; traffic between +10 % and +50 %	Change of size for all individual land-uses (except green areas) between −7 % and + 33 %; pollutant generation from traffic +30 %	Swales for streets designed to remove about 0–40 % of pollutants	RCP 2.6, 4.5, and 8.5
Security	Change of pollutant generation between −2 % and +38 % for all individual land-uses; traffic between +30 and +70 %	Change of size for all individual land-uses (except green areas) between −2 and +38 %; pollutant generation from traffic +50 %.	Swales for streets designed to remove about 0–10 % of pollutants	RCP 2.6, 4.5, and 8.5

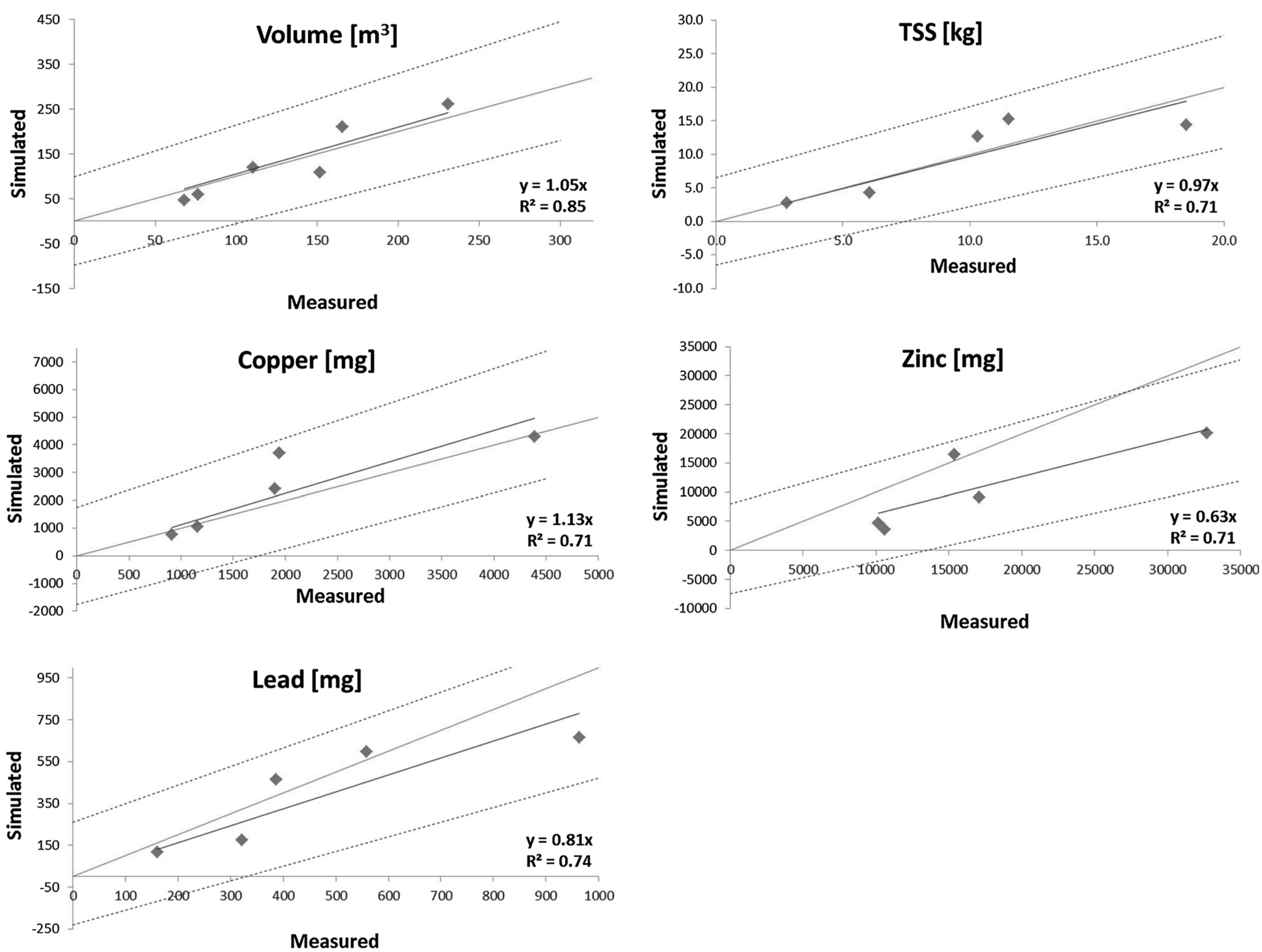

Fig. 1 Evaluation of the validation runs for the suburban catchment (runoff volume, TSS, and heavy metals)

to calibrate the model on the Central catchment and then to validate it on the Suburban catchment. To test the acceptability of this procedure, it was repeated in the reversed order (calibration on the Suburban catchment, validation on the Central catchment), and yielded acceptable results. Within the constraints of limited calibration/validation data, these results were considered as acceptable.

Loads Simulated for Individual Scenarios

TSS and total Zn loads in the two test catchments are shown in Figs. 2 and 3 for the four scenarios simulated, in the form of boxplots. Values obtained for the future scenarios include all model setups for the respective SSP (i.e., $N = 21$) and climate inputs from the RCPs as listed in Table 4. For brevity, the plots of Cu and Pb were omitted, because both metal loads were highly correlated with TSS loads (correlation coefficient >0.9; p levels <0.001) and, therefore, their boxplot shapes were almost identical to those of TSS. In these boxplots, the base denotes the first quartile (Q1, 25 %), the line in the central part of the box indicates the median (50 %), and the roof marks the 3rd quartile (Q3, 75 %). The lower and upper limits of the box are extended by the whiskers, whose extent was set equal to $1.5 \times (Q3 - Q1)$. Furthermore, negative data, which were produced in some cases by calculations of prediction intervals based on the fitted linear regressions from validation runs, were excluded from those plots and further analysis, because there was no physically based justification of their existence.

Generally, the TSS and metal loads for individual scenarios show large variability for all four scenarios, as indicated by the upper and lower ends of the whiskers. Uncertainties attributed to three general sources were assessed: (1) climate input (RCPs); (2) social-economic factors (SSP); and (3) catchment response modeling. Cumulative uncertainties in TSS loads for the three sources are exemplified in Fig. 4 for the suburban catchment and the Intermediate scenario.

Data in Fig. 4 demonstrate that the uncertainty attributed to the catchment modeling process was significantly higher than those attributed to the RCPs and SSPs. The results of the validation runs showed that the runoff volumes were reproduced with the highest accuracy ($s = 1.05$ and $R^2 = 0.85$). Therefore, most of the uncertainty can be attributed to the simulations of stormwater quality (pollutant loads). In order to determine if further analysis of simulated loads would be meaningful in the context of high uncertainties noted, the load results for individual scenarios were compared to the base scenario and the differences were assessed for statistical significance using the ANOVA procedure at a 95 % confidence level. The comparisons of average pollutant loads to the base loads are summarized in Table 6 for three scenarios, and the load differences are expressed as percentages of the Base scenario loads. Furthermore, the loads which the ANOVA analysis identified as not being significantly different from those corresponding to the Base scenario are marked with an asterisk. This designation applied to five cases in the Intermediate scenario simulations; TSS, Cu, and Pb loads in the Central catchment, and TSS and Cu loads in the Suburban catchment.

Comparisons of loads from the two catchments studied for different scenarios indicate similar trends; with reference to the base loads, the loads of all pollutants significantly decrease in the Sustainability scenario, somewhat increase in the Intermediate scenario, and significantly increase in the Security scenario. Based on the ANOVA analysis, the differences in loads among the three future scenarios were statistically significant in all the cases, and the Sustainability and Security scenarios produced loads significantly different from those associated with the Base scenario. However, for the earlier listed five cases in the Intermediate scenario, the differences from the Base

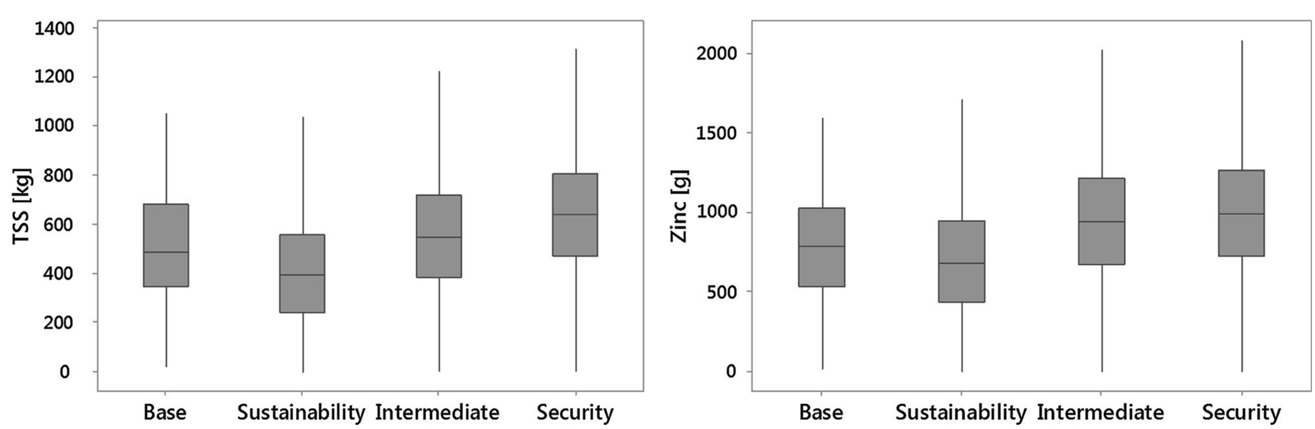

Fig. 2 TSS and zinc loads from the Central catchment simulated for the current (base) and three future scenarios

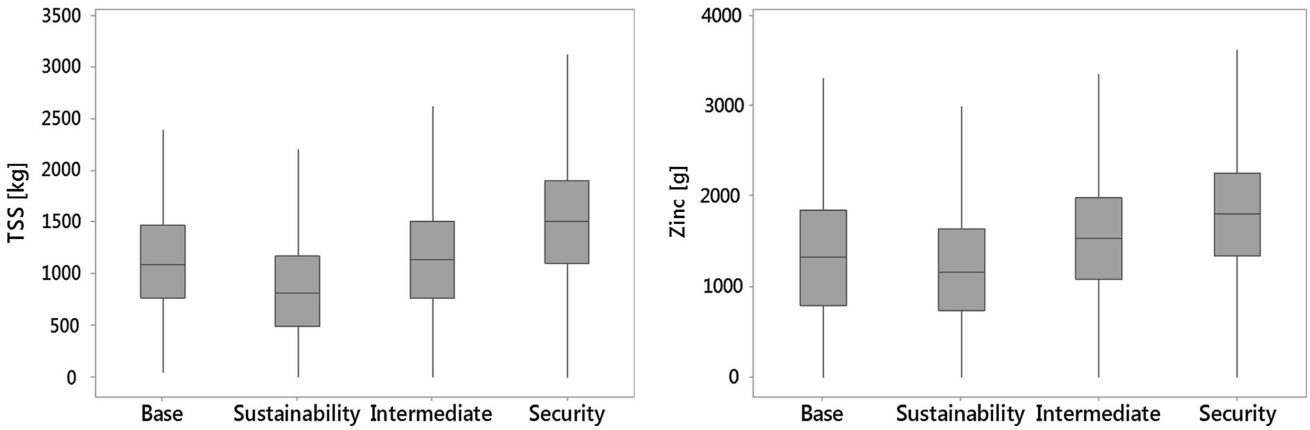

Fig. 3 TSS and zinc loads from the Suburban catchment simulated for the current (base) and three future scenarios

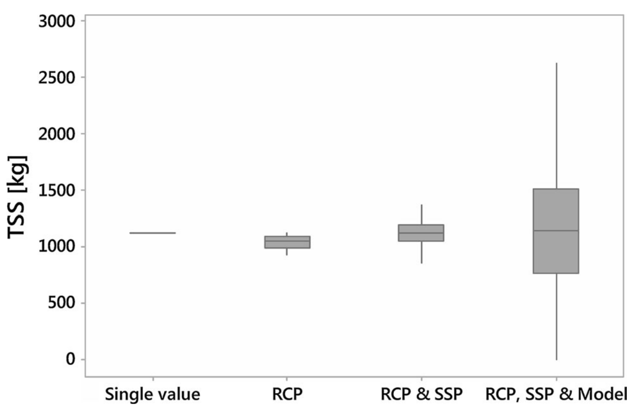

Fig. 4 Cumulative uncertainties for the three sources addressed (climatic input, socio-economic factors, and catchment modeling) for the suburban catchment and the Intermediate scenario

scenario loads were not statistically significant, and the changes in pollutant loads produced by climatic and socio-economic factors (4–10 %) were insignificant, mostly because of high uncertainties in the catchment modeling process. Furthermore, in both catchments, the Intermediate scenario included relatively well functioning BMPs/LIDs of limited extent, which could compensate for the effects of climatic changes as well as the adverse changes in socio-economic factors. One exception to such controls were loads of zinc from both catchments, where roof surfaces contributed relatively high fractions of the catchment loads (up to 50 and 70 %, for the suburban and central catchments, respectively), but no BMPs/LIDs measures for controlling zinc in roof runoff were incorporated into the Intermediate scenario. Potentially high zinc contributions from roof and building materials were reported e.g., by Davis et al. (2001), with zinc contributions from commercial buildings reaching up to 80 % of total loads. The Pb load from the suburban catchment was also significantly different from that corresponding to the base scenario.

For the Sustainability scenario, the TSS and metal loads were significantly smaller than those in the Base scenario, as a result of relatively small changes in climate and socio-economic factors assumed in the Sustainability scenario. Furthermore, well-designed (and maintained) BMPs/LIDs were incorporated in both catchments and could not only compensate for future changes caused by the driving forces, but even somewhat improve the stormwater quality in comparison to the base scenario. Even though the performance of such control measures is site specific and highly variable (Backström 2002), the BMPs/LIDs considered have the potential to reduce significantly pollutant loads in stormwater runoff, as documented in the literature. For example, Barret et al. (1998) reported a TSS-load reduction of up to 85 % for grassed swales and roadside filter strips, and for biofilters, Hatt et al. (2009) reported removal rates

Table 6 Average pollutant loads and percentages changes compared to the base scenario (* no statistically significant difference compared to the base scenario)

		Base	Sustainability	Intermediate	Security
Central	TSS (kg)	512	412 (−20 %)	556 (+9 %)*	635 (+24 %)
	Cu (g)	171	126 (−26 %)	181 (+5 %)*	208 (+22 %)
	Pb (g)	25	21 (−16 %)	27 (+10 %)*	29 (+16 %)
	Zn (g)	784	708 (−11 %)	948 (+21 %)	990 (+26 %)
Suburban	TSS (kg)	1110	852 (−23 %)	1150 (+4 %)*	1500 (+35 %)
	Cu (g)	300	252 (−16 %)	318 (+6 %)*	386 (+28 %)
	Pb (g)	45	38 (−16 %)	51 (+15 %)	65 (+44 %)
	Zn (g)	1380	1220 (−12 %)	1540 (+12 %)	1790 (+30 %)

for TSS and heavy metals loads of about 90 %. However, to deliver satisfactory pollutant load reductions in a long term, the BMPs/LIDs have to be properly maintained, by e.g., mowing the grass in swales and removing sediment and debris. Concerning such maintenance, Blecken et al. (2015) noted that proper maintenance is often hindered by ambiguities in assigning the ownership and operational responsibilities for BMP/LID facilities, and the lack of willingness to pay for potentially high maintenance costs.

In the Security scenario, future pollutant loads increase significantly in both catchments, as a result of relatively high climatic changes combined with progressing intensification of land-use in the central catchment, or progressing urbanization of the suburban catchment (i.e., converting green areas into urban developments). Additionally, the BMPs/LIDs designed for the Base scenario become undersized in the future.

When comparing the two catchments with respect to their response to the future scenarios, it can be noted that relative changes in pollutant loads were generally higher for the suburban catchment in the Security scenario, whereas no obvious differences could be noted for the other future scenarios (i.e. Sustainability and Intermediate). Street surfaces in the two catchments had different shares of directly connected land surfaces (i.e. parking areas, connected roofs and streets); for the suburban catchment this share was 31 % and for the central catchment it was just 7 %. Compared to the central catchment, street surfaces in the suburban catchment, therefore, contributed a large proportion of pollutants; e.g., for the Security scenario such a contribution was about 45 % of total TSS, whereas for the central catchment it was just 32 % of total TSS. For the Sustainability and Intermediate scenarios grassed swales targeting streets worked relatively well, whereas in the Security scenario grassed swales were undersized and that contributed to increased loads. This explains different responses of the test catchments to future scenarios and underlines the importance of incorporating well-designed BMPs/LIDs targeting the pollution hotspots in urban catchments.

Finally it can be noticed, that even though the suburban catchment is about 8.5 times larger than the central catchment, its pollutant loads were approximately only twice as large. This is caused by low contributions of green areas to catchment pollutant loads, less than 1 % for all scenarios. In the suburban catchment, 42 % of the surface is occupied by green areas, whose contribution to the catchment loads was insignificant even in future climate conditions. This is somehow contradictory to the earlier published literature. Borris et al. (2014a, b) were using SWMM for modeling runoff and noted the importance of pervious areas and their potential to contribute to catchment runoff and consequently to pollutant loads in a changing climate, with up-scaled precipitation. Consequently, catchments with high proportions of pervious areas generally showed high relative changes in runoff volumes and TSS loads in future climate conditions, due to runoff contributions from pervious areas. Such a response was not found in the present study with a different catchment model, in which runoff coefficients for green areas were not altered during calibration, since the observed rainfall/runoff events were not sensitive to those coefficients. This lack of sensitivity may be caused by the nature of calibration events, which did not generate much runoff from green areas. In any case, the WinnSLAMM default values are based on long-term measurements in different catchments (Pitt and Voorhees 1989) and represent much more robust data than those collected in this study. It seems therefore likely that different simulation engines may produce different responses to future conditions, because of differences in approaches to modeling catchment runoff and its quality.

Relative Effects of Socio-Economic (SSP) and Climate Change (RCP) Scenarios on Simulation Results

In order to assess the relative importance of climatic changes compared to changes in socio-economic factors, the RCP/SSP-matrix was used and for a chosen SSP, different RCPs were applied and vice versa. This procedure is exemplified in Figs. 5 and 6 for TSS and Zn loads from the suburban and central catchments, respectively, and the following choices of scenarios: (1) Invariable SSP: the Intermediate scenario, and three RCPs (2.6, 4.5 and 8.5), and (2) Invariable RCP (RCP = 4.5) and three SSPs (Sustainability, Intermediate and Security).

Plots for Cu and Pb showed similar patterns compared to those for TSS and are not shown for the sake of brevity. An ANOVA analysis indicated that for the load distributions, obtained by holding the SSP invariable and varying the RCP and vice versa, were significantly different from each other at a 95 % confidence level. However, a visual examination of data in Figs. 5 and 6 indicates that changes in socio-economic factors (SSPs) produced significantly higher variability in pollutant loads compared to the effects of changes in the climatic input (RCPs). This was also the case when testing the two remaining RCPs (2.6 and 8.5) as invariable RCPs, showing small differences in the loads shown in Figs. 5 and 6 (i.e. 1–2 %). Pollutant loads were, therefore, more sensitive to changes in land-use and the application of BMPs/LIDs than to climatic changes (i.e., increased rainfall depth and intensity).

Combined effects of climatic and socio-economic changes on stormwater runoff quality have been rarely addressed so far. Borris et al. (2013) considered such combined effects and identified urbanization as an

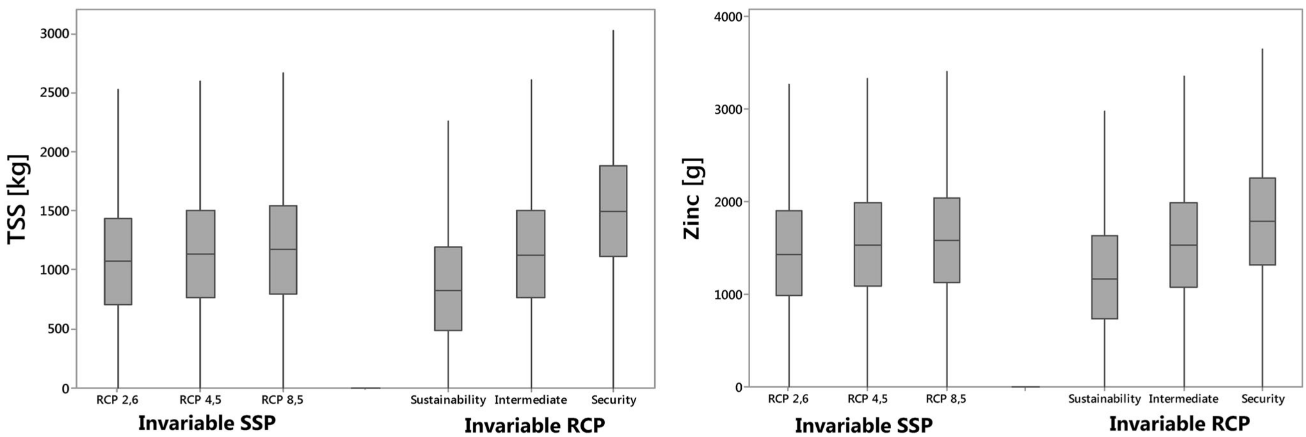

Fig. 5 Relative importance of RCPs and SSPs with respect to TSS and Zn loads from the suburban catchment

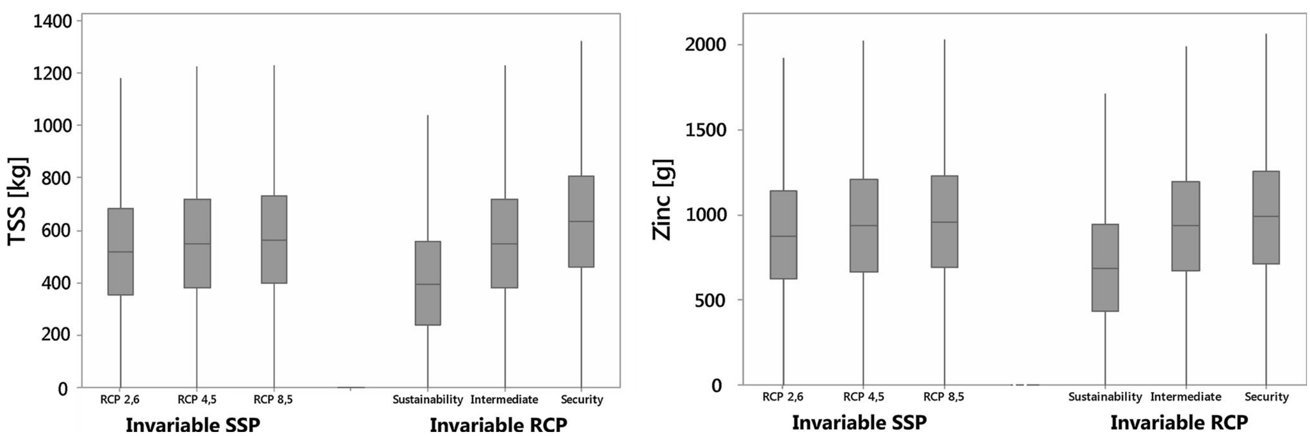

Fig. 6 Relative importance of RCPs and SSPs with respect to TSS and Zn loads from the central catchment

important factor with respect to changes in stormwater quality. However, their conclusions were affected by the limitations of the modeling approach and the lack of model calibration data. Studies focusing on stormwater quantity generally reached similar findings (Semadeni-Davies et al. 2008; Lafontaine et al. 2015) with respect to the influence of urbanization; it was identified as a factor of crucial importance in future climate and socio-economic impact studies. Furthermore, the above and the earlier literature (e.g., Waters et al. 2003) identified the runoff control measures (BMPs/LIDs) as key adaptation instruments for mitigating the combined effects of urbanization and climate change on urban flooding problems.

Correlations of Pollutant Loads with Pollutant Controls and Sources Assumed in Socio–Economic Scenarios (SSPs)

The importance of two pollutant sources (streets and roofs), and control measures attenuating emissions from such sources (BMPs), was assessed by correlation analysis for individual socio-economic scenarios (SSPs) and pollutants (TSS, Cu, Pb and Zn) in both test catchments (suburban and central). Results of such analysis are presented in Table 7 displaying the significant socio-economic factors and their correlation coefficients (r) for the respective pollutant loads. The SSP factors were considered as significant if their r was greater than 0.3. The p levels for the displayed r's were generally smaller than 0.001.

In the Sustainability scenario, with the exception of Zn in the central catchment, only the performance of BMPs/LIDs was of significance with respect to pollutant loads and their reduction (note the negative r values). As shown earlier in Figs. 2, 3, pollutant loads could be significantly reduced, compared to the Base scenario, by incorporating well-designed (and maintained) BMPs/LIDs targeting pollution hotspots.

In the Intermediate scenario, the performance of BMPs/LIDs was of significance only for the suburban catchment. Street surfaces were producing a large proportion of pollutants loads in that catchment, and those loads were

Table 7 Correlation of pollutant loads to socio-economic factors in two test catchments (suburban and central)

		Suburban catchment				Central catchment			
		TSS	Cu	Pb	Zn	TSS	Cu	Pb	Zn
Sustainability	BMP	−0.822	−0.844	−0.753	−0.628	−0.909	−0.905	−0.906	−0.895
	Streets	–	–	–	–	–	–	–	–
	Roofs	–	–	–	–	–	–	–	0.41
Intermediate	BMP	−0.513	−0.445	−0.418	–	–	–	–	–
	Streets	0.513	0.359	0.371	–	–	–	–	–
	Roofs	–	–	–	0.45	0.679	0.485	0.76	0.874
Security	BMP	–	–	–	–	–	–	–	–
	Streets	0.608	0.330	0.431	–	–	–	–	–
	Roofs	–	–	–	–	0.69	0.538	0.739	0.876

effectively reduced by grassed swales incorporated in this scenario. In the central catchment, only roofs were contributing significantly to catchment loads of all pollutants. The observed differences in responses of pollutant sources underline the importance of locally fine-tuned control measures.

In the Security scenario roof surfaces were significantly correlated to pollutant loads in the central catchment and street surfaces in the suburban catchment. In this scenario, the incorporated BMPs/LIDs were ineffective, because they were undersized.

Finally, it can be noted that TSS loads were significantly correlated with roof surface areas, in both, the Intermediate and Security scenarios in the central catchment. Egodawatta et al. (2009) studied pollutant build-up and wash-off processes on roof surfaces and concluded that build-up reached a maximum after some days and a first flush was observed during wash-off. In WinSLAMM the contribution from roof surfaces is calculated by standard concentration values, which do not take such processes into account. Therefore, that simulation engines involving build-up/wash-off sub-models (e.g., SWMM) may produce pollutant loads different from those produced by WinSLAMM.

Conclusions

A source-based stormwater quality model was employed to study combined effects of changes in climate and socio-economic factors on stormwater quality, within a new scenario framework for climate change research and future scenarios. This framework included a matrix of representative concentration pathways (RCPs) and shared socio-economic pathways (SSPs), allowing to study their relative as well as combined importance. Within the realm of limitations of the modeling tool employed, limited calibration data and uncertainties in future scenarios, the following conclusions are drawn:

- The WinSLAMM model realistically reproduced the limited catchment runoff data, comprising runoff volumes and loads of TSS, Cu, Pb and Zn, available for the two test catchments studied. Furthermore, the model was found effective in applying environmental controls (BMPs) targeting specific pollution sources.
- Among the three major sources of high uncertainty in simulated pollutant loads, the simulation process was clearly dominant, when compared to climate change and socio-economic factors. In spite of these uncertainties, the differences between pollutant loads for the Base scenario and Sustainability and Security scenarios, were statistically significant.
- The two test catchments studied generally showed similar responses to the future scenarios. However, in the Security scenario, the suburban catchment showed higher changes in pollutant loads, and this could be explained by the influence of street surfaces (i.e., pollutant sources) and grassed swales controlling pollution from those surfaces in future conditions.
- Pollutant loads were more sensitive to changes in socio-economic factors, described by the SSPs (shared socio-economic pathways), than to climatic changes, which were described by the RCPs (representative concentration pathways).
- Well-designed BMPs/LIDs targeting the pollution hotspots can significantly reduce the pollutant loads in the Sustainability scenario. However, the implementation of such measures may involve appreciable land acquisition and maintenance costs.
- The application of a source-based modeling approach offered benefits while identifying pollution hotspots in the current and future scenarios. This helped to design BMPs/LIDs targeting such hotspots. Furthermore this approach allowed for altering pollutant generation in future scenarios in a way that corresponds to changes in size and intensity of individual land-uses. Thus, one could evaluate which land-uses are most sensitive to

potential future changes with respect to their contribution to pollutant loads.

- Various stormwater quality simulation engines are likely to produce different results in future scenarios, as noted here for two specific cases: (i) In the catchments studied, green areas had minimal effects on pollutant loads in future scenarios; this observation disagrees with that from some earlier studies conducted with a different simulation engine, and (ii) the areas of roof surfaces were highly correlated with TSS loads in future scenarios; this may differ from results obtained with models employing the build-up/wash-off approaches in simulation of roof runoff pollutant loads.

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