Assessment of LID practices for restoring pre-development runoff regime in an urbanized catchment in southern Finland

Mingfu Guan, Nora Sillanpää and Harri Koivusalo

ABSTRACT

This study quantifies the effects of common stormwater management techniques on urban runoff generation. Simulated flow rates for different low impact development (LID) scenarios were compared with observed flow rates during different urban construction phases in a catchment (12.3 ha) that was developed from natural forest to a residential area over a monitoring period of 5 years. The Storm Water Management Model (SWMM) was calibrated and validated against the observed flow rates in the fully developed catchment conditions, and it was then applied to parameterize the LID measures and produce scenarios of their hydrological impacts. The results from the LID scenarios were compared with the observed flow rates in the pre-development and the partially developed catchment conditions. The results show that LID controls reduce urban runoff towards the flow conditions in the partially developed catchment, but the reduction effect diminishes during large rainfall events. The hydrographs with LID are still clearly different from the observed pre-development levels. Although the full restoration of pre-development flow conditions was not feasible, a combination of several measures controlling both volumes and retention times of storm runoff appeared to be effective for managing the stormwater runoff and mitigating the negative impacts of urban development.

Key words | LID practices, pre-development flow, stormwater runoff, SWMM

Mingfu Guan (corresponding author)
Nora Sillanpää
Harri Koivusalo
Department of Civil and Environmental Engineering,
Aalto University School of Engineering,
P.O. Box 15200,
FI-00076 Aalto,
Finland
E-mail: *mingfu.guan@hotmail.com*

Mingfu Guan
School of Civil Engineering,
University of Leeds,
LS2 9JT Leeds,
UK

INTRODUCTION

Urban development strongly alters the catchment-scale water cycle. To mitigate adverse hydrological and water quality impacts of rapid urbanization, a number of stormwater management techniques have been developed and adopted, but there is still a significant debate over the best approaches (Freni *et al.* 2010; Burns *et al.* 2012; Shuster & Rhea 2013). An increasingly attractive approach is decentralization and source control which uses a limited number of control measures distributed throughout a catchment (Booth & Jackson 1997). The terminology related to the control measures varies in different countries, but we use low impact development (LID) to represent the control techniques in this study (Dietz 2007). They generally include infiltration-based technologies and retention-based technologies. The performance of these technologies in restoring catchment scale pre-development runoff regimes has been neither well quantified nor well understood. Therefore, it is crucial and necessary to evaluate the effectiveness of the control measures and their combined impacts before implementation.

Some source control techniques have been investigated in terms of their impacts on hydrology in urban catchments (Carter & Jackson 2007; Ashbolt *et al.* 2013; Bursztа-Adamiak & Mrowiec 2013; Petrucci *et al.* 2013). These studies discussed how urban runoff is changed due to the implementation of such techniques, but substantial measured hydrological data were not available to evaluate the capability of the techniques to restore pre-development flow conditions. Thus, there is a need for data from a pre-development phase to a fully developed phase in a catchment, which seldom exist (Meierdiercks *et al.* 2010; Sillanpää & Koivusalo 2015). Unique, good quality hydrological and meteorological datasets were gathered in a small developing catchment located in southern Finland by Sillanpää (2013). In this urbanized catchment, we performed a pilot study on the feasibility of LID practices. Burns *et al.*

doi: 10.2166/wst.2015.129

(2012) pointed out that urban stormwater management should emphasize the restoration of natural hydrologic processes at small scales, aiming to restore natural flow regimes at larger scales downstream. They also argued that there is a possibility to successfully obtain the key elements of the pre-development flow conditions only by a combination of retention-based measures and infiltration-based techniques. Therefore, this study evaluates several single LID practices and their combinations with the goal of restoring the pre-development runoff regime as closely as possible.

The LID simulations of the current study are built upon the model presented by Guan *et al.* (2015). The main aims of the study are to evaluate the effectiveness and feasibility of several potential LID practices on restoring pre-development flow conditions in an urban catchment located in the high latitude area.

METHODOLOGY

The Saunalahdenranta study catchment is located in the city of Espoo, southern Finland. During the years 2001–2006, the catchment was rapidly developed from a rural area to a medium-density residential area. The catchment hydrology greatly changed along with the local urban construction (Sillanpää 2013). The catchment area is about 12.3 ha with an imperviousness of about 38.7% in the fully developed phase, 22.3% in the partially developed phase, and about 1.5% in the pre-development phase. Flow rates were determined based on a pressure transducer that was installed into a v-notch weir (90% notch angle). The Storm Water Management Model (SWMM) was selected to perform the hydrological analysis in the urban catchment. The catchment area was divided into 93 subcatchments. The subcatchment characteristics were determined based on the topographic and stormwater network datasets using the ArcGIS toolbox. The details about the setup of the model parameters are described by Guan *et al.* (2015). In this study, the new model scenarios were produced with the LID tools of SWMM (Rossman 2010).

Stormwater management techniques are generally developed for two main purposes: the mitigation of hydrologic changes and the improvement of water quality. The focus of this paper is only on the stormwater quantity aspects. The evaluation of the control measures is conducted based on their ability to restore the pre-development runoff regime as closely as possible, and where possible, to harvest rainwater for daily by the local residents. The land use in the urban catchment mainly contains of three types (Figure 1):

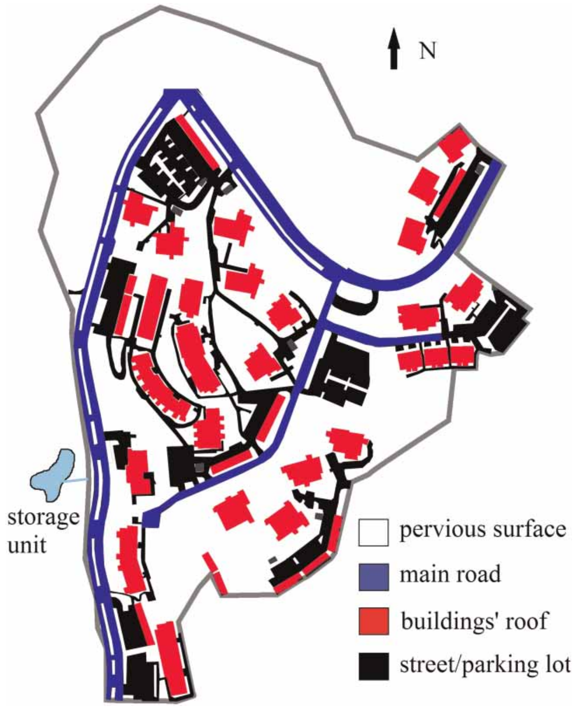

Figure 1 | Land use type of the Saunalahdenranta catchment located in southern Finland.

building roofs (about 1.26 ha), asphalt/concrete roads and parking lots (about 4.8 ha in total). To control runoff in each surface type, the following hypothetical practices were designed. Building roofs were treated as rain barrels or green roofs. In the parking lots and streets other than main roads the LID tools were the porous pavements in a total area of about 1.3 ha. A storage unit was the LID solution near the catchment outlet to control the temporal outflow distribution. Accordingly, the designed scenarios with distinct techniques included the following.

1. Rain barrel (RB): the size of RB is commonly determined based on local historical rainfall data; here an equivalent volume of roof area multiplied by 0.9 m was used for each building. The total storage volume was about 1,134 m^3 in the whole catchment.
2. Green roof (GR): All roofs were assumed to be green roofs with a sandy loam substrate thickness of 100 mm.
3. Porous pavement (PP): The pavement consists of a porous pavement layer (150 mm) and a storage layer (300 mm) underneath. The pavement layer has a void ratio of 0.2 (voids/solids) and permeability of 1,000 mm/h. The storage layer has a void ratio of 0.6 and permeability of 500 mm/h.
4. Storage unit (ST): The storage unit includes three configurations represented by the functional curve $A = ah^b$,

including ($630\,m^3$ for $a = 800$, $b = 0.3$), ($946\,m^3$ for $a = 1{,}200$, $b = 0.3$), and ($1{,}102\,m^3$ for $a = 1{,}200$, $b = 0.1$), where A is the surface area (m^2), and h is the storage depth (m).

5. The combination of the single controls: RB + PP, RB + ST, PP + ST, RB + PP + ST.

As the design of the LID may be different in reality, the resulting hydrological outcomes may vary with the setup of the LID. For the five scenarios, we have set the capacity of each measure as highly as possible. Despite some uncertainties from the LID setup, the focus of this study on whether LID can restore the pre-development flow regime can be reasonably well explored.

To investigate the impacts of rainfall event magnitude on urban runoff, we chose four single rainfall events with varying rainfall depths (E1, E2, E3 and E4 in Table 1) and evaluated the hydrological performance of the LID scenarios listed above. A long-term continuous simulation (E5) was also conducted, based on which, a flow-frequency curve proposed by Fennessey et al. (2001) was adopted to assess the hydrological impacts of LID techniques for a large range of flow rates. For all the events E1–E5 that were simulated with the model for the fully developed phase and the LID practices, the observed rainfall and runoff were available from the pre-development catchment.

Model calibration and validation in the studied catchment were performed using 12 rainfall-runoff events with different patterns and magnitudes by Guan et al. (2014). The model showed very good performance in predicting the runoff hydrograph in the fully developed catchment conditions. Both the coefficient of determination and the Nash–Sutcliffe model efficiency coefficient had high values, mostly above 0.90.

Table 1 | The selected rainfall events

Event	Depth (mm)	Duration (hh:mm)
E1	2.6	1:40
E2	11.4	1:30
E3	55.8	3:30
E4	16.8	7:40
E5	222.6	16/08/2001–05/11/2001

RESULTS AND DISCUSSION

Figure 2 and Table 2 show that both the peak flow and the total volume for E1 are reduced due to the implementation of the control measures. The reduction is in the range of 25.3–92.0% for the peak flow, and 24.5–78.3% for the total runoff volume. RB, GR and PP decrease the overall flow hydrograph from high flow to low flow, even though the

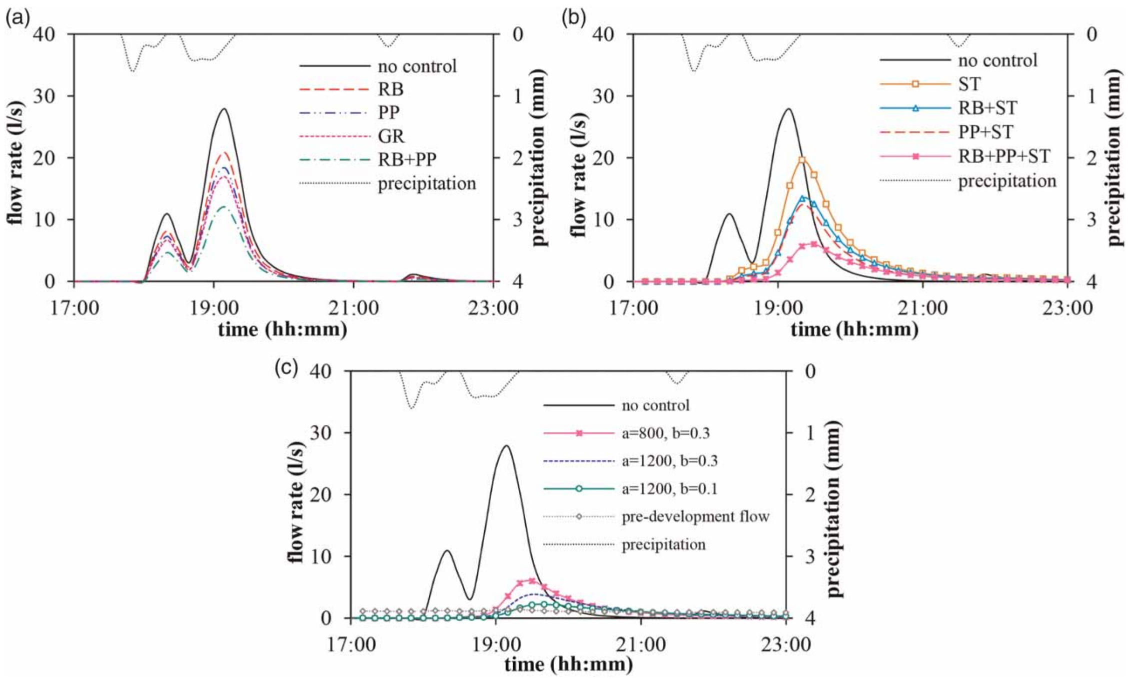

Figure 2 | The simulated hydrographs without and with different LID controls for E1, and the observed pre-development flow.

Table 2 | The changes of peak flow and total runoff volume due to LID controls for the event E1

Techniques		Peak with control (l/s)	Observed peak (l/s)	Reduction of peak flow (%)	Reduction of volume (%)
RB		20.8	1.4	25.3	24.5
GR		16.9		41.9	39.1
PP		18.4		34.1	34.5
RB + PP		12.1		56.7	56.4
ST		19.7	1.4	29.4	12.2
RB + ST		13.4		51.8	36.0
PP + ST		12.4		55.3	45.8
RB + PP + ST	$a = 800$, $b = 0.3$	6.0	1.4	78.3	67.3
	$a = 1{,}200$, $b = 0.3$	3.9		86.1	72.0
	$a = 1{,}200$, $b = 0.1$	2.2		92.0	78.3

occurrence time of peaks is not affected. Different from RB, GR and PP, ST not only causes a reduction of peak flows, but delays the occurrence time of peaks (Figure 2(b) and 2(c)). Both the rising and recession limbs of the flow hydrograph are effectively flattened after the control via ST. Nonetheless, the reduction of the overall runoff volume (12.2%) is much smaller in comparison to the decrease of the peak flow (29.4%), which indicates an overall weaker effect of ST on runoff regime than those of RB, PP and GR.

Both RB and GR have an influence on the stormwater runoff from the building roofs. Although the hydrological effects of RB are slightly lower than those of GR, RB is advantageous through its low-cost, easy-implementation, and support for stormwater reuse by residents. It has been shown that the rainwater harvesting systems have the highest potential quantitative performance in climatic regions with frequent rainfall events similar to Finland (Palla *et al.* 2012). Thus, RB was further evaluated and combined with other controls without GR.

As expected, the combined systems are more effective in reducing the peak flow and the overall runoff volume of E1 than the approaches based on only one LID technique. When set against the advantages of single control techniques, a combination of several measures is found to be a better option to implement stormwater management. Figure 2(b) shows that these combined controls greatly change the flow hydrographs both in terms of high and low flows. The most effective combination, RB + PP + ST, decreases the peak flow by 78.3% and the runoff volume by 67.3%. Three simulations with different storage curves were performed. Figure 2(c) implies that the higher storage capacity yields more reduction of the peak flow. For the scenario ($a = 1{,}200$, $b = 0.1$), the peak flow reduces to a low level of 2.2 l/s, although it is still higher than the observed natural peak flow (1.4 l/s). The peak is decreased by 92.0% and the overall runoff volume is reduced by 78.3%. In this aspect, the key flow elements are close to the pre-development flow conditions although it must be noted that the monitoring of such low flow rates can be inaccurate. The delivered outcomes by the combination of these control measures achieve a good restoration towards pre-development flow during small storms.

Two more tests (E2 and E3 with larger magnitudes) were performed. Figure 3(a) shows that the LID controls during E2 produce hydrological effects that are similar to those during E1. The combined system, RB + PP + ST ($a = 1{,}200$, $b = 0.1$), reduces the peak flow by 91.4%. The resulting runoff regime is significantly changed, but the peak flow remains larger than the observed pre-development levels of 4.3 l/s (Figure 3(a)). Figure 3(b) indicates that the hydrological effects of the LID controls are notably diminished during E3, which has a much higher rainfall depth. The maximum reduction rate of the peak flow is only 32.3%, which is much smaller than the over 90% reduction during E1 and E2. Still, all flows with LID practices are clearly different from the observed pre-development flows both in terms of peak flow and runoff volume. For E3, the volume of ST only slightly influences the simulated flow rates, which is greatly different from the results of E1 and E2, because the capacity of ST is exceeded by the high peak flow rates and total runoff volume. As pervious surfaces eventually start generating direct runoff during major rainfall events, the total storm runoff will sharply increase along with rainfall magnitude and intensity, and thereby the LID practices for controlling stormwater runoff become more challenging during a major high intensity storm. It has also been pointed out that urbanization causes proportionally larger changes in the runoff

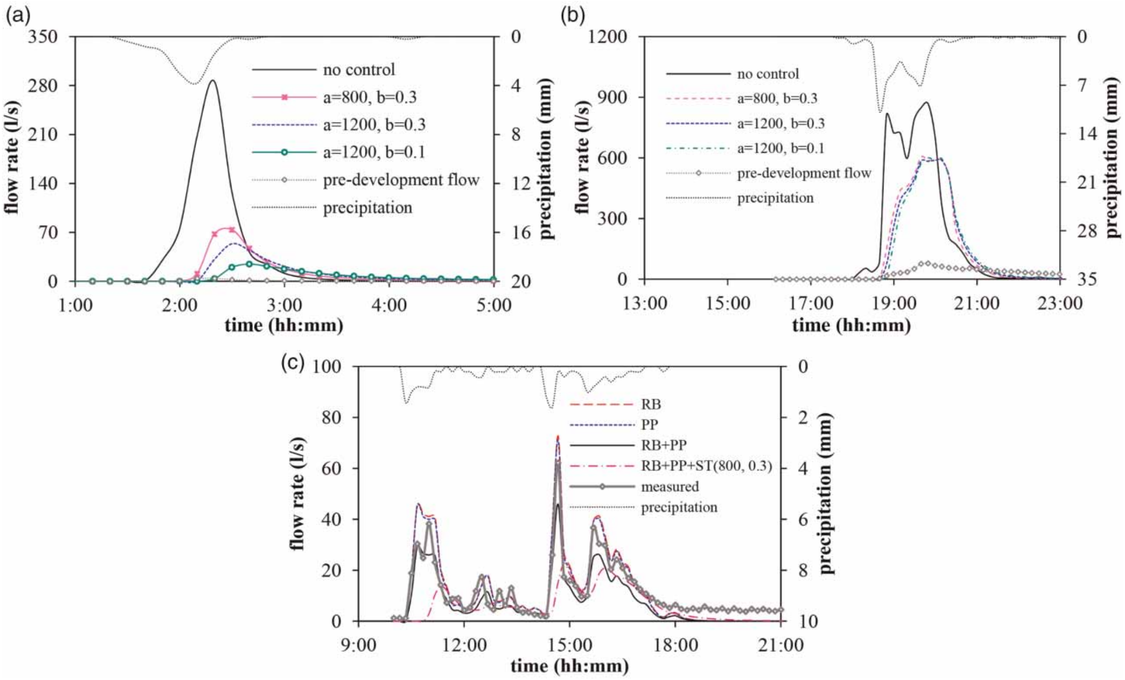

Figure 3 | The simulated LID hydrographs for the fully developed catchment and the observed pre-development flow for (a) E2 and (b) E3; (c) the simulated LID hydrographs and the measured hydrographs for partially developed catchment conditions for E4.

response during frequent minor storms compared with large, infrequent storm events (Hawley & Bledsoe 2011; Sillanpää & Koivusalo 2015). Despite a significant reduction of peak flow due to LID practices during E3, the flow is still much bigger than the pre-development flows. Apparently, during large storms, it is more important to alleviate flooding than to mimic pre-development flows. Thereby the corresponding erosion in streams also can be reduced.

Since we have rainfall-runoff measurements during the whole construction period of the catchment, we can investigate whether LID practices can restore the flow conditions of medium-density urban land use towards the conditions of a low-density urban land use. Figure 3(c) illustrates rainfall and runoff for E4. The simulated hydrographs are presented for several LID practices and the observed hydrograph is from the partially developed catchment conditions when the catchment imperviousness was about 22.3%. It is clear that the key features of the measured runoff hydrograph in the partially developed catchment conditions are within in the modelled band of LID scenarios. Also, the scenarios relying on single LID practices, RB or PP, exhibit hydrographs close to the observed flow rates. Although the LID practices in the medium-density urban area were not able to mimic the pre-development flow conditions, they were successful in restoring flow conditions towards a low-density urban area. An important reason is that, in contrast to pre-development flows, runoff in the partially developed catchment is drained and routed via the same pipe sewer system as in the fully developed phase. Overall, the restoration of pre-development flows via LID measures seems to be extremely challenging but nonetheless, the LID measures have remarkable effects on reducing the negative hydrological impacts of urbanization towards the flow conditions in the catchment with lower imperviousness.

Similar to the findings by Petrucci *et al.* (2013), Figure 4(a) indicates that GR, RB, PP reduce both low and high flows, whereas ST causes increases in the high-frequency flow rates and reductions in the low-frequency flow rates. It is clear that ST performs better in increasing the low flows for the frequency $f > 0.06$, which is the intersection of the curves representing ST and the fully developed catchment without control (Figure 4(a)). Figure 4(b) and 4(c) demonstrates that the combined controls clearly change the runoff flow rates in the post-development catchment in terms of both high flows and low flows. However, there still is a clear difference between the controlled flows and the measured pre-development flows (Figure 4(c)). It seems hardly possible to fully restore the observed pre-development flow regimes with a mildly sloping flow-frequency curve. The fundamental reason for this is that the mechanisms of runoff production and flow routing are different between a rural catchment and an urban

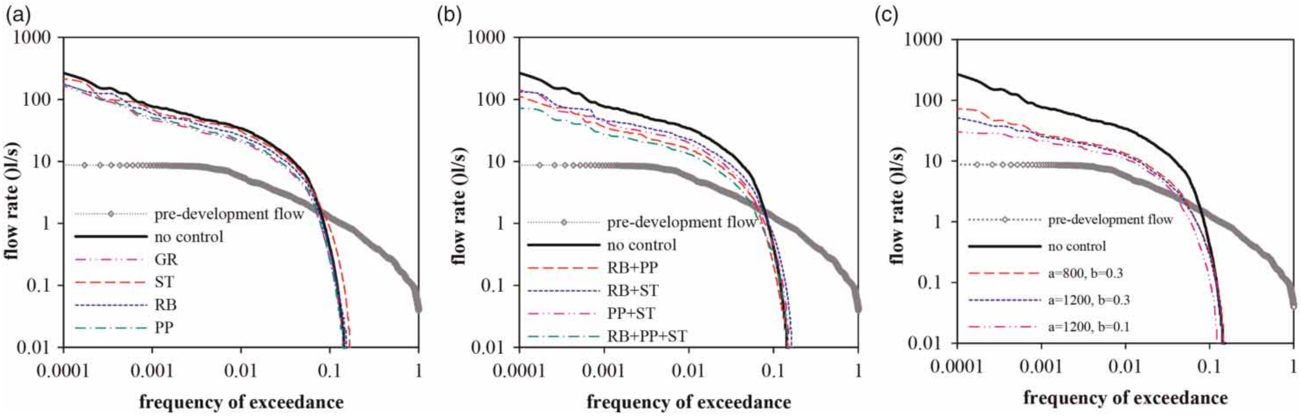

Figure 4 | Simulated flow-frequency curves for the fully developed catchment without LID and with LID controls, and the observed pre-development flow-frequency curve for the continuous scenario E5; the intersection between the curve and the *y*-axis shows the maximum peak flow during the simulation period, and the intersection with the *x*-axis shows the fraction of time during which a flow is detected at the outlet.

catchment with LID controls. It is well known that pre-development flows are generally routed by subsurface pathways. Although the small baseflows are not the focus of the study, it should be noted that subsurface flow component was not modelled by SWMM in our simulations. This causes the simulated curves to have less baseflow than the measured pre-development curve that over 90% of the time comprises baseflow below 1 l/s. The phenomenon has also been shown in the measured flow-frequency curve in the post-development phase (Guan *et al.* 2015). The simulated curves that underestimate baseflow can also be explained from the viewpoint of infiltration loss. The continuous simulation of E5 in the post-development catchment conditions without LID practices generates an infiltration loss of 137.8 mm (61.9% of the total rainfall). With the inclusion of the combined scenario, the simulation yields an increase in the infiltration loss up to 177.2 mm, comprising 79.6% of the total rainfall. The increase in infiltration will admittedly be converted to soil water storage, low baseflows and evapotranspiration over a longer time period.

CONCLUSION

This study investigated the effects of several LID practices on restoring the pre-development runoff regime in an urbanized catchment in southern Finland. In the light of the above results, the main findings are as follows:

1. LID practices in the post-development conditions were not able to fully restore pre-development flow regimes.
2. The fundamental reason for the difference between pre-development and development conditions (with or without LID) was the change in runoff pathways before and after development.
3. Combination of several LID measures led to clearly larger changes in runoff regime than single measures.
4. LID was able to restore the flow regimes towards a low-density urban land use.
5. Finally, the effects of LID practices diminished during rainfall events of high magnitude.

ACKNOWLEDGEMENTS

This work is funded by Aalto University School of Engineering and Maa-ja vesitekniikan tukiry. The authors thank Helsinki Region Environmental Services Authority HSY for the GIS data received for model calibration.

REFERENCES

Ashbolt, S., Aryal, S., Petrone, K., McIntosh, B. S., Maheepala, S., Chowdhury, R. & Gardner, T. 2013 Can stormwater harvesting restore pre-development flows in urban catchments in South East Queensland? *Water Science and Technology* **67** (2), 446–451.

Booth, D. B. & Jackson, C. R. 1997 Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *JAWRA Journal of the American Water Resources Association* **33** (5), 1077–1090.

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R. & Hatt, B. E. 2012 Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning* **105** (3), 230–240.

Burszta-Adamiak, E. & Mrowiec, M. 2013 Modelling of green roofs' hydrologic performance using EPA's SWMM. *Water Science and Technology* **68** (1), 36–42.
Carter, T. & Jackson, C. R. 2007 Vegetated roofs for stormwater management at multiple spatial scales. *Landscape and Urban Planning* **80** (1–2), 84–94.
Dietz, M. 2007 Low impact development practices: a review of current research and recommendations for future directions. *Water, Air, and Soil Pollution* **186** (1–4), 351–363.
Fennessey, L., Hamlett, J., Aron, G. & LaSota, D. 2001 Changes in runoff due to stormwater management pond regulations. *Journal of Hydrologic Engineering* **6** (4), 317–327.
Freni, G., Mannina, G. & Viviani, G. 2010 Urban storm-water quality management: centralized versus source control. *Journal of Water Resources Planning and Management* **136** (2), 268–278.
Guan, M., Sillanpää, N. & Koivusalo, H. 2015 Modelling and assessment of hydrological changes in a developing urban catchment. *Hydrological Processes*. doi:10.1002/hyp.10410.
Hawley, R. J. & Bledsoe, B. P. 2011 How do flow peaks and durations change in suburbanizing semi-arid watersheds? A southern California case study. *Journal of Hydrology* **405** (1–2), 69–82.
Meierdiercks, K. L., Smith, J. A., Baeck, M. L. & Miller, A. J. 2010 Heterogeneity of hydrologic response in urban watersheds1. *JAWRA Journal of the American Water Resources Association* **46** (6), 1221–1237.
Palla, A., Gnecco, I., Lanza, L. G. & La Barbera, P. 2012 Performance analysis of domestic rainwater harvesting systems under various European climate zones. *Resources, Conservation and Recycling* **62** (0), 71–80.
Petrucci, G., Rioust, E., Deroubaix, J.-F. & Tassin, B. 2013 Do stormwater source control policies deliver the right hydrologic outcomes?. *Journal of Hydrology* **485** (0), 188–200.
Rossman 2010 *Storm Water Management Model User's Manual Version 5.0*. US EPA National Risk Management Research Laboratory, Cincinnati, OH, USA.
Shuster, W. & Rhea, L. 2013 Catchment-scale hydrologic implications of parcel-level stormwater management (Ohio USA). *Journal of Hydrology* **485** (0), 177–187.
Sillanpää, N. 2013 Effects of Suburban Development on Runoff Generation and Water Quality. PhD Doctoral Dissertation, Department of Civil and Environmental Engineering, Aalto University, Helsinki.
Sillanpää, N. & Koivusalo, H. 2015 Impacts of urban development on runoff event characteristics and unit hydrographs across warm and cold seasons in high latitudes. *Journal of Hydrology* **521** (0), 328–340.

First received 16 October 2014; accepted in revised form 5 March 2015. Available online 19 March 2015