Modeling and assessment of hydrological changes in a developing urban catchment

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Abstract: Urbanization strongly changes natural catchment by increasing impervious coverage and by creating a need for efficient drainage systems. Such land cover changes lead to more rapid hydrological response to storms and change distribution of peak and low flows. This study aims to explore and assess how gradual hydrological changes occur during urban development from rural area to a medium-density residential catchment. The Stormwater Management Model (SWMM) is utilized to simulate a series of scenarios in a same developing urban catchment. Sub-hourly hydro-meteorological data in warm season is used to calibrate and validate the model in the fully developed catchment in 2006. The validated model is then applied to other cases in development stage and runoff management scenarios. Based on the simulations and observations, three key problems are solved: (1) how catchment hydrology changes with land cover change; (2) how urban development changes pre-development flows; (3) how stormwater management techniques affect catchment hydrology. The results show that the low-frequency flow rates had remarkably increased from 2004 to 2006 along with the increase of impervious areas. Urbanization in the residential catchment expands the runoff contributing area, accelerates hydrological response, raises peak flows in an order of magnitude of over 10, and more than doubles the total runoff volume. The effects of several LID controls on runoff hydrograph were simulated, and the techniques were able to reduce flows towards the pre-development levels. However, the partly restored flow regime was still clearly changed in comparison to the pre-development flow conditions.

Keywords: urban hydrological modeling, SWMM, urbanization, hydrological changes, LID control

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INTRODUCTION

Urbanization leads to dramatic land cover change and the increase of impervious surface, which greatly alter the water cycle. The main hydrological impacts are the increase of total and direct runoff volumes and peak flows associated with faster response time, and the decrease of infiltration and base flow (Cheng and Wang, 2002; Shuster *et al.*, 2005; Dietz and Clausen, 2008; Du *et al.*, 2012). However, some studies found no clear increase in annual runoff coefficients in an urbanizing catchment. For example, the study by (Brun and Band, 2000) detected no significant increase of annual runoff in the Baltimore Metropolitan area of the USA, with 20% increases of imperviousness in urban development between 1970 and 1987. The study by (Chang, 2003) also showed a slight increase, < 2%, in annual runoff when land use was developed from natural area to low-density suburban catchment in a simulation study of a southeastern Pennsylvania watershed. Runoff behavior is known to be related to multiple factors, such as soil types, hyetograph, drainage intensity, and extent and distribution of constructed areas. The complexity of study catchments, the uncertainty of future conditions, and the lack of a good quality dataset might limit our understanding about past, current, and future hydrological behaviors in developing urban catchments. Thus, there is a need to conduct a thorough assessment of hydrological impacts with a support of good quality long-term monitoring data in small urbanizing catchments.

Urban hydrological models have been widely used to better understand and evaluate urban water quantity and quality responses to potential land cover change and climate change in recent decades (Ando *et al.*, 1984; Tsihrintzis and Hamid, 1998; Vaze and Chiew, 2003; Jang *et al.*, 2007; Du *et al.*, 2012). When calibrated and validated against stormwater quantity and quality data, the models can be applied to produce scenarios of runoff generation and pollutant loading with urban stormwater. A widely used example of these models is the Storm Water Management Model (SWMM), which supports simulation of surface hydrological process, sewer drainage network flows, and stormwater quality (Hsu *et al.*, 2000; Denault *et al.*, 2006; Meierdiercks *et al.*, 2010). The suite of available modeling techniques is boosting their applications in the practical design of drainage networks and the assessment of urban runoff and loads.

Over the last few decades, a range of management approaches have been developed to mitigate the adverse hydrological and water quality impacts of urbanization. These approaches include infiltration-based technologies and retention-based technologies (Fletcher *et al.*, 2013). Vegetated roofs have been considered as a major advantage over other stormwater retention systems, and they may achieve annual retention in the order of a reduction of 55–65% of effective rainfall (Mitchell and Morello, 2009). However, the feasibility and performance of the techniques to restore the pre-development flow still remain a significant debate. Low impact development (LID) tools are examples of stormwater management to detain, store, infiltrate, or treat urban runoff, and so reduce the hydrological impacts of urban development. Some studies (Alfredo *et al.*, 2010; Jia *et al.*, 2012) incorporated LID tools in SWMM and produced simulations for assessing the hydrological impacts of LID and possibilities to restore pre-development flows via LID control in urban catchments. Alfredo et al. (2010) point out that care must be taken in interpreting the results of impact analyses until the suitability of the modeling techniques are demonstrated through validation against field data. A combination of an urban hydrological model with good-quality, long-term monitoring data is needed to ensure that the model is suited for the application to practical problems. There is a particular need for data from catchments that are gradually developed during the urban construction. Such good-quality dataset from catchments under development are still rare but fortunately have started to become available (Sillanpää, 2013; Sillanpää and Koivusalo, 2014).

This study aims to evaluate hydrological changes in an urbanizing catchment through an application of the Stormwater Management Model (SWMM). The model is tested and applied to produce a set of scenarios to better understand the hydrological impacts of urbanization and to explore the possibility to restore pre-development flows via retention-based techniques. To achieve these objectives, the following four steps are introduced: (1) calibration and validation of model in the scenario of a fully developed catchment in 2006; (2) detection of hydrological changes in different development phases; (3) analysis of how runoff changes with catchment development from rural to medium-density urbanized catchment, and (4) model scenarios of the hydrological impacts of retention-based techniques and the possibility to restore pre-development flows in urbanized catchment. The model application rests on the 5-year hydrological dataset gathered from an urbanizing catchment in Southern Finland. The findings can be further utilized in the development of appropriate urban runoff management schemes for the local climate.

STUDY SITE AND DATA COLLECTION

Urban development from 2001-2006

The study catchment is located in the city of Espoo, southern Finland (Fig.1), and has an area of approximately 12.3 ha (estimated based on the DEM data) after urban construction. The catchment was rapidly developed from a rural area to a residential area during 2001-2006. Table 1 shows the changes that occurred in the total catchment area and impervious surfaces (IS) due to the construction works. In 2001, the catchment mainly consisted of coniferous forest and had an area of about 8.5 ha. An existing main road was constructed and a separate storm sewer network was installed during the summer of 2001. In early 2002, the sewers were constructed under the main streets, which were left unpaved, and later in 2002 the catchment area was expanded to about 11.5 ha because of the sewer works (Kotola and Nurminen, 2003). During the years 2001-2002, the greatest changes occurred in the location of the catchment boundaries, but the imperviousness remained low (about 1.5% IS). The main streets were paved with asphalt in two phases during July and September of 2003, leading to a clear increase in the imperviousness. The majority of the paving work at the building sites was performed during the years 2004-2005, when the imperviousness increased from 22.3% to 33.4%. In March 2006, trees were clear-felled and road construction work started at a boundary area of the catchment. The residential buildings were completed by the end of the monitoring period in October 2006, and the catchment was fully transformed into a medium-density residential area (about 38.7% IS). Stormwater runoff from the catchment was conveyed via a separate sewer system to a nearby small bay in the Baltic Sea.

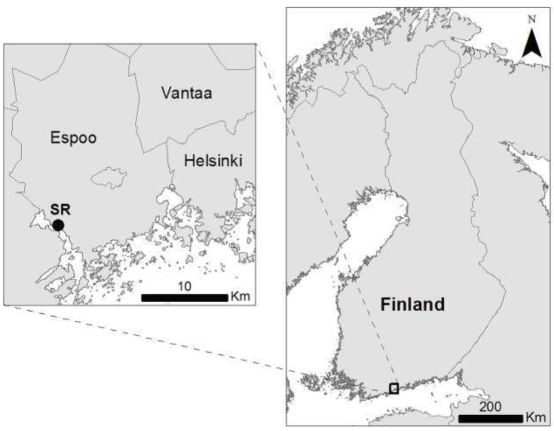


Fig.1 Study site of the developing catchment SR

Table 1. Total area and impervious area at the developing catchment

Summary	2001-2002	May 2004	May 2005	OCT 2006
Phase	pre-development	partially developed		fully developed
Estimated total area (ha)	8.5-11.5	12.3	12.3	12.3
Imperviousness (% IS)	~1.5%	~22.3%	~33.4%	~38.7%

Rainfall-runoff measurements

Precipitation and flow were monitored during the construction period from 2001-2006 in the urban catchment. The detailed description can be found in (Sillanpää, 2013). For the monitoring of precipitation, a weather station was equipped with an ARG100 tipping bucket rain gauge, adjusted for a volume resolution of 0.2 mm. Rain gauge was located near the flow monitoring weir, about 2-3 m above ground level on a roof of the monitoring equipment shelter. For the first four years, the data logger recorded rainfall intensity as ten-minute precipitation sums and, starting from September 2005, as two-minute sums. The temporal resolution of the measured flow was equal to the precipitation. The flow rates were determined based on the water depth recorded at the outlet of the catchment.

Spatial data

The digital elevation model (DEM), with a 2m×2m grid cell size, was provided by the National Land Survey of Finland in ASCII Grid format. Buildings are not depicted in the model. Instead, building cell values have been set according to a surface approximating the ground level at the site of the building. In this study, the DEM dataset was used to delineate the urban catchment and calculate the catchment characteristics. Storm sewer GIS layers were obtained from the Helsinki Region Environmental Services Authority HSY.

METHODOLOGY

Stormwater Management Model

The EPA Stormwater Management Model (SWMM) is selected to simulate and evaluate urban hydrological response to rainfall events in the study catchment. SWMM is a dynamic hydrology-hydraulic-water quality simulation model which can be used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Rossman, 2010). It accounts for spatial variability of catchment properties by dividing a catchment into a number of subcatchments. Each subcatchment is treated as a nonlinear reservoir, which receives inflows from precipitation and generates outflows and losses based on the assigned catchment parameters such as area, average slope, flow width, imperviousness, depression storage, and Manning's roughness. Overland flow is routed between sub-areas, between subcatchments, or between entry points of a drainage system. The drained flow is transported through the sewer network system of links and nodes. Three flow-routing methods are included in the model; therein, Kinematic Wave routing was used here. The GREEN-AMPT infiltration model was chosen to calculate soil infiltration loss (Rawls *et al.*, 1992).

Urban catchment delineation

The catchment was initially delineated based on DEM combined with sewer network using the ArcGIS tool, and then it was manually modified according to the in-situ observations of stormwater inlets within the area. The catchment was divided into 93 subcatchments, with an average area of 0.135 ha. The catchment is drained through the stormwater network, consisting of 80 manholes and 77 pipes with circular shape (diameter: 250 mm to 650 mm). The flow is drained to the sea at the outlet shown in Fig.3. Fig. 2(a) shows the subcatchments, the sewer network, and the outlet of each subcatchment. Furthermore, the impervious surfaces for each developed phase was manually digitized based on the 2011 aerial photo images in ArcGIS and aerial photo in the corresponding year. Fig. 2(b) illustrates the impervious and pervious surfaces in the urban catchment in 2006.

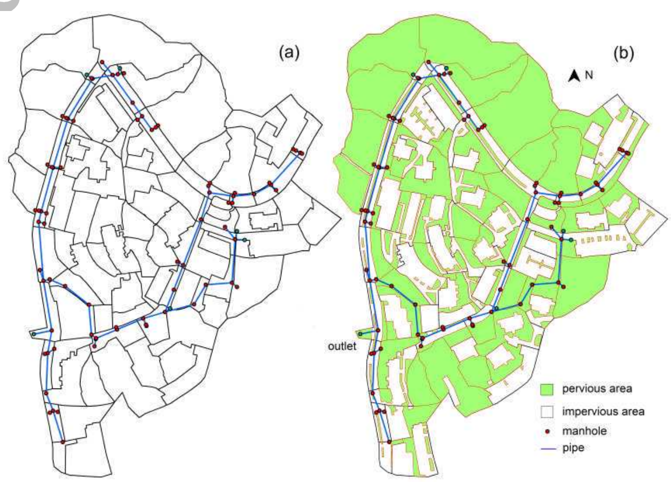


Fig.3 (a) subdivision of the urban catchment; (b) impervious area and pervious area in the study catchment

Estimation of hydrological parameters

SWMM requires the input of parameters related to catchment characteristics, sewer network and soil. The average slope of and imperviousness of the subcatchments were initially derived from spatial data. The initial values of the following parameters were derived following literatures (Rawls *et al.*, 1992; Rossman, 2010): Manning's roughness for overland surfaces and conduits, soil infiltration parameters, and surface depression storage. The flow width is defined as the 'characteristic width of the overland flow path for sheet flow runoff. It is typically regarded as a calibration parameter (Park *et al.*, 2008), although there are ways to deduce an initial estimate of its value even without calibration. According to Rossman (2010), the flow width (W) can be calculated by dividing the subcatchment area (A) by the length of the longest overland flow path (L) in the subcatchment (Eq.1), which is used to determine the initial estimation of flow width.

$$W = \frac{A}{L} \tag{1}$$

The flow length was calculated using the ArcGIS toolbox. Inevitably, the initial estimation of the parameters required by the model can cause a variety of errors to the simulation. Thus, the flow width was allowed to vary in a range of ±20% around the initial estimation for model calibration.

Assessment approach

The flow chart of the methodology and analysis steps is demonstrated in Fig. 3. SWMM is developed for modeling the rainfall-stormflow relationship in constructed urban catchments, and it is not well suited for modeling rural unconstructed areas. In our catchment that was gradually developed, we calibrated and validated the model for the conditions of the fully developed catchment in 2006 (Step 1 in Fig. 3). The validated model thus provided a reference for simulating runoff in comparison to the earlier development phases. To comprehensively explore the hydrological response in an urbanizing catchment, the following three questions were aimed to be answered:

(1) How does urban hydrology change in different development phases with distinct imperviousness? (Step 2)

(2) How does urban development change pre-development hydrology in a rural area? (Step 3)

(3) How do stormwater management techniques affect hydrology in a periurban catchment? (Step 4)

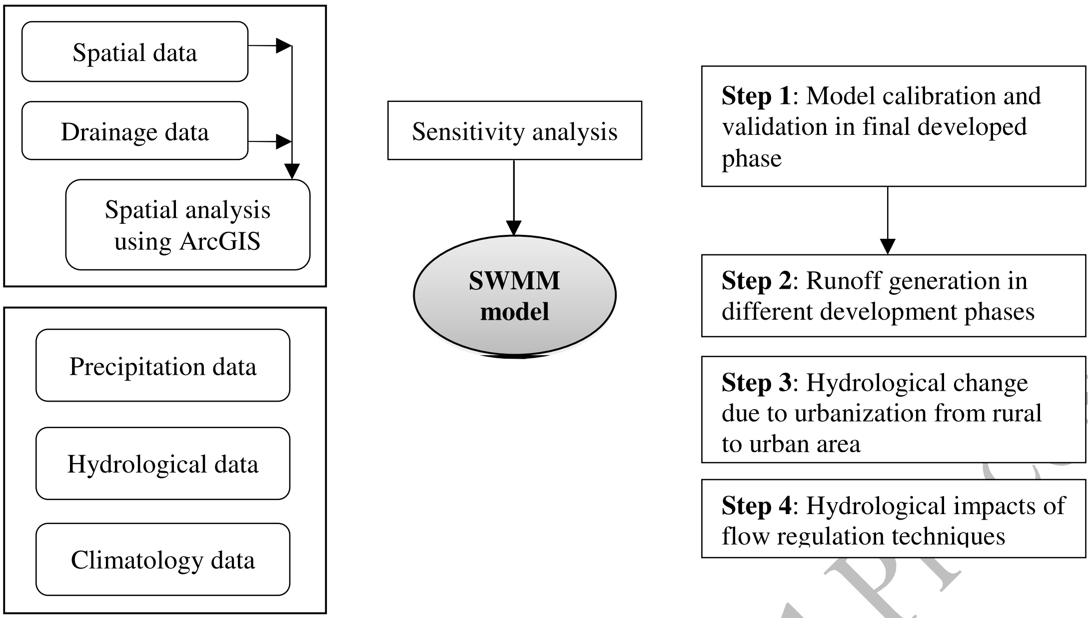


Fig. 3 Flow chart of the methodology

Table 2. Summary of rainfall-runoff events for simulation

Event code	Start	end	Precipitation depth (mm)	Duration (h)	Purpose
C1	3/9/06 20:40	3/9/06 21:08	5.0	0:28	calibration
C2	3/9/06 23:46	3/9/06 3:06	5.0	3:30	calibration
C3	21/10/06 23:20	22/10/06 3:34	6.2	4:14	calibration
C4	01/10/06 7:28	01/10/06 14:02	12.2	6:34	calibration
C5	01/10/06 16:28	01/10/06 23:48	19.6	7:20	calibration
C6	23/10/06 13:48	24/10/06 0:32	37.2	10:44	calibration
V1	7/10/06 15:30	7/10/06 16:12	3.0	0:42	validation
V2	22/10/06 12:28	22/10/06 18:32	5.2	8:04	validation
V3	26/10/06 15:32	26/10/06 20:54	7.8	5.22	validation
V4	8/10/06 0:14	8/10/06 4:46	9.0	4:32	validation
V5	24/10/06 17:40	24/10/06 22:10	12.6	4.30	validation
V6	27/10/06 1:36	27/10/06 7:56	23.4	6:20	validation
E1	03/06/2006	28/10/2006	continuous simulation		
E2	03/05/2005	15/09/2005	continuous simulation in the final developed scenario		
E3	03/05/2004	30/09/2004	continuous simulation in the final developed scenario		
E4	01/06/2002	30/10/2002	continuous simulation in the final developed scenario		
E5	16/08/2001	25/10/2001	continuous simulation in the final developed scenario		
E6	16/08/2001	25/10/2001	continuous simulation with VC in the final developed scenario		
E7	16/08/2001	25/10/2001	continuous simulation with FRC in the final developed scenario		
E8	16/08/2001	25/10/2001	simulation with VC and FRC in the final developed scenario		

In Finland, the annual air temperature ranges from 4°C to more than 5°C, and generally November to April belongs to the snow period or frozen period. The rainfall-runoff events only in a warm period (June 2006 to October 2006) were chosen for the model calibration and validation in this study. Table 2 lists the selected rainfall-runoff events. The event rainfall depth ranged from 3.0 mm to 37.2 mm, and the duration of the events was in the range of 28 minutes to 11 hours. The set of events characterized the diversity of the rainfall patterns for calibration and validation. Six events varying from 5.0 mm to 37.2 mm in depth were used for calibration. The six events were coded as C1, C2, C3, C4, C5 and C6 (Table 2). The model was manually calibrated to achieve the best fit between the observed and simulated flow rates. The model was then validated against the other six rainfall-runoff events in 2006 with depth from 3.0 mm to 23.4 mm (V1 to V6 in Table 2). The model performance was quantified using the coefficient of determination (R^2) (Hirsch *et al.*, 1992) and the Nash–Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970).

$$\mathrm{R}^2 = \left[\frac{\sum_{\mathrm{t}} \left(Q_{\mathrm{o,t}} - \overline{Q_{\mathrm{o}}}\right)\left(Q_{\mathrm{m,t}} - \overline{Q_{\mathrm{m}}}\right)}{\sqrt{\sum_{\mathrm{t}} \left(Q_{\mathrm{o,t}} - \overline{Q_{\mathrm{o}}}\right)^2 \sum_{\mathrm{t}} \left(Q_{\mathrm{m,t}} - \overline{Q_{\mathrm{m}}}\right)^2}} \right]^2 \tag{2}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{\mathrm{t}} \left(Q_{\mathrm{o,t}} - Q_{\mathrm{m,t}}\right)^2}{\sum_{\mathrm{t}} \left(Q_{\mathrm{o,t}} - \overline{Q_{\mathrm{o}}}\right)^2} \tag{3}$$

where $Q_{o,t}$ is the observed discharge (m^3/s) at time t , $Q_{m,t}$ is the modeled discharge (m^3/s) at time t, $\overline{Q_{\mathrm{o}}}$ is the average for the observed discharge (m^3/s), and $\overline{Q_{\mathrm{m}}}$ is the average for the modeled discharge (m^3/s).

To resolve Step 3, continuous simulations (E1, E2 and E3 in Table 2) were conducted. The rainfall recorded in the pre-development rural years 2001 and 2002 (E4 and E5) were also simulated using the calibrated model for the fully developed catchment. The observed data was then compared with the simulated runoff and flow rates in the fully developed catchment condition. To explore the possibility to restore pre-development hydrology, we used three stormwater management techniques: volume control approach (VC), flow rate control approach (FRC), and a combination of both. Three simulations (E6, E7 and E8) with these techniques were conducted. Therein vegetated roofs in all buildings of the fully developed catchment were assumed for VC, and for FRC, a storage unit nearby the outlet was installed. The parameters were assigned to values following literatures (Petrucci *et al.*, 2013) and the SWMM user's manual (Rossman, 2010). Although the data does not support calibration and validation of the control simulations, we still can make a model-based quantification to evaluate the hydrological impacts of stormwater management measures and further investigate the possibility to restore the pre-development hydrology.

RESULTS AND INTERPRETATION

Model calibration and validation

Six events (C1-C6) recorded in the warm period of 2006 were selected to calibrate the model (Table 2). These events were also used to conduct the sensitivity analysis of parameters using the method presented by (Krebs *et al.*, 2014). The following parameters were adjusted during the model calibration: slope, flow width, Manning's *n* for overland flow and pipes, surface storage depth, as well as soil infiltration parameters. The information from the Geological Survey of Finland demonstrates that the study site is covered by a thin layer of sandy till and bedrock is below it. The initial values for the infiltration model GREEN_AMPT were set as shown in Table 3. The values were then adjusted during the model calibration by studying how large rainfall events produce runoff from both impervious and pervious areas. The calibrated values are 4.21 mm/h for the saturated hydraulic conductivity, 88.9 mm for suction head, and 0.217 for initial soil moisture deficit. For other parameters, the calibrated values do not greatly differ from the initial value.

Table 3. Calibration for key parameters; note: $S_{initial}$ represents the initial estimation of slope based on the DEM data by ArcGIS tool; $W_{initial}$ is the initial value of flow width estimated by ArcGIS tool and Eq.(1); both were allowed to fluctuate in a range of ±20% during the calibration

Parameters	**Surface type**	**Range**		**Initial value**	**Calibrated value**
		Min.	Max.		
Slope ±20%	×	×	×	GIS-estimation	$S_{initial}$
Width ±20%	×	×	×	Eq.(1)	$80\%W_{initial}$
Imperviousness (%)	×	×	×	GIS-estimation	$IMP_{initial}$
Manning's *n* for impervious area	asphalt/concrete	0.011	0.015	0.013	0.014
Manning's *n* for pervious area	grass/tree	0.15	0.8	0.3	0.3
Manning's *n* for conduit	concrete/PVC	0.011	0.015	0.011	0.012
D_storage for impervious area (mm)		0.0	2.5	1.3	0.7
D_storage for pervious area (mm)	lawn/forest	2.5	7.6	7.0	6.0
saturated hydraulic conductivity (mm/h)	infiltration model GREEN_AMPT	1.02	116.13	10.922	4.21
suction head (mm)		47.3	260.4	109.982	88.9
initial soil moisture deficit		0.097	0.375	0.263	0.217

Table 4 demonstrates the value of R^2 and NSE for the calibration and validation events. For the calibration simulations, R^2 ranges from 0.92 to 0.96. The event C6 has the highest NSE of 0.95; the lowest value of 0.82 is for the event C2. The high values of the fitness coefficients in calibration assure the data quality in terms of consistency between the rainfall and runoff observations. Fig. 5 illustrates the measured and calibrated flow rates of the six calibrated events. It indicates that the modeled results, except for the distinct peak flow in C6, agree with the measured data for both single events and sequences of events. For validation simulations, all of R^2 reach value ≥ 0.95 except the event V3, where a smaller $R^2 = 0.84$ because of the underestimation of the low flow. As for RSE, the value for all six validation events is larger than or equal to 0.90. In Fig. 4, the simulations were shown to have an equally good fitting with the observed data for both small and large rainfall events. Overall, the model validation shows a performance comparable with the calibration period, which ensures the reliability of the model for describing the hydrological behavior of the constructed catchment.

Table 4. Statistics of model performance

	Event code	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Calibration	**R^2**	0.96	0.93	0.94	0.92	0.93	0.96
	NSE	0.92	0.82	0.87	0.85	0.87	0.95
	Event code	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**
Validation	**R^2**	0.95	0.97	0.84	0.96	0.96	0.95
	NSE	0.91	0.96	0.90	0.90	0.92	0.93

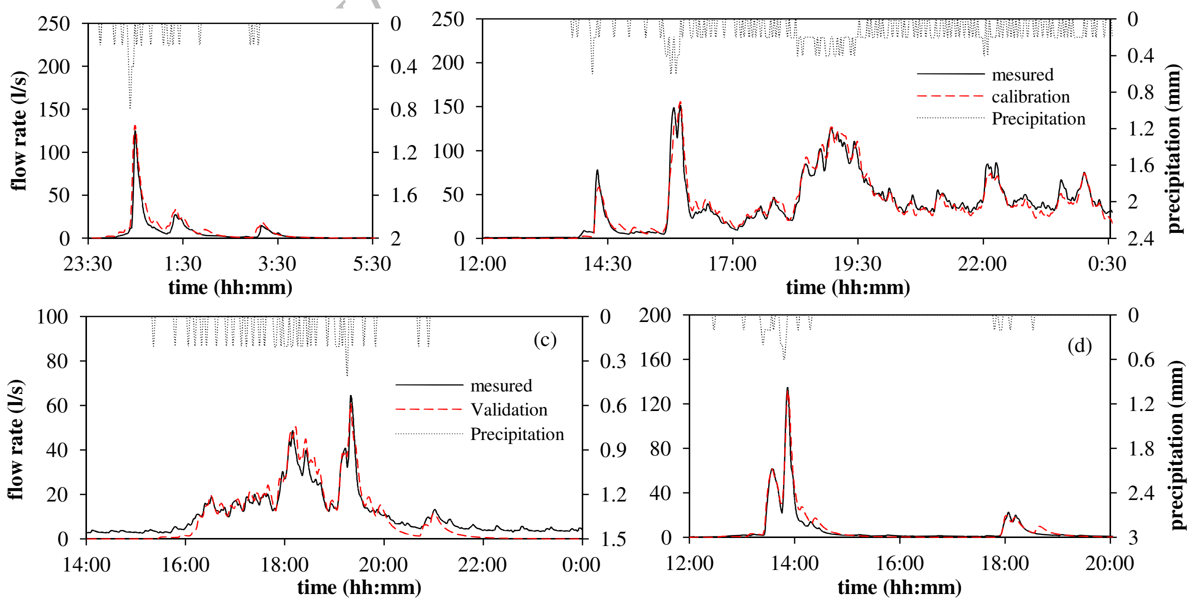


Fig. 4 (a) The worse fitting calibration event C2; (b) the best fitting calibration event C6; (c) the worse fitting validation event V3; (d) the best fitting validation event V6

A comparison between the modeled and measured peak flows during the selected events (C1-C6 and V1-V6) is conducted and illustrated in Fig. 5. It shows that the model hardly overestimates the peak flows during the calibration period, yet the peak flows are slightly underestimated for the validation. Still, both the calibration and validation achieve high values of $R^2 > 0.96$, and both slopes of regression lines are close to 1:1 line.

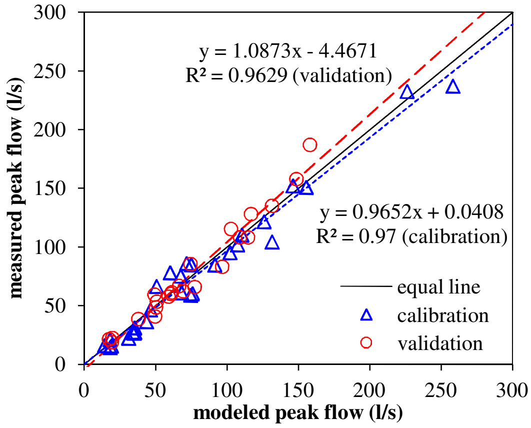


Fig. 5 Comparison of the modeled and measured peak flow discharge during the rainfall events

Hydrological changes in the developing catchment

To evaluate the hydrological changes in different development phases, the 'flow versus frequency' curves (Fennessey *et al.*, 2001) were calculated from long-term simulations of warm periods during 2001-2006 (E1, E2, E3, E4 and E5). The flow-frequency curve visualizes the changes in flow regimes both for extreme events and low flows. In consideration of the parameters sensitivity listed in Table 3, the most negative and positive combinations of these parameters are used for simulation to define an error band which is plotted in Fig. 6. It is shown that there is a clear difference over the error band between the observed flows (2001-2005) and the fully developed scenarios. Fig. 6(a) shows the observed and simulated reference curves of the fully developed year 2006 in which the model was calibrated and validated. Overall, the comparison shows a good fit for flow rates greater than 10 l/s. Yet, the model underestimates high-frequency low flow rates, because the low flows that are generated through infiltration loss and routed by subsurface pathways are not well simulated by the model that mainly focuses on surface runoff. The observed flow-frequency curves in the pre-development phases 2001-2002 and the partially developed phases 2004-2005 are also compared to the simulated curves in the fully developed phase with the input of rainfall in corresponding years and plotted in Fig. 6(b-e). From the pre-development phase to the fully developed catchment, it can be seen that the low-frequency high flow is increased, e.g. the maximal peak flow in the simulation period of 2001 is increased from 8.8 l/s to 285.5 l/s by an order of over 30 (Fig. 6b), and in the rural year 2002 it is also raised by over 10 times (Fig. 6c). Yet, the observed high-frequency low flows in both rural years are reduced and occur in a much shorter time. This reveals that the urban development results in a flashy effect on the flow-frequency curve. Although the pre-development years 2001 and 2002 have a similar imperviousness, the increase of high flow rates from rural area to fully developed catchment is much smaller in 2002 than that in 2001; because the rainfall patterns between the two years are different, the extreme event in 2002 causes the pervious areas to contribute to the runoff which compensates a part of runoff losses. Fig. 6(d,e) reveals that the urban construction from the partially developed phase to the fully developed phase led to a considerable increase of low-frequency high flows, for example, the simulated maximal flow in the fully developed catchment (38.7% IS) is 500.4 l/s, which is nearly double the observed peak flow 227.7 l/s in 2004 (22.3% IS). The low flow rates still occur more frequently in the lower imperviousness phase.

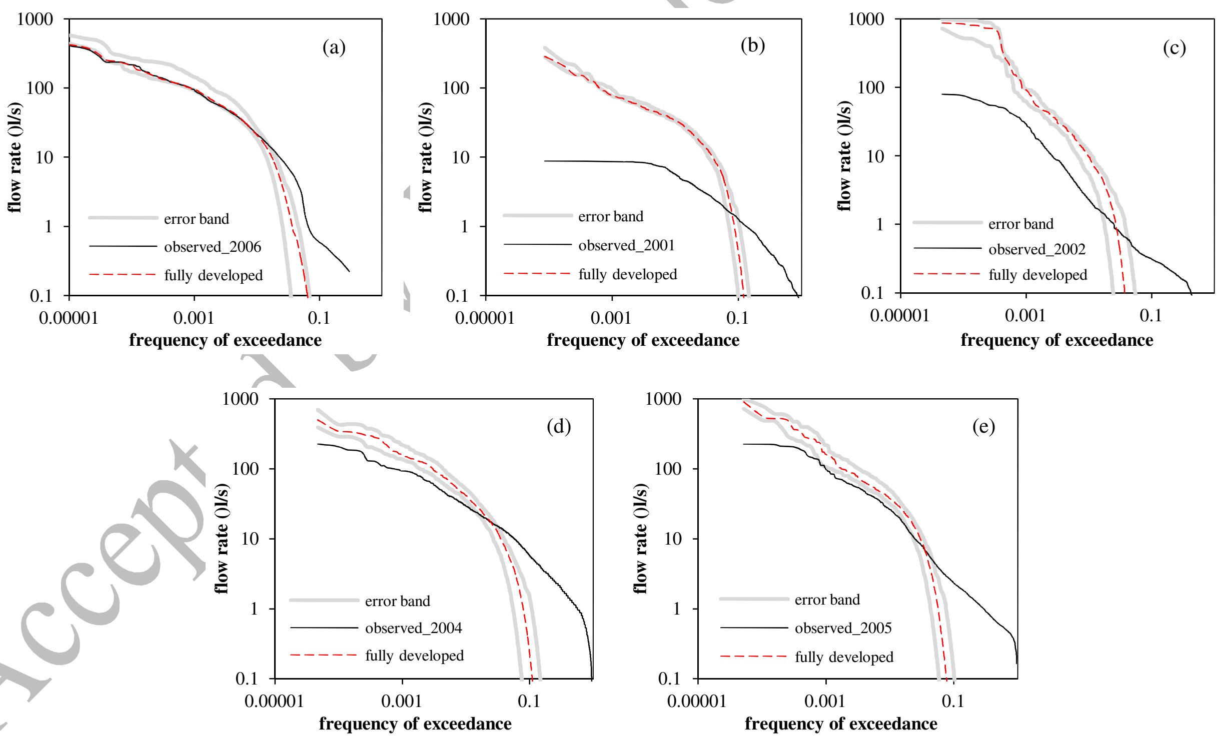


Fig. 6 Flow-frequency curves for (a) the reference year 2006, (b) the pre-development year 2001, (c) the pre-development year 2002, (d) the partially developed phase 2004, and (e) the partially developed phase 2005; where the intersection between the curve and the y-axis shows the maximal peak flow during the simulation period, and the intersection with the x-axis shows the fraction of time during which a flow is detected at the outlet. The fully developed curves characterize the simulated flow in a fully developed scenario during the rainfall in the corresponding year.

Fig. 7 demonstrates the measured runoff-precipitation ratios (R-P ratio) and the simulated ratios using the model for the fully developed conditions during the warm periods of 2001-2006. The focus of the calibration and validation is on surface runoff during single events. The limitation of the model in simulating small base flows leads to an underestimation by 37% in the total cumulative runoff for the fully developed catchment condition in 2006. The difference is considered in the simulations of runoff caused by the rainfall in other years. As expected, urban development from the pre-development phase to the fully developed catchment results in a remarkable change of total measured runoff volume. Under the condition in 2001, R-P ratio is raised by 60% - 120% in comparison to that in the fully developed condition, and the increase is even sharper in 2002, reaching 170% - 270% .In consideration of the underestimation (37%) in simulating the total cumulative runoff, the R-P ratio from the partially developed condition in 2005 (33.4% IS) to the fully developed catchment in 2006 (38.7% IS) is also slightly increased. The increase of total runoff volume is attributed to the expansion of runoff contributing area and the construction of impervious surfaces. However, we can see that the simulated R-P ratio in the fully developed condition has a notably smaller value than the observed data in the partially developed phase 2004, i.e. urban construction from 2004 (22.3% IS) to 2006 (38.7% IS) reduces the total runoff by 21.2%-42.5%. This insight conflicts with the well-known traditional understanding about hydrological impacts of urbanization. Based on on-site observations and small atypical fluctuations in the flow measurements, the increase in observed runoff in 2004 can be explained by artificial pumping that occurred at the building sites. The weather conditions in summer 2004 were exceptionally wet, and the construction sites were kept dry by pumping water from the building pits to the storm sewer network. Fig. 8(a) plots the temporal change of the cumulative runoff from March 5, 2004 to September 30, 2004 for the simulated final development scenario and the measured intermediate development phase 2004. It clearly implies that the measured runoff volume shows larger accumulations than the simulated runoff after July 2004, and the difference is accumulated as measured higher low flows between the events. Fig. 8(b-d) demonstrates the comparisons of three selected rainfall events with the depth of 10.4 mm, 8.4 mm and 21.2 mm respectively. It is found that the flow rate with the lower imperviousness is considerably smaller than that with higher imperviousness, but both flow processes have a high consistency with each other along with the magnitude of rainfall. Artificial pumping likely affected runoff also in 2005, yet to a smaller extent than in 2004.

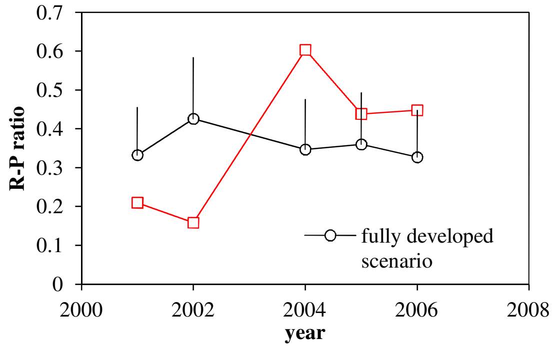


Fig. 7 Runoff-precipitation ratios for the observed construction phases from 2001-2005 and the corresponding simulations in the fully developed scenario; note: the vertical line at each dot point represents the range of the value with 37% underestimation; 2001-2002 is the pre-development phase, 2004-2005 is the partially developed phase, and 2006 is the reference year.

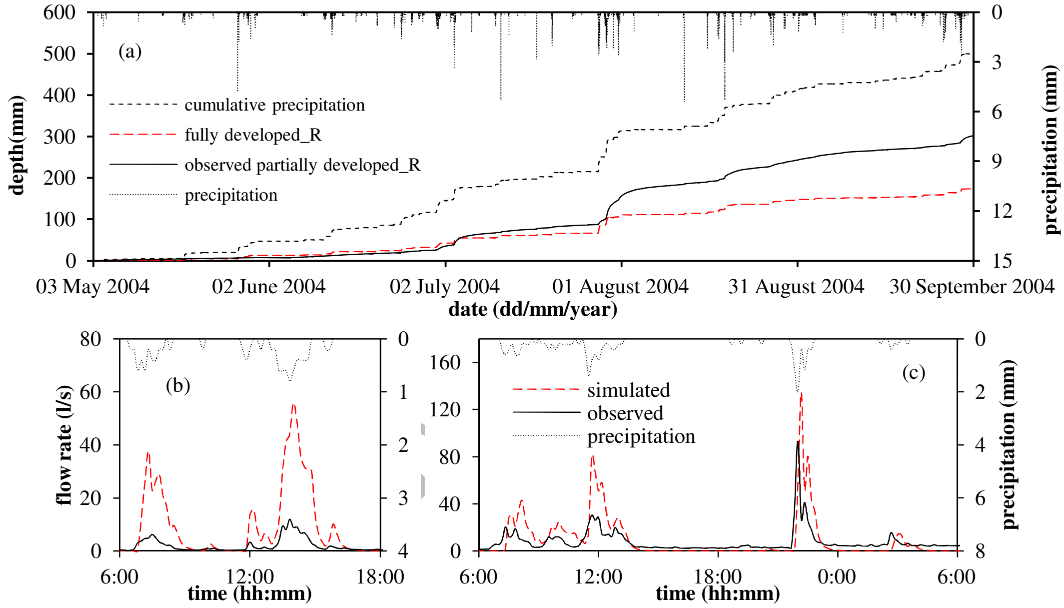


Fig. 8 (a) the observed cumulative runoff in the partially developed scenario and the simulation in the fully developed catchment from March 5 to September 30, 2004; the observed flow rate in 2004 and the simulation in the final developed scenario on: (b) 18 May 2004, and (c) 26 August 2004.

Fig. 9(a) plots the observed total runoff from the rural catchment in 2002 and the simulation results after development. As expected, the simulated total runoff after development is considerably larger than that in the rural area before development. Before a major rainfall event on July 5, 2002, the cumulative runoff from the rural catchment is only 3.15 mm, while it reaches 10.87 mm under the modeled condition of developed catchment with an increase of approximately 2.5 times. After July 5, 2002, the observed runoff increases to about 14.8 mm, which is much smaller than the simulated runoff of 48.2 mm from the fully developed catchment. In consideration of 37% derivation, the true difference will be bigger. The measured cumulative runoff after July 5, 2002 no longer rises because of strong evapotranspiration and soil infiltration losses. It is only 28.3 mm on October 29, 2002. However, for the development scenario, the simulated cumulative runoff rises closely with the increase of rainfall depth, and after urban development, it is increased to 69.4 mm from 28.3 mm. From a single event point of view, Fig. 9(b) illustrates the observed flow in the rural area and the simulated flow after development during a rainfall of 58.4 mm in depth. We can see that there is only one flow peak before development; the peak flow is 78.7 l/s and the flow process lasts for over 20 hours. However, the urbanization causes two flow peaks responding to rainfall and raises the peak flow to 869.2 l/s, but the flow duration shortens sharply to only about 6 hours. The flow in urbanized catchment has a quicker response to rainfall indicated by a high rate of rise and falls from peak flow to zero flow conditions.

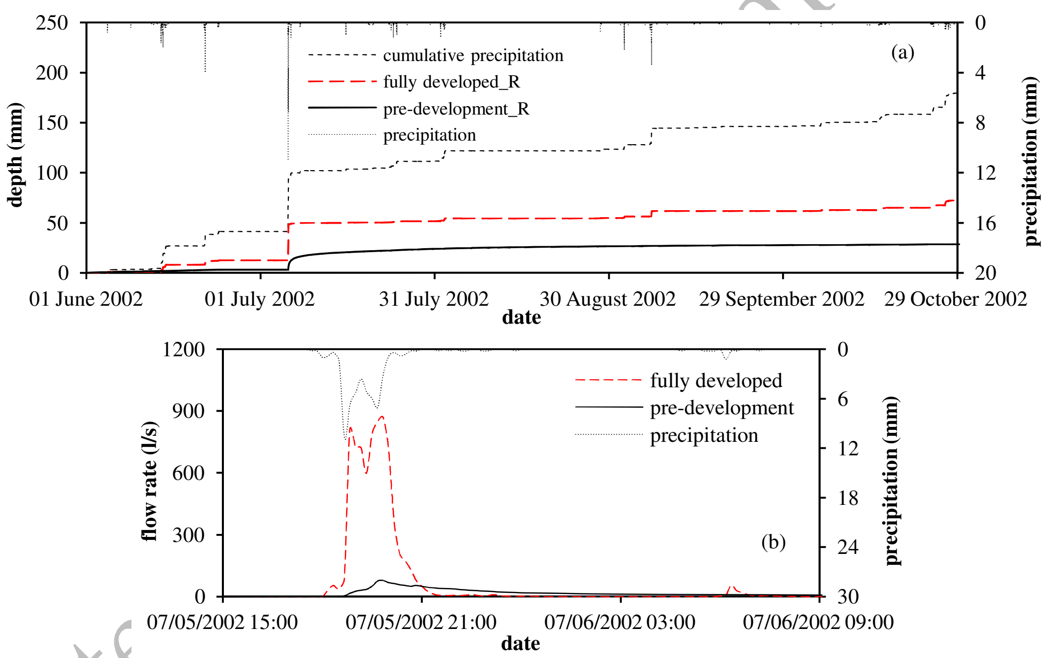
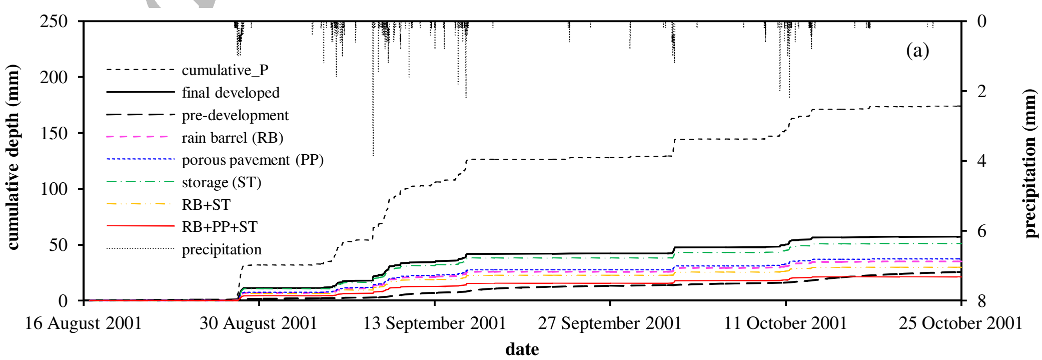


Fig. 9 (a) The observed cumulative rural runoff and simulated runoff after development from June 1, to October 29, 2002; (b) the observed pre-development flow and simulated flow for a single event in fully developed catchment

Possibility to restore pre-development hydrology

Continuous simulations E6, E7, and E8 were implemented. The LID techniques, rain barrel (RB) and porous pavement (PP), were used in the model, and a storage unit (ST) near the outlet was set. In view of Rossman (2010), the parameters associated with RB and PP was set. For RB, the addressed area is approximately 1.26 ha; a rain barrel with a volume of 27 m^3 was installed next to each building's roof. The area for the porous pavement was about 1.3 ha covering all streets and parking lots except the main road. For PP, vegetation volume fraction was set as 0.3 in surface layer; pavement thickness was 150 mm and permeability was 1000 mm/h; storage height of the pavement was 300 mm with a conductivity of 500 mm/h. For ST, the storage curve used a functional curve $Area=ah^b$, where a = 800 m, h_{max} = 1 m and b = 0.3. The results with and without LID controls were plotted in Fig. 10. Fig. 10(a) shows that all the LID techniques result in a significant reduction in the cumulative runoff towards the runoff volume in a rural scenario, and the combination of rain barrel, porous pavement and storage unit attains the best influence on reducing the total runoff volume by 62.9%. The cumulative runoff volume in the fully developed catchment with RB+PP+ST is 21.2 mm (29.0 mm with the inclusion of 37% underestimation in simulating the total runoff) which is closing to the pre-development runoff volume, 25.4 mm. This implies the significant effects of LID practices on reducing runoff volume. Fig. 10(b) plots the simulated flow-frequency curves in several scenarios and the observed pre-development flow data. The comparison reveals that 1) the control approaches including single and combined techniques neither restore low-frequency flow rates nor high-frequency flow rates, and the flow pattern in an urbanized catchment is still far flashier than that in a rural area, 2) RB and PP achieves a flow-frequency curve always lower than that without control, i.e. both low-frequency and high-frequency flow rates are reduced, 3) flow rate control approach such as ST causes an increase in high-frequency flow rates, but a reduction of low-frequency flow rates, and 4) a combination of RB+PP+ST has the best effects on changing the curve towards the observed flow-frequency curve, but again this is insufficient to restore pre-development flow and particularly the high flows are much larger than the pre-development flow rates.



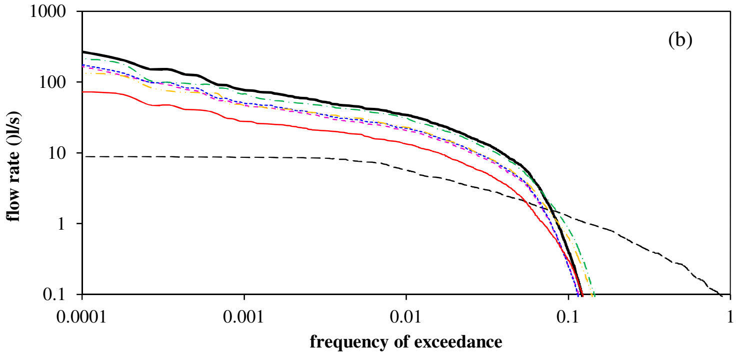


Fig. 10 (a) Cumulative runoff volumes, and (b) flow-frequency curves for final developed phase without control, with RB, PP, ST, RB+ST and a combination of three, as well as observed pre-development data.

From a single-event point of view, Fig. 11 demonstrates that the effect of GR and PP is on reducing the flow rates from low flows to extreme flow rates under the condition of not changing the flow pattern and affecting the time of concentration. The effects of the approaches with a flow rate control, ST, lie in two aspects: reducing peak flow rate, and delaying the flow hydrograph. This means that flow rate control results in a flattening of the flow hydrograph, which is towards the typical flow pattern in a rural area. The combination of RB+ST and RB+PP+ST has both advantages of the two types of techniques. For example, in the event of Fig. 11(a), the peak flow is reduced by 74%, the occurrence time of the peak is delayed by 10 minutes, and the flow after rainfall lasts longer than 1 hour. However, it can be seen that the regulated peak, 73.7 l/s, is still 18 times larger than the pre-development peak flow, 4.3 l/s, for the event. Although the key elements, such as peak flow and occurring time, are nearly restored by the approach RB+PP+ST (a=1200, b=0.01) for the small event (2.6 mm in rainfall depth) in Fig. 11(b), the observed low flows occurring before and after the event during pre-development period are not well reproduced. Overall, the total runoff volume and the key elements for small events can be attained through a combination of several techniques, yet the unique hydrograph of the observed natural flows are still far from being fully restored although over 54% of the impervious surfaces was addressed using LID techniques. It can be inferred that to treat all impervious surfaces (e.g. to address the main road by LID technique) might bring a further decrease of stormwater runoff. However, as such the runoff management example applied in the current study is a realistic scenario of a LID retrofit for an existing urban area, whereas the treatment of nearly all impervious areas is easier to achieve in a planning stage of new residential areas. Moreover, based on the results it seems difficult to eliminate the huge difference between urban flow and pre-development flow, for example, the event in Fig.

11(a). The results suggest that stormwater management techniques used in this study mitigate the negative effects of urbanization on catchment hydrology; however, they are insufficient to restore the pre-development flow regimes.

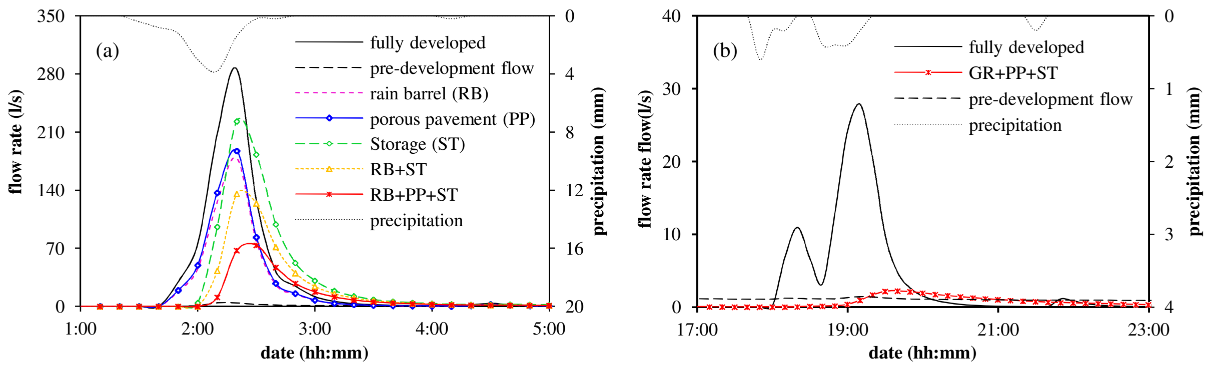


Fig. 11 Flow rates of two single-events for the observed rural scenario, the reference scenario 2006 without control, with RB, PP, ST, GR+ST and a combination of three; (a) rainfall depth = 11.4 mm; (b) rainfall depth = 2.6 mm

DISCUSSION

Model sensitivity and uncertainty

The simulations in this study were conducted by model calibration and validation against field data. However, inevitably there are some uncertainties from model parameters and measured data in urban hydrological modeling (Feyen *et al.*, 2007; Dotto *et al.*, 2014). SWMM has been regarded to be appropriate for urban catchment, but the application in a rural area is still rare and debatable. The fully developed catchment in 2006 was only a medium-density residential area with an imperviousness of 38.7%, i.e. 61.3% of the catchment was still covered by pervious area. So the runoff production from the pervious surfaces probably cannot be predicted as precisely as that from an impervious area, which might bring some errors to the simulations. The errors were primarily focused on the prediction of low base flows. For example, in the events of V3 (Fig.4), the observed base flows after rainfall lasted for a period, yet the simulated base flows vanished soon after rainfall ended. The model involves a series of uncertain parameters, and although they were calibrated and validated, this cannot fully assure the suitability of the model for all rainfall events. It has been reported that SWMM simulations were sensitive to the imperviousness, the surface depression storage, Manning's n for overland flow, and pipe flow (Barco *et al.*, 2008; Krebs *et al.*, 2014). In this particular site, we found that the Manning's n for overland flow and pipe flow affects the magnitude and occurrence time of peak flow at the outlet, but the sensitivity is insignificant when the values are defined in the corresponding min-to-max range. The depth of depression storage mainly affects the flows generated during extremely small storms, or those in the starting period of rainfall. For other conditions the effects diminish. It was also found that the simulations are mostly sensitive to the imperviousness, because it directly estimates the size of the runoff contributing area from the extent of impervious surface. In this study, the imperviousness was estimated based on ArcGIS and an aerial image from 2006, so some deviations can occur inevitably but the estimation reasonably ensured the real conditions of 2006. Although we defined a fluctuation range of slope and flow width based on the initial estimation, and regarded them as calibration parameters, the uncertainty from both parameters still cannot be avoided. Another uncertainty stems from the soil infiltration parameters in the GREEN_AMPT model. The urbanization in the study site changed the land cover surface, not only in terms of the impervious surface, but also the artificial construction of the pervious area, such as the constructed lawns. The diversity of the pervious area makes it more difficult to estimate the soil infiltration coefficient. The fact that there were not enough rainfall events with a large total depth in the calibration year limited the calibration and validation of the infiltration parameters. However, for this particular study catchment, the rainfall with a depth < 37.2 mm can at least be predicted well. Additionally, some sewer network data is missing in the middle region of the catchment, so the flows there had to be drained to the nearby main pipe directly, which can accelerate hydrological response to a certain extent and, thereby, probably affect the outflow pattern. This is considered as another uncertainty source of the model, but the model outputs shows that the current network data is enough for a hydrological changes assessment in the studied catchment. The contribution of evapotranspiration to urban hydrology is important to urban water balance (Fletcher *et al.*, 2013). However, no study has reported the good performance of SWMM in quantifying the urban evapotranspiration. Thus, for the continuous simulations, the simulated cumulative runoff probably has some discrepancies. Such measured datasets, as rainfall and flow rates, have inherent uncertainty due to the random and systematic errors associated with the measurement device and this uncertainty increases the data requirements for model calibration (Mourad *et al.*, 2005; Dotto *et al.*, 2014).

Hydrological impacts of urban development

It is well known that urbanization and the increase of impervious surfaces lead to higher runoff peaks and a flashy runoff response to rainstorms. This hypothesis has been verified through experimental observations and urban hydrological modeling (Cheng and Wang, 2002; Burns *et al.*, 2005; Jang *et al.*, 2007). However, these studies compared urban catchments representing different development densities instead of being able to compare measured development phases in one catchment and, hence, the results are affected by other catchment characteristics and weather conditions in addition to urbanization. The investigation on hydrological changes in a developing catchment was rarely seen because of the scarce and limited observed data, particularly in a small-scale catchment where the hydrological impacts are more clearly seen (Burns *et al.*, 2005; Sillanpää and Koivusalo, 2014). This study explored the hydrological changes in a small developing catchment with a good quality dataset, and the results improve the insights on the hydrological effects of urbanization. During the construction period, IS increased from undeveloped conditions to nearly 40%. It was found that urban development from a rural area to a medium-density residential land use results in a flashy flow-frequency curve. Urbanization causes the low-frequency flow rate to increase considerably, but high-frequency low flow to diminish quickly. Also, the total runoff volume is increased remarkably due to urbanization; for example, the increasing order reaches 0.6-1.2 from the pre-development phase in 2001 to the fully developed catchment in 2006, and 1.7-2.7 from 2002 to 2006. From a single event point of view, the flow pattern is changed. Urban development accelerates the response of runoff to rainfall indicated by a high rate of rising to peak and falling to zero flow conditions. The catchment expansion and the sharp increase in impervious surface are inevitably the major reasons resulting in the increase in the runoff generation. However, in Section 4.2, we also found that ongoing urban construction can increase the total runoff volume above the levels corresponding to the final development stage. Similar findings have also been reported by (Line and White, 2007). They noted that 70% of the rainfall produced runoff at a construction site during the house construction phase at a small construction site in North Carolina and that the annual runoff ratio during the house construction phase was higher than that during the clearing and grading phase and after development. It was explained that the high runoff ratio during the building construction was caused by the lack of established vegetation in pervious areas and the reduced infiltration rate due to compaction caused by heavy machinery. These factors have likely affected the unexpectedly high runoff volumes in the building construction year in 2004. Yet, in the current study, we also found that artificial drainage activities occurred during the building construction phase, which increased total outflow. This is considered as the primary reason that the runoff ratio during the house construction phase was higher than that after development, although the construction phase had a smaller imperviousness.

Restoration of rural hydrology

Stormwater management techniques have been reported to mitigate negative hydrological impacts of urban development in recent studies (Carter and Jackson, 2007; Burns *et al.*, 2012; Jia *et al.*, 2012). The approaches include infiltration-based techniques and retention-based techniques. Each approach has its advantages and disadvantages (Fletcher *et al.*, 2013). Burns et al. (2012) indicated that key elements of the rural hydrology could only be successfully achieved by a combination of retention-based methods to deal with peak flows and runoff volume, and infiltration-based techniques to address infiltration loss due to land cover changes. In this study, we explored the hydrological impacts of several LID regulations on hydrology in a final developed periurban catchment and investigated how to restore the pre-development regimes flow. It is found that both control measures cause a significant effect on reducing total runoff volume and peak flow rate on a event scale. Supporting the results by Pertucci et al. (2013) for French catchments, the flow rate control approach causes an increase in higher-frequency flow rates but a reduction of lower-frequency flow rates by delaying the runoff hydrograph, and green roof and porous pavement reduce systematically both low-frequency and high-frequency flow rates. It should be noted that the techniques such as porous pavement lead to an increase of infiltration loss which must appear as subsurface flow and can further increase low flows. The subsurface component was not modeled by SWMM in our simulations which only focused on stormwater flows. Although the combined techniques have the best influence on flattening the flow-frequency curve, it is still far steeper in comparison with the observed curve in a rural area. The flow processes during a single event imply that the natural flow regime, characterized by low peak flows and longer duration, is far from being restored even though over 54% of the impervious areas have been treated by LID techniques. However, the modeled scenarios demonstrate the possibility to mitigate the negative impacts of urbanization on runoff generation. The restoration of low flow rates can be attained through flow-rate control, and volume control can be more effective in reducing runoff volume. The results underline the importance of further research for understanding the consequences of different stormwater management approaches on runoff generation on a catchment scale and developing more detailed hydrological principles for drainage design.

CONCLUSIONS

This study investigated hydrological change caused by urban development using SWMM. The model was firstly parameterized, calibrated, and validated in the final developed periurban catchment. Twelve rainfall events varying from 3.0 mm to 37.2 mm were selected for calibration and validation, which ensured the applicability and reliability of the model for simulating minor and major events. The validated model was then applied to other development phases and stormwater management scenarios with the input of rainfall from partially developed years and pre-development years. The proposed four questions were resolved and discussed. Based on the above results and discussion, the following can be concluded:

(1) In comparison with pre-development flow, the flow in the urbanized catchment has a faster hydrological response, much higher peak flows, as well as a larger total runoff volume. The flow-frequency curve after development is much steeper.

(2) The low-frequency high flow rates are also increased remarkably from the partially developed phase to the fully developed catchment, along with the increasing of impervious areas, but high-frequency low flow is reduced due to urban construction.

(3) Runoff generation may be temporally increased to abnormal levels by drainage activities during building construction.

(4) Stormwater management techniques can cause a reduction in flow towards pre-development levels, and a combination of volume control and flow rate control is recommended. There is a possible to restore the pre-development total runoff volume and the key elements of natural flows for some small events through combined regulations; however, to fully restore pre-development flow regimes remains far from being achieved. .

This study extends our knowledge of the hydrological change in a developing urban catchment through elucidating several potential questions. The outputs can be further utilized in the development of appropriate urban runoff management schemes for the local climate.

ACKNOWLEDGEMENT

This work was funded by Aalto University School of Engineering and the European Regional Development Fund (Urban laboratory for sustainable built environment). The authors thank the Helsinki Region Environmental Services Authority HSY for the GIS data received for model calibration.

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