Spatial Resolution and Parameterization of an Urban Hydrological Model

Requirements for the Evaluation of Low Impact Development Strategies at the City Scale

Gerald Krebs

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Abstract

The impacts of urbanization on the environment are widely acknowledged. Urban development implies the increase of impervious cover that is unable to provide hydrological functions of natural catchments, such as infiltration, evapotranspiration, and attenuation. Thus, increasing imperviousness alters the hydrological cycle, which is seen as increasing runoff volumes, larger runoff peak rates, and more severe pollutant loads. To mitigate these impacts, Low Impact Development (LID) tools have been developed. These aim to mimic hydrological processes of natural catchments reducing runoff and pollutant loads close to the source.

Hydrological modelling is one option to evaluate the performance of LID strategies before implementation. However, such an assessment requires an explicit modelling strategy. Such a strategy implies the availability of detailed spatial data for model development and rainfall-runoff data at a sufficient temporal resolution for model calibration. Such data are often not available for larger urban catchments hampering the evaluation of LID strategies at the city-scale. This study presents a methodology for the parameterization of a hydrological model to a large urban catchment where the explicit simulation of various LID tools for urban stormwater management is supported. Several aspects of urban hydrological modelling were investigated under consideration of limited availability of data and with the focus to retain the possibility for explicit LID simulation. These aspects include (i) the implications of surface discretization approaches on simulation results, (ii) the impact of spatial resolution on simulated runoff, (iii) the impact of an automated DEM-based delineation approach on catchment properties and simulation results, and (iv) the parameterization of a large, ungauged catchment. Finally, a green roof model was parameterized to allow its implementation into a large scale urban catchment model.

While both a coarser spatial resolution and a DEM-based delineation affect the simulation results, conducted simulations allowed the determination of a suitable threshold for the reduction in spatial resolution that can reasonably well replicate the dynamics of urban runoff. Results concerning the parameter inter-changeability show that the transfer of parameter values calibrated to monitored study catchments using a surface-type based surface discretization is a feasible way to parameterize large, urban catchments.

Tiivistelmä

Kaupungistumisen ympäristövaikutukset ovat laajalti tiedossa. Kaupunkirakentaminen lisää vettä läpäisemättömän pinnan suhteellista osuutta, mikä näkyy alueen hydrologiassa pienentyneenä imeytymisenä ja haihduntana sekä lyhentyneenä sadannan ja valunnan välisenä viipeenä. Nämä muutokset johtavat suurempiin valunnan kokonaismääriin ja huippuvirtaamiin sekä kasvaviin ympäristökuormiin. Näiden haitallisten vaikutusten lieventämiseksi on kehitetty rakenneratkaisuja, jotka edistävät luonnollisemman vedenkierron säilyttämistä kaupunkialueilla (Low Impact Development, LID).

Hydrologisia mallilaskelmia voidaan hyödyntää eri rakenneratkaisuvaihtoehtojen vaikuttavuuden arviointiin ennen toteutusta. Mallin tulee kuitenkin kyetä esittämään hulevesien hallintaan käytetyt rakenneratkaisut tarkasti omilla paikoillaan. Lisäksi tarvitaan tarkka kaupunkialueen pintojen ja kuivatusverkon paikkatieto sekä ajallisesti tiheä sadanta- ja valuntatieto mallin kalibroimiseen ja testaamiseen. Tällaista tietoa ei usein ole saatavilla suuremmille kaupunkivaluma-alueille, vaikeuttaen LID-tarkasteluja kokonaisten kaupunginosien mittakaavassa. Tutkimuksessa esitetään suuremmillekin kaupunkivaluma-alueille soveltuvia menetelmiä hydrologisen mallin parametrisointiin erilaisten LID-ratkaisujen toiminnan arvioimiseksi. Useita kaupunkihydrologiseen mallintamiseen liittyviä näkökulmia tarkasteltiin huomioiden rajoitukset datan saatavuudessa sekä tarve LID-ratkaisujen kuvaamiseen tarkasti omilla paikoillaan. Tarkastellut näkökulmat olivat: (i) kaupunkipintojen diskretointitavan vaikutus mallituloksiin, (ii) paikkakuvauksen resoluution vaikutus mallituloksiin, (iii) automaattisen digitaaliseen korkeusaineistoon (Digital Elevation Model, DEM) pohjautuvan osavaluma-alueiden tunnistamisen vaikutukset valuma-alueominaisuuksiin ja mallituloksiin sekä (iv) suuren kaupunkivaluma-alueen, jolta puuttuvat virtaamamittaukset, parametrisointi. Lopuksi parametrisoitiin viherkattojen hydrologista käyttäytymistä kuvaava malli sen liittämiseksi suuren kaupunkivaluma-alueen hydrologisen mallin osaksi.

Sekä paikkakuvauksen resoluution että DEM:iin perustuvan valuma-aluerajauksen todettiin vaikuttavan mallituloksiin. Tulosten perusteella oli mahdollista tunnistaa paikkaresoluutiolle kynnysarvo, jota tiheämmän resoluution käyttö ei merkittävästi parantanut laskettujen kaupunkivaluntojen tarkkuutta. Parametrien keskinäistä vaihtokelpoisuutta koskevat tulokset osoittivat, että pienten tutkimusvaluma-alueiden eri kaupunkipinnoille määritettyjä parametriarvoja voidaan käyttää tuottamaan uskottavia laskennallisia valuntoja läheisille, suuremmille kaupunkialueille, joilta valuntamittaukset puuttuvat.

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<div align="right">Espoo, March 2016</div>

<div align="right">Gerald Krebs</div>

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[1] Thank you, Mama and Papa. Even though I was rarely at home during my dissertation, your education prepared me for the challenges of life, including this work.

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CONTENTS

LIST OF ABBREVIATIONS

AP	rainfall measurement station at catchment 2
C1-C11	calibration events of the green roof model
CAL	calibration sequences for the study catchments
DEM	digital elevation model
EIA	effective impervious area
ES	excessive catchment surface
GLUE	Generalized Likelihood Uncertainty Estimation
HR	high resolution
KS-test	statistical Kolmogorov-Smirnov test
LID	Low Impact Development
LR	low resolution
LR DEM	low resolution with individual surfaces using a DEM
LR IS	low resolution with individual surfaces
LR WA	low resolution with weighted average surfaces
LSB	rainfall station at the Lahti Science and Business Park
OS	overlapping catchment surface
PET	potential evapotranspiration
SUDS	Sustainable Urban Drainage Systems
SWMM	Stormwater Management Model
TIA	total impervious area
US EPA	United States Environmental Protection Agency
VAL AP	validation sequences for the study catchments (AP rainfall)
VAL LSB	validation sequences for the study catchments (LSB rainfall)
V_1, V_2, V_3	parameter sets based on the catchments 1, 2, and 3, respectively
V1-V13	validation events of the green roof model
V_{Ref}	reference parameter set based on literature
WSUD	Water Sensitive Urban Design

LIST OF SYMBOLS

A	[L²]	catchment area (catchment model)
con	[LT⁻¹]	soil hydraulic conductivity (green roof model)
$con\ s$	[-]	soil conductivity slope (green roof model)
C_{PET}	[-]	PET scaling coefficient (green roof model)
D_{stat}	[-]	statistical difference in the Kolmogorov-Smirnov test
D	[L]	surface depression storage (catchment model)
d	[L]	conduit diameter (catchment model)
d_{min}	[L]	conduit diameter threshold (catchment model)
dmt	[L]	drainage mat thickness (green roof model)
d_s	[L]	surface depression storage (green roof model)
E	[-]	Nash-Sutcliffe efficiency
fc	[-]	soil field capacity (green roof model)
FW	[L]	flow width (catchment model)
I	[%]	fraction of impervious cover (catchment model)
k	[-]	coefficient for flow width computation (catchment model)
L	[L]	length of the overland flow path (catchment model)
n	[-]	the Manning's roughness coefficient for drainage mat flow (green roof model)
n_c	[-]	the Manning's roughness coefficient for conduit flow (catchment model)
n_o	[-]	the Manning's roughness coefficient for overland flow (catchment model)
n_s	[-]	the Manning's roughness coefficient for surface flow (green roof model)
p	[-]	soil porosity (green roof model)
p-value	[-]	p-value in the Kolmogorov-Smirnov test
PFE	[%]	peak flow error
Q_m	[L³T⁻¹]	modelled flow

Q_o	[L³T⁻¹]	observed flow
$\bar{Q}_m$	[L³T⁻¹]	modelled mean flow
$\bar{Q}_o$	[L³T⁻¹]	observed mean flow
$Q_{m,p}$	[L³T⁻¹]	modelled peak flow
$Q_{o,p}$	[L³T⁻¹]	observed peak flow
r_{QoQm}	[-]	linear correlation coefficient
S	[%]	surface slope (catchment model)
s	[%]	surface slope (green roof model)
sh	[L]	soil suction head (green roof model)
SSE	[(L³T⁻²)²]	sum of squared errors
t	[L]	soil thickness (green roof model)
V_m	[L³]	modelled flow volume
V_o	[L³]	observed flow volume
VE	[%]	volume error
vf	[-]	drainage mat void fraction (green roof model)
vvf	[-]	vegetation volume fraction (green roof model)
wp	[-]	soil wilting point (green roof model)

LIST OF FIGURES

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LIST OF APPENDED PAPERS

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

Paper I **Krebs, Gerald**; Kokkonen, Teemu; Valtanen, Marjo; Koivusalo, Harri; Setälä, Heikki (2013). A high resolution application of a stormwater management model (SWMM) using genetic parameter optimization. *Urban Water Journal* 10(6), 394-410. ISSN 1573-062X. DOI: 10.1080/1573062X.2012.739631

Paper II **Krebs, Gerald**; Kokkonen, Teemu; Valtanen, Marjo; Setälä, Heikki; Koivusalo, Harri (2014). Spatial resolution considerations for urban hydrological modelling. *Journal of Hydrology* 512, 482-497. ISSN 0022-1694. DOI: 10.1016/j.jhydrol.2014.03.013

Paper III **Krebs, Gerald**; Kokkonen, Teemu; Setälä, Heikki; Koivusalo; Harri. Parameterization of a hydrological model for a large, ungauged urban catchment. *Journal of Hydrology*, Revised and submitted December 2015.

Paper IV **Krebs, Gerald**; Kuoppamäki, Kirsi; Kokkonen, Teemu; Koivusalo, Harri (2016). Simulation of green roof test bed runoff. *Hydrological Processes* 30(2), 250-262. ISSN 1099-1085. DOI: 10.1002/hyp.10605

AUTHOR'S CONTRIBUTION

Paper I   The author was mainly responsible for the design of the research, the analysis and quality assurance of the rainfall-runoff data, and the writing of the paper, and fully responsible for the calibration and validation of the hydrological model. Dr. Valtanen was responsible for collecting rainfall-runoff data, provided support during the analysis of the data and participated in the writing of the paper. Dr. Kokkonen and Prof. Koivusalo participated in the design of the research and the writing of the paper. Prof. Setälä participated in the writing of the paper.

Paper II   The author was mainly responsible for the design of the research, the analysis and quality assurance of the rainfall-runoff data, and the writing of the paper, and fully responsible for the calibration and validation of the hydrological models as well as for conducted analyses on spatial model resolutions. Dr. Valtanen was responsible for collecting rainfall-runoff data, provided support during the analysis of the data and participated in the writing of the paper. Dr. Kokkonen and Prof. Koivusalo participated in the design of the research and the writing of the paper. Prof. Setälä participated in the writing of the paper.

Paper III   The author was mainly responsible for the design of the research and the writing of the paper, and fully responsible for analyses conducted with the hydrological model. Dr. Kokkonen and Prof. Koivusalo participated in the design of the research and the writing of the paper. Prof. Setälä participated in the writing of the paper.

Paper IV   The author was mainly responsible for the design of the research, the analysis and quality assurance of the rainfall-runoff data, and the writing of the paper, and fully responsible for the calibration and validation of the hydrological model. Dr. Kuoppamäki was responsible for collecting rainfall-runoff data, provided support during the analysis of the data and participated in the writing of the paper. Dr. Kokkonen and Prof. Koivusalo participated in the design of the research and the writing of the paper.

1 INTRODUCTION

1.1 Background

1.1.1 Urbanization and impacts on the environment

Human society is experiencing a clear shift towards urban living. While in the year 2000 71% of the European population lived in urban areas, this number is expected to increase to 78% in 2030 (United Nations 2012). A similar trend can be observed in Finland, where the urban population is expected to increase from 82% in the year 2000 to 86% in 2030 (United Nations 2012).

The land-cover changes associated with urbanization result in increased imperviousness when natural areas are replaced by streets, parking lots, pavements, and roof tops. These common surfaces of the urban landscape are unable to provide the hydrological functions present in natural catchments, such as infiltration, storage, and attenuation. Often, urbanization also involves the alteration of natural water courses (Zoppou 2001). Consequently, urbanization alters the hydrological cycle (Shuster *et al.* 2005) seen as a change in both the type and the magnitude of the runoff process (Arnold Jr and Gibbons 1996, Booth and Jackson 1997, Lee and Heaney 2003, Marsalek *et al.* 2007). These changes imply higher runoff volumes (Leopold 1968, Cheng and Wang 2002, Lee and Heaney 2003, Shuster *et al.* 2005, Marsalek *et al.* 2007, Bedan and Clausen 2009, Burns *et al.* 2012, Valtanen *et al.* 2014a, Sillanpää and Koivusalo 2015), higher peak flow rates (Leopold 1968, Cheng and Wang 2002, Lee and Heaney 2003, Shuster *et al.* 2005, Bedan and Clausen 2009, Burns *et al.* 2012, Sillanpää and Koivusalo 2015), an increase of runoff events (Marsalek *et al.* 2007, Valtanen *et al.* 2014a), and a reduction in infiltration (Arnold Jr and Gibbons 1996, Cheng and Wang 2002, Marsalek *et al.* 2007, Haase 2009). Furthermore, during dry periods impervious surfaces build up pollutants (e.g. from traffic) that are washed off during rainfall events (Arnold Jr and Gibbons 1996), resulting in higher pollutant loads (Lee and Heaney 2003, Dougherty *et al.* 2006, Bedan and Clausen 2009, Valtanen *et al.* 2014b). These pollutant loads result in degrading water quality of receiving water bodies (Leopold 1968, Bannerman *et al.* 1993, Schueler 1994, Ruth 2003, Schueler *et al.* 2009).

1.1.2 Low Impact Development (LID)

The aim of conventional stormwater management systems is the conveyance of stormwater runoff from the site through effective drainage (Maksimovic 2000,

Roy *et al.* 2008, Sillanpää 2013) to protect structures and prevent flooding. While this concept has been applied in most cities for the past century, it has two major limitations: conventional stormwater systems (i) do not sufficiently, if at all, address water quality issues (Zhou 2014) as stormwater is commonly routed to receiving water bodies without adequate treatment, and (ii) have limited flexibility to respond to urban dynamics (both growth and decline) and the potential climate change (Sieker *et al.* 2008).

A consequence of these limitations was the development of stormwater management principles that mimic processes of natural catchments and aim to treat and reduce runoff at the source (Maksimovic 2000, US EPA 2000). These concepts are referred to as Low Impact Development (LID) in the US, Water Sensitive Urban Design (WSUD) in Australia (Roy *et al.* 2008), and Sustainable Urban Drainage Systems (SUDS) in the UK (Butler and Davies 2011). They consist of a range of tools and planning strategies utilizing hydrological functions that are provided by natural catchments, such as infiltration, evapotranspiration, storage, and attenuation (US EPA 2000, Ahiablame *et al.* 2012, Stovin *et al.* 2012). Even though a full replication of the predevelopment hydrologic scheme may be unattainable (Guan *et al.* 2015) LID tools can effectively reduce runoff and contaminant loads at the source of generation (Dietz 2007, Dietz and Clausen 2008, Bedan and Clausen 2009). LID includes engineered solutions, such as green roofs, bio-retention, vegetative swales, rain barrels, or pervious pavers but also planning strategies such as settlement layouts that minimize the need for impervious surfaces, the disconnection of impervious areas from the drainage system, or the conservation of existing urban green areas (e.g. Ahiablame *et al.* 2012). LID tools can be applied to retrofit existing urban areas or implemented into stormwater management strategies for new urban developments. Runoff from urban impervious areas can be re-directed to rain barrels, bio-retention facilities, or available urban green areas. Green roofs and pervious pavers provide an option to mitigate urban runoff by reduction of urban imperviousness (US EPA 2000). The effectiveness of LID tools in mitigating the hydrological impacts of urbanization is well documented by numerous experimental studies. The ability to substantially reduce runoff from impervious traffic and roof areas was shown for pervious pavers (e.g. Booth and Leavitt 1999, Dreelin *et al.* 2006, Dietz and Clausen 2008, Fassman and Blackbourn 2010) and bio-retention cells (e.g. Davis 2008, Dietz and Clausen 2008, Li *et al.* 2009). Steffen *et al.* (2013) suggested a high potential for rainwater harvesting to reduce the urban runoff volume while at the same time providing supplemental water supply. The hydrologic performance of green roofs to mitigate urban hydrological impacts is generally recognized (Section 1.1.3).

1.1.3   Green roofs

Urban imperviousness typically consists of traffic related surfaces and rooftops (Schueler 1994). Rooftops account for 30-50% of urban imperviousness (Lee and Heaney 2003, Stovin, 2010) and thus substantially contribute to urban runoff. Thus, by increasing retention and evapotranspiration losses, green roofs have the potential to cut down runoff volume and intensity in densely built ur-

ban areas (Berndtsson 2010). The potential of green roof retention and peak flow reduction for stormwater management has been reported for a variety of climate conditions (Berndtsson 2010, Ahiablame *et al.* 2012, Li and Babcock Jr 2014). Green roofs are commonly categorized as extensive (substrate layer ≤ 150 mm) and intensive green roofs (substrate layer > 150 mm) (Mentens *et al.* 2006). While intensive green roofs, due to their thicker substrate layer, provide better stormwater retention than extensive green roofs, the latter, due to the slimmer and thus lighter structure, can be retrofitted on existing roofs and installed on almost all surface slopes (Mentens *et al.* 2006). Earlier studies show that the performance of even similar green roofs varies substantially, as the ability for retention depends on the local climate (Stovin *et al.* 2012, Carson *et al.* 2013). Moran *et al.* (2004) reported that two extensive green roofs in North Carolina, USA, retained 60% of the monitored rainfall and reduced the peak flow by 85%. Bengtsson *et al.* (2005) reported a rainfall retention of 46% for an extensive green roof in Southern Sweden. Carter and Rasmussen (2006) found an average green roof retention of 70% for an extensive green roof in Georgia, USA. Carson *et al.* (2013) reported a retention of 36-61% for three different green roof types in New York, USA, and observed a decreasing retention with event precipitation. Similar conclusions were drawn by Teemusk and Mander (2007) who reported that their extensive green roof in Estonia retained small-moderate rains well, but showed poor retention for large rains. In the Mediter-ranean climate, Palla *et al.* (2008b) found that their intensive green roof (sub-strate layer 350 mm) retained 85% of the recorded rainfall and reduced the peak flow in average by 97%. In UK climate conditions, an extensive green roof re-tained 34% of the monitored rainfall and achieved an average peak flow reduc-tion of 57% (Stovin 2010). For the same roof, the annual retention was 50% (Stovin *et al.* 2012). A volume retention of 66% and a median peak flow reduc-tion of 93% was monitored for an extensive roof in Auckland, New Zealand (Voyde *et al.* 2010a). Burszta-Adamiak and Mrowiec (2013) observed a volume retention of 30-78% for three green roofs in Poland.

While the hydrologic performance of LID tools is generally recognized, their benefit at the catchment scale is still debated (Palla and Gnecco 2015). Limited availability of field data for LID installations at the catchment scale hampers model calibration and validation (Loperfido *et al.* 2014). Furthermore, the ne-cessitated explicit modelling strategy (Amaguchi *et al.* 2012) requires a high spatial resolution (Palla and Gnecco 2015). Thus, fewer studies are available that assessed the effect of green roofs on stormwater runoff at the catchment scale. Mentens *et al.* (2006) estimated, based on existing literature, that a vegetated cover for 10% of existing roofs could reduce the annual runoff by 2.7% for the city of Brussels, Belgium. Carter and Jackson (2007) simulated green roofs for a 237 ha catchment (imperviousness 54%, roof area 16%) using the curve number approach and concluded that even though green roofs have a potential to repli-cate parts of the pre-development hydrographs, they cannot solely be relied on for stormwater management. Using the same approach, Palla *et al.* (2008a) estimated that a 10% extensive green roof coverage for a catchment in Genova, Italy, could reduce both runoff volume and peak flow rate by approximately 5%.

Mobilia *et al.* (2014) estimated a 30% reduction in the long term runoff coefficients for a south Italian catchment with an imperviousness of 67% and a roof area of 16%. Versini *et al.* (2015, 2016) estimated a reduction in runoff volume by 15-45% for two urban catchments in France. They conducted a detailed disaggregation that could support LID modelling on large scale but the results were so far reported only for small watersheds (2.4-5.5 km²).

1.1.4   Hydrological assessment methods

Hydro-meteorological data provides the foundation for any kind of hydrological assessment. In principle, two main methods can be distinguished, depending on the way collected data is utilized: (i) statistical analysis and (ii) hydrological modelling. Both methods have been extensively applied to assess the hydrology of urban catchments. Statistical analysis (e.g. correlation, regression) aims to develop relationships between catchment variables (e.g. the fraction of impervious cover, soil types, or land-use), rainfall variables (e.g. the peak intensity or the event rainfall depth), and runoff variables (such as the peak flow, runoff volume, or pollutant loads). Developed relationships allow predictions of e.g. pollutant loads based on the land-use type. Examples of urban hydrological assessments using statistical methods include the studies of Leopold (1968), Melanen (1981), Melanen and Laukkanen (1981), Bannerman *et al.* (1993), Booth and Jackson (1997), and more recently Sillanpää (2013), Valtanen *et al.* (2014a, b), and Sillanpää and Koivusalo (2015). Hydrological modelling on the other hand, utilizes data to calibrate a simulator of the hydrological catchment processes. The simulator might rely on empirical relationships, physical laws, or a combination of the two (see Section 1.1.5). A calibrated model can then serve as a tool to predict the impact of scenarios on the catchment hydrology (e.g. land-use changes, climate change). Examples of urban hydrological modelling include the studies of Lee and Heaney (2003), Barco *et al.* (2008), Goldstein *et al.* (2010), Beling *et al.* (2011), Amaguchi *et al.* (2012), Palla and Gnecco (2015), and Versini *et al.* (2015, 2016).

1.1.5   Rainfall-runoff modelling

The theoretical foundations of rainfall-runoff modelling date back to the 17th and 18th century and are based on hydrological and hydraulic relationships established by scientists such as de Saint-Venant (1797-1886), Darcy (1803-1858), Manning (1816-1897), or Richards (1904-1993) (Loague 2010a). Hydrological models can be categorized according to the implemented concept and methods (Grayson and Blöschl 2000). A model can be either *deterministic* or *stochastic*. While a *deterministic* model will always produce identical results for same input parameters this is not the case for a *stochastic* model, where one or more parameters are randomly selected from defined distributions. A further distinction is made between *empirical*, *conceptual*, and *physically-based* models. *Empirical* models are purely based on calibrated relationships between input and output data. In *conceptual* models, basic hydrological processes, such as runoff, infiltration, and evaporation, are separated and their description relies on sim-

plified physical laws. These laws however, are often based on empirical relations that require model calibration. *Physically-based* models have been developed to minimize the need for calibration. These models rely on physical laws in which parameters represent measurable physical quantities. Finally, models are categorized whether they consider spatial parameter variation (*distributed*) or neglect it (*lumped*).

The empirical rational method (Mulvany 1851) is by many considered as the first rainfall-runoff model allowing the estimation of peak flow rates. Due to its simplicity, this method is still today commonly used to predict stormwater runoff peaks. As a first attempt to distributed modelling Ross (1921) proposed a time contour approach that allows the generation of a catchment hydrograph. The unit-hydrograph method proposed by Sherman (1932) estimates direct runoff from effective rainfall and is still today one of the most widely used methods to assess the catchment response to rainfall (Loague 2010b). Mockus (1949) elaborated the foundation of the empirical Soil Conservation Service – Curve Number (SCS-CN) approach to estimate total and peak runoff for individual storm events. Almost thirty years after the initial proposal (Sherman 1932), Dooge (1959) proposed a general theory of the unit hydrograph. The conceptual Stanford Watershed Model (Crawford and Linsley 1966) represents an early computer-based modelling approach (Zoppou 2001). The blueprint for a physically-based distributed hydrological model by Freeze and Harlan (1969) provided the base for one of the first process-based distributed hydrological models (Freeze 1971). Abbott *et al.* (1986) introduced the distributed, process-based SHE model as a response to the need to assess the hydrological impact of man-made catchment changes (e.g. deforestation, urbanization). Fully distributed models have high requirements concerning both computational power and field data measurements of hydrological variables. As a consequence, so-called semi-distributed models were developed to combine the advantages of simple lumped parameter models and process-based distributed model descriptions. An example is the TOPMODEL by Beven and Kirkby (1979). TOPMODEL simplifies the spatial description of the catchment by establishing a relationship between distributed observations on catchment topography and contributing areas.

Runoff in urban areas is dominated by processes on impervious surfaces (Boyd *et al.* 1993) with no or very little sub-surface flow (Zoppou 2001). It is characterized by a fast catchment response to rainfall (Rodriguez *et al.* 2005) due to drainage systems designed to efficiently discharge runoff from the catchment (Sieker *et al.* 2008). Thus the focus of models specifically developed to assess the hydrological response of urban areas differs somewhat from general hydrological models. Most urban models can be categorized as *deterministic-distributed* (Nix 1994) and are commonly capable to simulate both stormwater quantity and quality. In principle they consist of two main components: (i) rainfall-runoff modelling (conversion of rainfall into runoff under consideration of initial and continuous losses such as evapotranspiration and infiltration) and (ii) transport modelling (routing of runoff through the drainage network) (Zoppou 2001). If water quality is simulated, pollutant build-up (during dry periods) and wash-off (during periods of surface runoff) are computed for surfaces and there-

after routed through the drainage network. Models that were capable of simulating stormwater quantity and quality emerged in the 1970's and are used to evaluate the effectiveness of stormwater management strategies (Zoppou 2001, Loague 2010a). Zoppou (2001) provided a good review on the capabilities and limitations of numerous urban stormwater models. While Zoppou (2001) acknowledged that the conducted review is not comprehensive, it indicates the large number of models available. An example is the Hydrologic Simulation Program-Fortran (HSPF) (e.g. Bicknell *et al.* 1993) developed by the US Environmental Protection Agency (US EPA) that represents an enhancement of the Stanford Watershed Model (Crawford and Linsley 1966). HSPF is one of the most comprehensive models on catchment hydrology and water quality and was developed to simulate water quantity and quality processes for agricultural and rural watersheds (Zoppou 2001) but is also applicable for assessments in urban catchments. The Stormwater Management Model (SWMM) (Huber and Dickinson 1988, Rossman 2010) was developed by US EPA around the same time (1971), and was explicitly designed to simulate urban stormwater quantity and quality. SWMM and its various proprietary platforms (e.g. PCSWMM, XP-SWMM) are among the most widely used models for urban hydrological assessments. Further examples are STORM (Hydrologic Engineering Center 1977), the Hydrologic Modeling System HEC-HMS (Charley *et al.* 1995), MIKE-SWMM, a combination of MIKE 11 (DHI 2003) and SWMM, and MIKE-SHE (DHI 2007), that combines MIKE 11 and SHE.

A wide range of models is available to simulate the effect of LID tools on urban stormwater. Elliott and Trowsdale (2007) evaluated the capabilities of ten stormwater models in simulating LID processes, including the Model for Urban Stormwater Improvement Conceptualization MUSIC (Wong *et al.* 2002), SWMM (Rossman 2009), and the Source Loading and Management Model SLAMM (Pitt and Voorhes 2004). To assess the performance of green roofs, modelling attempts have been conducted using both comprehensive stormwater modelling packages and specifically developed models. The curve number (CN) and storage node approaches of SWMM were used by Carter and Jackson (2007) and Alfredo *et al.* (2010) to replicate the hydrologic behaviour of a monitored green roof while Burszta-Adamiak and Mrowiec (2013) applied SWMM's bioretention LID module to simulate green roof runoff. Furthermore, She and Pang (2010) coupled the SWMM runoff module with an evapotranspiration and infiltration module and Metselaar (2012) used the Soil Water Atmosphere and Plant model (SWAP) to simulate green roof runoff. Further modelling attempts have been conducted using storage-routing models (Kasmin *et al.* 2010, Stovin *et al.* 2013, Vesuviano *et al.* 2014) and more complex models such as HYDRUS-1D (Hilten *et al.* 2008) and SWMS-2D (Palla *et al.* 2011). Besides hydrological modelling also data driven approaches have been conducted for exploring the hydrological response of green roofs. Villarreal and Bengtsson (2005) developed unit hydrographs, Zhang and Guo (2013) developed an analytical probabilistic model, and Carson *et al.* (2013) used regression analysis to determine a polynomial equation to replicate monitored green roof runoff.

1.2 Research gap

LID tools represent small-scale hydrological processes that necessitate an explicit modelling strategy (Amaguchi *et al.* 2012). However, they are still commonly simulated by the alteration of lumped model parameters (Eric *et al.* 2012), specifically for assessments at the catchment scale (e.g. Carter and Jackson 2007, Montalto *et al.* 2007, Palla *et al.* 2008a). Explicit modelling approaches at the catchment scale, on the other hand, have been applied to relatively small urban areas so far (Amaguchi *et al.* 2012, Palla and Gnecco 2015, Rosa *et al.* 2015, Versini *et al.* 2015, 2016). A spatially explicit modelling strategy requires detailed spatial data concerning both the catchment surface and the drainage network for model development. Furthermore, rainfall and runoff data at high temporal resolution are required as model input and for model calibration. However, detailed spatial data for both the surface and the drainage network are not available for many urban catchments (Cantone and Schmidt 2009, Gironás *et al.* 2010, Jankowfsky *et al.* 2013). Recently, high resolution digital elevation models (DEM) have become available for many urban regions and have been utilized in several hydrological assessments in urban areas (Brown *et al.* 2007, Mason *et al.* 2007, Fewtrell *et al.* 2008, Neal *et al.* 2009, Daniel *et al.* 2010). The stormwater flow in urban areas is affected by obstacles (such as street curbs) (Smith and Vidmar 1994) and these small scale features remain unsatisfactorily represented also in high resolution terrain models (Gironás *et al.* 2010, Fewtrell *et al.* 2011, Sampson *et al.* 2012). Furthermore, many urban catchments are ungauged and thus rainfall-runoff data for model calibration are not always available (Sefton and Howarth 1998, Seibert 1999, Rodriguez *et al.* 2005, 2013, Kay *et al.* 2007, Cantone and Schmidt, 2009). While data can be acquired and complemented for smaller urban areas through on-site observations and intensive measurement campaigns, such an approach is not feasible for the hydrological assessment of larger urban areas. Consequently, hydrological assessments of larger areas have to be conducted using less information (Jacqueminet *et al.* 2013) and alternative ways are needed to parameterize ungauged catchments (Merz and Blöschl 2004, Andréassian *et al.* 2006).

Reduction of spatial model resolution is a logical response to the limited availability of spatial data as a less detailed conceptualization requires less detailed information. Commonly, the number of subcatchments is reduced during this process and model parameters are aggregated to larger units. However, perturbations in spatial resolution affect the simulated runoff peak rates (Zaghloul 1981, Stephenson 1989, Elliott *et al.* 2009, Ghosh and Hellweger 2012) and to a lesser extent the simulated runoff volume (Park *et al.* 2008, Elliott *et al.* 2009, Ghosh and Hellweger 2012). Thus, a reduction in spatial resolution poses a challenge when the temporal dynamics of urban runoff shall be maintained. Furthermore, subcatchment aggregation and associated lumped model parameters prevent the explicit modelling of LID tools. A DEM-based catchment delineation approach affects basic catchment properties such as the catchment boundaries and the catchment surface area (Jankowfsky *et al.* 2013) and consequently the simulated runoff. However, to the knowledge of the author of this thesis, no studies are available that evaluated the extent of this effect specifically for urban

areas. The parameterization of ungauged areas is often referred to as model regionalization (Blöschl and Sivapalan 1995). Numerous studies have investigated various approaches for model regionalization including regression analysis (e.g. Sefton and Howarth 1998, Seibert 1999, Kokkonen *et al.* 2003, Götzinger and Bárdossy 2007), site-similarity approaches (e.g. Kokkonen *et al.* 2003, Kay *et al.* 2007), and the spatial proximity approach (e.g. Parajka *et al.* 2005). However, none of the studies specifically addressed the model regionalization in urban areas.

The performance of green roofs to manage stormwater quantity and quality has been reported for a variety of climate conditions (Berndtsson 2010, Ahiablame *et al.* 2012, Li and Babcock Jr 2014). However, the green roof retention depends on a number of factors, including the local climate (Stovin *et al.* 2012, Carson *et al.* 2013), rainfall accumulation and intensity (Carter and Rasmussen 2006), seasonality (Mentens *et al.* 2006, Villarreal 2007), the substrate depth (VanWoert *et al.* 2005), and the roof slope (VanWoert *et al.* 2005, Villarreal and Bengtsson 2005). Thus, green roof studies over extended periods and across a range of climate zones are needed to understand their potential for stormwater management (Carson *et al.* 2013).

Numerous studies have attempted the simulation of green roof runoff with varying success (see Section 1.1.3). Based on these previous green roof studies three main conclusions can be drawn: (i) the importance of data for model calibration (e.g. Alfredo *et al.* 2010), (ii) the impact of climate conditions on model parameters (e.g. Stovin 2010), (iii) the importance of evapotranspiration rate quantification for green roof retention (e.g. Palla *et al.* 2008b, Kasmin *et al.* 2010).

1.3 Objectives

Based on the research needs stated in Section 1.2, the main objective of this study is the development of a methodology for the hydrological assessment of LID tools for large urban catchments. The study is conducted in the city of Lahti, Finland, and the Stormwater Management Model (SWMM) serves as the modelling platform. Data from three study catchments (further referred to as catchments 1, 2, and 3, see Section 2.1) that were monitored for two years, were available to develop SWMM parameterizations. The parameterizations were subsequently applied to the large Vesijärvi catchment (Section 2.1) that serves as a target area for model regionalization.

The first paper (Paper **I**) reports the parameterization of the high-resolution (HR) model of the most urbanized study catchment (catchment 1) including a spatial analysis of the catchment, a model parameter sensitivity analysis and a subsequent model calibration and validation. The second paper (Paper **II**) complements the results of Paper **I** with the parameterization of the HR models of the residential (catchment 2) and suburban (catchment 3) study catchments. Furthermore, Paper **II** investigates the impact of spatial resolution perturbations on simulated runoff for a commonly used lumped surface aggregation and a novel method, where a detailed surface-type based catchment disaggregation is

maintained. The third paper (Paper **III**) studies the impact of a DEM based delineation approach on simulated runoff and evaluates the hydrological applicability of parameter sets calibrated to monitored study catchments to a large, ungauged catchment. Finally, the fourth paper (Paper **IV**) reports the parameterization of the SWMM green roof module to monitored green roof test bed data including a parameter sensitivity analysis and a specific focus on continuous runoff simulations. Figure 1 illustrates the steps conducted to meet the objective of this dissertation and the content of the appended papers (Paper **I-IV**).

More specifically, the objectives of this dissertation are to

(i)   develop a surface discretization approach that allows explicit simulation of LID tools and is both applicable to a large area and able to replicate the dynamics of urban runoff,

(ii)   define a suitable minimum spatial resolution that is both feasible for a large area and able to sufficiently replicate the dynamics of urban runoff under the restriction of availability in spatial data,

(iii)   evaluate the impact of simplifications that are induced by an automated delineation method that neglects details of the urban landscape,

(iv)   define an approach to parameterize a large, ungauged urban catchment,

(v)   parameterize a green roof model to data collected under Nordic climate conditions with the focus on continuous simulations that include the restoration of green roof retention capacity during inter-event periods.
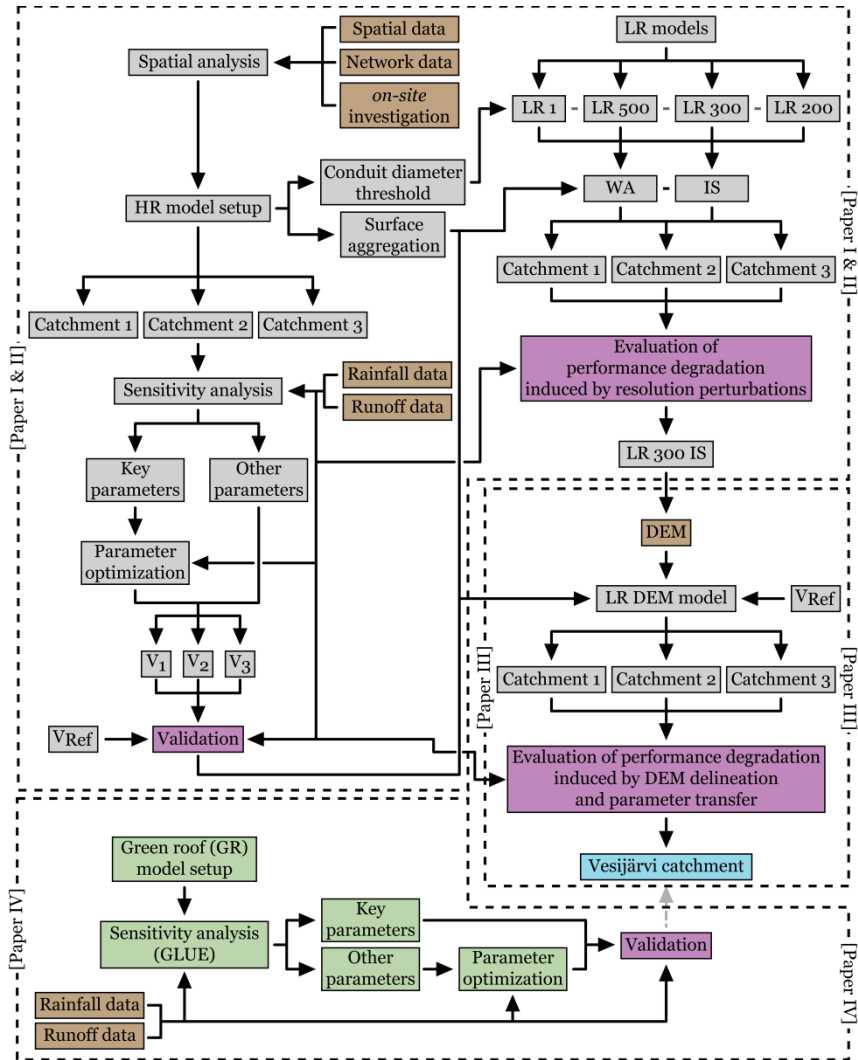
Figure 1 Graphical outline of the research. The colour codes refer to model input data (brown), process steps during the study catchment model development (grey), process steps during the green roof model development (green), model validation steps (purple), and simulations conducted for the Vesijärvi catchment (blue).

2 STUDY SITE AND DATA

2.1   Study sites

The three study catchments used in this research are located in the city of Lahti, Southern Finland (60.9°N, 25.6°E, population 104000 in 2013) (Figure 2). The city belongs to the boreal climate zone with a mean annual precipitation of 633 mm and a mean annual air temperature of 4.1°C (Kersalo and Pirinen 2009). Soils in the Lahti area are dominated by sandy soils, fine-grained sand soils, and sandy till soils; the bedrock is mainly formed of granite, granodiorite, and para-gneiss (Geological Survey of Finland 2015). The city of Lahti covers an area of ca. 154 km² and is crossed by the Salpausselkä ridge in east-west direction that divides the city into northern and southern drainage basins. The city centre is located by the Lake Vesijärvi that receives the stormwater runoff from the north-western part of the city while the north-eastern part of the city drains into the river Kymijoki. The southern part of the city drains into the river Porvoonjoki. Stormwater in the city of Lahti is drained through a separate stormwater sewer network covering a total conduit length of 394 km and over 70 km of open ditches; additionally, 16 km of combined sewer conduits are operated (Lahti Aqua OY 2015a). The connection of real estate properties to both wastewater and stormwater sewer networks is mandatory (Lahti Aqua OY 2015b).

  The study catchments (Figure 2, Paper **I**, **II**) vary in their degree of urbaniza-tion. The most urbanized catchment 1 (5.87 ha) is located in the city centre and characterized by a total impervious area (TIA) of 5.04 ha covering 86% of the catchment. Catchment 2 (6.63 ha) is located ca. 1 km south-east of catchment 1 and characterized by an imperviousness of 54% (3.56 ha). The least urbanized catchment 3 (12.59 ha) is situated ca. 4 km north of catchment 1 and has a TIA of 2.37 ha (19%). The land-use of the catchments ranges from apartment blocks and office buildings in catchment 1, a mixture of apartment blocks and detached housing in catchment 2, to typical sub-urban residential housing in catchment 3. While both catchment 1 and 2 are fully developed, a large fraction (ca. 50%) of catchment 3 consists of natural forest.
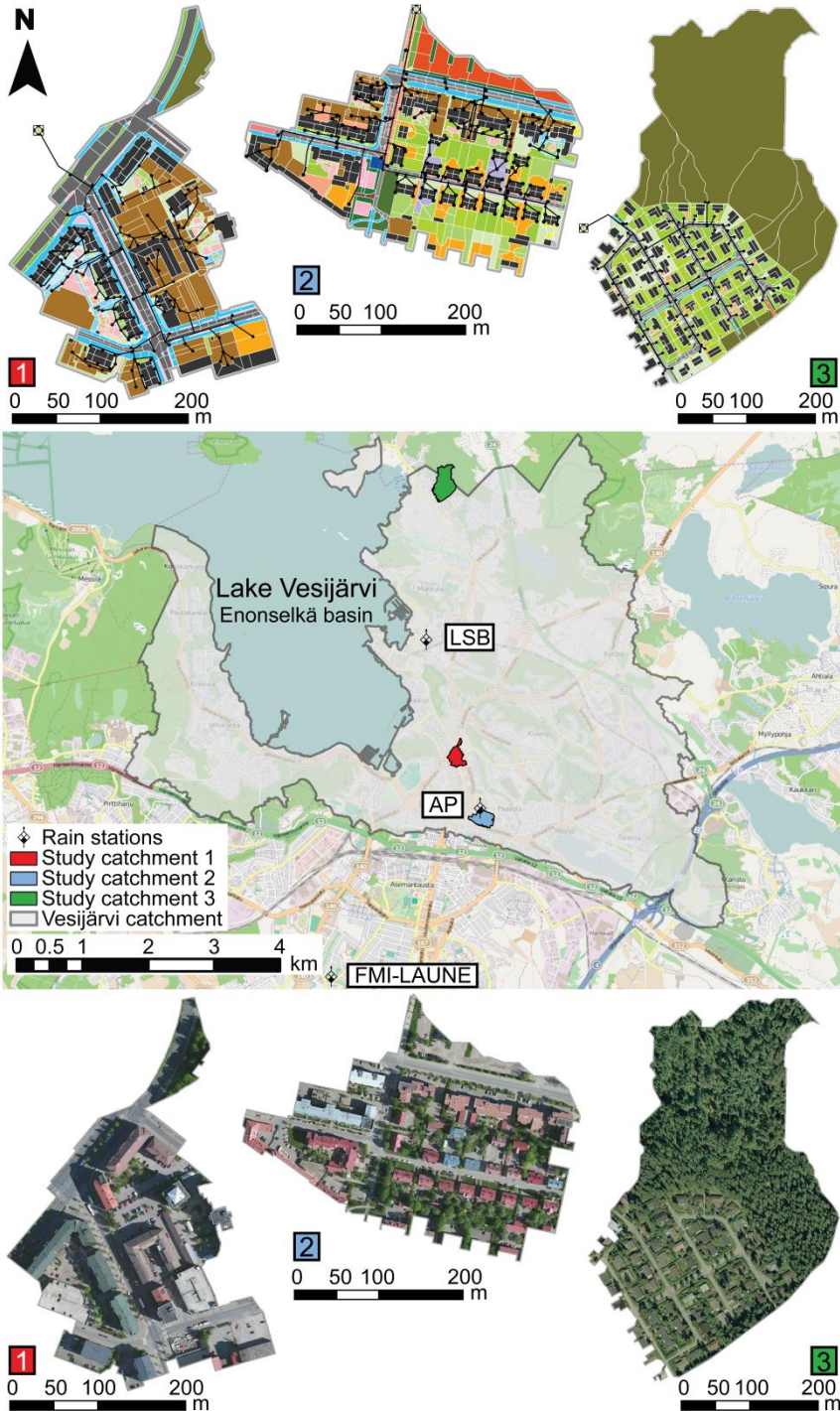
Figure 2   Overview of the study site. Both aerial images and the high resolution (HR) model discretization are illustrated for the study catchments 1, 2, and 3. The location of the study catchments within the Vesijärvi catchment is shown along with the location of the rainfall stations AP, LSB, and FMI-LAUNE (modified from Paper **II**).

The Vesijärvi catchment (Paper **III**) is in the current study defined as the area that drains into the Enonselkä basin of Lake Vesijärvi and belongs to the city of Lahti (Figure 2). The Vesijärvi catchment covers an area of 29.8 km² and is drained by a separate stormwater sewer network and, to a smaller degree, by open streams. A total of 71 outfalls (points where the network drains into the receiving water body) were identified for the Vesijärvi catchment. The Vesijärvi catchment is characterized by an imperviousness of 27.3% comprising traffic related surfaces (611 ha or 20.5% of the catchment) and roof tops (203 ha or 6.8%). The largest fraction of the catchment is covered by forested areas (1108 ha or 37.2%) followed by other green areas (995 ha or 33.4%), including e.g. public parks and housing yards. The different surface types identified along with spatial properties for each study catchment and the Vesijärvi catchment are given in Paper **III** (Table 1).

2.2 Green roof test beds

The experimental green roofs, each of 2 m² in size (1 m x 2 m) are located in the city of Lahti and were established in Summer 2013 (Paper **IV**). The test beds consist of plywood floors (slope 8%) surrounded by walls of 15 cm height of the same material (Figure 3). The floors and walls are covered by a roofing membrane made of HD polyethylene, followed by a 25 mm Nophadrain 5+1 mat (Figure 3B) (Veg Tech AB 2014a), and a 10 mm water holding fabric ("VT-filt") (Veg Tech AB 2014b). These layers are covered by a 60-70 mm thick substrate of crushed brick (85%), compost (5%), peat (5%), and crushed bark (5%). Finally, a 30-40 mm thick readymade roof mat (produced by Veg Tech AB, Sweden) with vegetation (*Sedum*, mosses, herbs, and grasses) is installed on top of the substrate. This green roof test bed construction has 5 replicates.
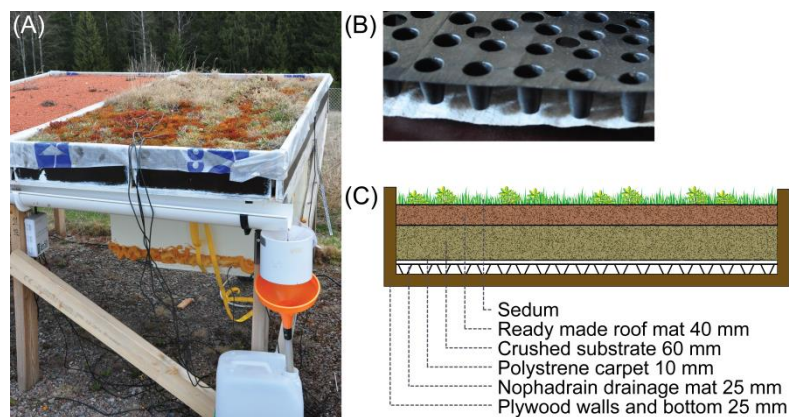
Figure 3 A green roof test bed (A) with the water collection including a gutter, a rain gauge, a funnel and a canister. Data from the rain gauge and from the sensors measuring soil temperature and moisture (the black wires in the picture) was collected in loggers that were situated below the test bed (the white box). The smaller picture (B) shows the installed drainage mat (Nophadrain drainage mat 5+1, Veg Tech AB 2014a) below the substrate. A cross-section of the test bed structure is illustrated on the right hand side (C) (modified from Paper **IV**).

2.3 Hydro-meteorological data

2.3.1 Study catchments

Runoff from the three study catchments (Paper **I, II, III**) was recorded between 2008-2010 at a 1 minute recording interval using an ultra-sonic flowmeter (Nivus PCM4) (Valtanen *et al.* 2014a, b). Rainfall data was available from two tipping bucket gauges at the outfall of catchment 2 (AP, 1 min recording interval, 1.0 and 4.9 km from catchments 1 and 3, respectively) and at the Lahti Science and Business Park (LSB, 10 min recording interval, 1.7, 2.7, and 2.3 km from catchments 1, 2, and 3, respectively), and from the Finnish Meteorological Institute (FMI) measurement station located in Lahti-Laune (Figure 2). Rainfall at FMI-LAUNE was measured using a present weather sensor (hourly data) and a Tretyakov-type rain gauge (daily data). All rainfall data were corrected using monthly coefficients (Kuusisto 1986).

Table 1 Rainfall events selected for each study catchment for calibration and validation, date, rainfall source (recording interval at AP and LSB was 1 and 10 minutes, respectively) event peak intensity, and event rainfall depth (modified from Paper **II**).

Calibration (catchment)	Validation (catchment)	Date	Rainfall source	Peak intensity [mm/5 min]	Rainfall depth [mm]
	1, 2	15.-16.6.2009	AP	0.45	5.0
	1, 2	7.-8.7.2009	AP	0.22	3.5
3	1, 2	9.-10.7.2009	AP	1.73	22.0
1, 2		13.7.2009	AP	0.86	15.8
3	1	7.10.2009	AP	0.44	8.0
1, 2		11.-12.6.2010	AP	2.71	10.2
1, 2		13.6.2010	AP	0.45	8.8
1, 2		15.-16.6.2010	AP	1.13	5.0
1, 2		19.-20.6.2010	AP	0.23	2.7
1, 2, 3		18.-19.7.2010	AP	0.65	5.2
	2	31.7.-1.8.2010	AP	1.50	10.8
	2	8.8.-9.8.2010	AP	5.78	12.6
	1, 3	14.8.2010	AP	3.64	12.0
	1	24.-25.8.2010	AP	0.86	9.6
	3	7.-8.7.2009	LSB	0.32	3.7
	1, 2	11.-12.7.2009	LSB	2.11	23.7
	1, 2	24.-25.7.2009	LSB	0.32	7.0
	3	31.7.-2.8.2009	LSB	2.19	14.3
	3	12.-13.8.2009	LSB	0.80	6.5
	1	26.-27.8.2009	LSB	1.34	9.8
	1, 2, 3	29.-30.8.2009	LSB	0.96	17.9
	1, 3	3.-4.9.2009	LSB	0.61	9.7
	3	6.9.2009	LSB	0.17	3.5
	3	11.-12.6.2010	LSB	0.90	6.2
	3	8.-9.8.2010	LSB	3.85	12.4

The accuracy of rainfall data is a major issue when it comes to successful model calibration and validation. Therefore, all available information was exploited to process continuous rainfall sequences for modelling purposes. Rainfall events from AP and LSB were checked for plausibility against daily and hourly rainfall data from FMI, measured runoff from the study catchments, and initial model simulations. Due to the higher recording frequency, AP data was used as the

primary source for model calibration and validation, while data from LSB was used as a source for additional model validation. Model calibration was conducted using an AP sequence (CAL) of 6 events for catchment 1, 5 events for catchment 2, and 3 events for catchment 3 (Table 1). The models were thereafter validated against the remaining AP rainfall events (VAL AP, 6, 6, and 1 events for catchments 1, 2, and 3, respectively) and events identified from the LSB dataset (VAL LSB, 5, 3, and 8 events for catchments 1, 2, and 3, respectively) (Table 1). As both rainfall datasets from AP and LSB were incomplete, rainfall data from FMI were used as model input for inter-event periods to allow for continuous simulation. Daily rainfall data from Lahti-Laune were found to be more accurate than accumulations recorded with the present weather sensor (Hutila 2012); therefore, the hourly rainfall data from Lahti-Laune were merely used to define the shape of sub daily events. The hourly data were scaled to force the 24 hour accumulation to be equal to the daily rain depth recorded with the Tretyakov-type rain gauge.

2.3.2   Green roof test beds

Runoff from the green roof test beds was continuously measured using Decagon ECRN-100 rain gauges at resolutions varying between 1 and 20 minutes (Paper **IV**). While all five replicates were monitored during the first year (2013), monitoring was restricted to three replicates in 2014. The green roof runoff from the tipping gauges was collected into containers, from which, for some events, the event runoff volume was recorded to test the reliability of the automated measurements.

Continuous rainfall measurements were available from an on-site tipping bucket gauge (ECRN-100) recording at the same interval used for the runoff measurements. The available rainfall-runoff data was analysed for consistency to identify suitable events for model calibration and validation. The analysis was, as for the rainfall-runoff data used for the study catchments (Paper **I**, **II**), conducted using rainfall data from FMI-LAUNE, measured green roof runoff, and initial model simulations. The obtained container runoff volumes indicated that all green roofs generate a similar runoff volume. Thus, it could be assumed that also continuous runoff curves had to be similar for all replicates. This assumption was supported by similar green roof hydrographs of all replicates when no operational malfunctions were evident. Out of the three green roofs monitored through 2013-2014, one green roof replicate was discarded due to problems with the data in 2013. For the remaining two green roof test beds, 11 events from 2013 were selected for model calibration while the model was validated against 13 events from 2014 (Table 2). Except for three events (C2, V9, and V10) (Table 2), for which the tipping gauge of the other replicate was malfunctioning (assumingly due to debris), the mean runoff of the two replicates was used for model calibration and validation.

Table 2   Hydro-meteorological properties of the simulated rainfall-runoff events for the green roof model and performance statistics (*E* and *VE*) for model simulations (modified from Paper **IV**).

		Date	Recording interval [min]	Duration [h]	Runoff [mm]	Rainfall depth [mm]	Runoff coefficient [-]	Peak intensity [mm/20 min]
CALIBRATION	C1	7.-8.8.2013	20	20	0.24	8.0	0.03	1.40
	C2	13.-16.8.2013	20	63	75.65	89.0	0.85	2.80
	C3	16.-18.8.2013	20	45	4.61	6.8	0.68	2.60
	C4	19.8.2013	20	12	1.55	3.2	0.48	0.80
	C5	12.-13.9.2013	20	23	0.29	5.0	0.06	2.60
	C6	20.-21.9.2013	20	35	5.89	10.0	0.59	2.40
	C7	22.-24.9.2013	20	48	6.05	6.4	0.94	0.80
	C8	25.-29.9.2013	20	105	3.46	4.2	0.82	1.00
	C9	8.-10.10.2013	20	49	3.75	6.4	0.59	1.40
	C10	10.-12.10.2013	20	40	2.99	3.4	0.88	0.60
	C11	17.-20.10.2013	20	65	22.53	26.8	0.84	2.60
		Entire period	20	505	127.01	169.2	0.75	
VALIDATION	V1	9.-14.5.2014	1	128	26.85	48.0	0.56	2.20
	V2	27.-30.5.2014	1	72	3.49	23.8	0.15	1.20
	V3	7.6.2014	1	7	0.49	11.0	0.04	6.20
	V4	9.-10.6.2014	1	27	0.49	14.4	0.03	5.20
	V5	12.-13.6.2014	1	37	16.03	24.0	0.67	3.80
	V6	16.-17.6.2014	1	24	1.37	6.8	0.20	1.00
	V7	19.-20.6.2014	10	20	1.13	4.0	0.28	0.80
	V8	21.-22.6.2014	10	27	3.16	4.8	0.66	2.20
	V9	22.-25.6.2014	10	64	28.27	31.6	0.89	1.60
	V10	29.6.-4.7.2014	10	125	18.70	25.0	0.75	4.80
	V11	11.-12.8.2014	10	13	0.35	8.4	0.04	2.80
	V12	18.-21.8.2014	10	88	8.52	38.2	0.22	3.20
	V13	25.-28.8.2014	10	63	8.63	14.2	0.61	1.20
		Entire period	1-10	695	117.49	254.2	0.46	

3 METHODS

3.1 Stormwater Management Model (SWMM)

The Stormwater Management Model (SWMM) used as the modelling platform in the current study was developed by the United States Environmental Protection Agency (US EPA) in 1971 and has thereafter undergone several major upgrades. The versions used in this study were 5.022 (study catchments and Vesijärvi catchment) and 5.107 (green roof test beds). SWMM was specifically developed for the hydrological assessment of urban areas and allows short- and long-term simulations for both water quantity and quality (Huber and Dickinson 1988, Rossman 2010).

SWMM conceptualizes the drainage system using a number of environmental compartments that again comprise several objects. The atmosphere compartment comprises, among others, rain gage and climatology objects; the land surface compartment receives precipitation from the atmosphere compartment and sends outflow to the groundwater compartment and surface runoff to the transport compartment; the groundwater compartment models sub-surface flow using aquifer objects; the transport compartment represents the drainage network using link and node objects. Simulations in SWMM are based on non-linear reservoirs that receive inflow from precipitation and adjacent catchments and generate outflow components including runoff, infiltration, and evaporation. The capacity of a reservoir is determined by the available surface storage provided by ponding, surface wetting, and interception. Surface runoff is generated after the surface water depth exceeds the available surface storage and is computed using the Manning equation. Conceptually, a catchment is disaggregated into a number of subcatchments where each of them consists of a pervious and impervious subarea (each with a specific set of parameter values) whose fractions are defined by the degree of imperviousness. While all surface water is subject to evaporation, infiltration occurs only on pervious catchment subareas (Rossman 2010). In the current study, flow routing in the drainage network (transport compartment) was computed using the dynamic wave theory. Dynamic wave routing solves the complete one-dimensional Saint-Venant flow equation using the Manning equation to relate the flow rate to the flow depth and friction slope (Rossman 2010). Infiltration computations in pervious areas were based on the Green-Ampt method (Rawls *et al.* 1992).

In 2010 (version 5.019) a LID module was implemented to allow for the simulation of e.g. bio-retention cells, pervious pavers, and infiltration trenches

(Rossman 2009, 2010). In SWMM, LIDs are conceptualized as a set of layers (e.g. soil layer, storage layer, drainage layer). A LID unit is modelled by solving the water mass balance over time for each layer; the water balance is computed as the difference between the inflow flux rate and the outflow flux rate (Rossman 2010). In the latest SWMM upgrade (version 5.1) this module was extended by a LID type dedicated to the simulation of green roofs. This LID type consists of three layers: (i) the surface layer, (ii) the soil layer, and (iii) the drainage mat layer. These three layers represent the typical structure of a green roof (e.g. Alfredo *et al.* 2010, Stovin *et al.* 2012) and each layer is defined by a set of parameters (Table 3).

3.2   HR models

3.2.1   Model setup

The high-resolution (HR) surface discretization used a surface-type based subdivision of the catchments (Paper **I**, **II**). The present surface types for each of the study catchments (Table 1 in Paper **III**) were identified with the help of spatial data (e.g. roof tops) and aerial images. For areas where there was no sufficient information available for surface classification, information was obtained by on-site visits. The surface map was then delineated into subcatchments based on the location of the receiving sewer network inlets and surface flow patterns that were determined during on-site visits in wet conditions (Figure 2). The available data on the sewer drainage network were incomplete for all study catchments requiring both manual interpolation of network sections (derived from on-site observations of network inlets not represented in the data) and complementation of missing invert elevations.

The catchment subdivision based on surface types with homogenous hydrological properties (e.g. asphalt, gravel, sheeted roof, etc.) resulted in subcatchments that are mostly either 100% pervious or 100% impervious. Consequently, the generally conducted subcatchment division into a pervious and impervious subarea in SWMM becomes obsolete for these subcatchments and only one value per parameter needs to be specified for the entire subcatchment. This procedure was also applied to subcatchments that comprised two subareas (gravel and stone paved surfaces, and asphalt in catchment 2). This simplification allows the reduction of the number of calibration parameters. The potentially larger depression storage D and Manning's n_o of the pervious subarea (surface cracks and seams) were accounted for in the parameter values for the entire surface. Subcatchments as well as conduits of the drainage network are characterized by a set of parameters that can be classified as hydrological/hydraulic or spatial/geometric parameters. The first type of parameters are typically calibration parameters and include the subcatchment depression storage D, the fraction of impervious cover I, the Manning's roughness n_o for overland flow, and the Manning's n_c for conduit flow. As these parameters are associated with a surface/conduit type they have same values for surfaces/conduits of the same type. On the other hand, the spatial/geometric parameters are spe-

cific to each subcatchment or conduit. These include the subcatchment area A, the slope S, invert elevations for conduits, and the conduit length. Initial model parameter values were either derived from spatial data (slope S and imperviousness I) or the literature, e.g. the Manning's roughness n_o for overland flow (Crawford and Linsley 1966, Engman 1986 listed in Huber and Dickinson 1988), soil infiltration parameters (Rawls *et al.* 1992, Oram 2012), the surface depression storage D (ASCE 1992), and the Manning's roughness n_c for conduit flow (Bizier 2007). The subcatchment flow width FW determines the responsiveness of a subcatchment and is usually determined through the length of the overland flow path L (Eq. 1) for each subcatchment. Alternatively, FW was also determined using Eq. 2 where a dimensionless coefficient k was used. While Eq. 1 represents a rather accurate but laborious method to determine FW, Eq. 2 is a simplification that allows the automated determination of FW for a large number of subcatchments (and consequently larger areas). The coefficient k was derived by first computing FW using Eq. 1 for a total of 2295 subcatchments and applied to Eq. 2. Simulations of the three study catchment HR models were conducted using both FW estimates (Eqs. 1-2) to evaluate the impact of the automated approach on runoff simulation.

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

$$FW = k\sqrt{A} \tag{2}$$

where FW [m] is the flow width, A [m²] is the subcatchment area, L [m] is the length of the overland flow path, and k [-] is a dimensionless coefficient.

3.2.2 Sensitivity analysis, calibration, and validation

A parameter sensitivity analysis for the HR models was conducted to identify key parameters for model calibration (Paper **I**, **II**). The model sensitivity was analysed for the catchment slope S, the flow width FW, the imperviousness I, the Manning's roughness coefficients for overland flow n_o and conduit flow n_c, the surface depression storage D, and the Green-Ampt infiltration parameters. Parameter perturbations were conducted for one parameter at a time with the remaining parameters fixed to their initial values. The Green-Ampt parameters, that are inter-dependent and associated with soil types, were perturbed by altering all three parameters at the same time following literature suggestions for typical soil types. The impact of parameter perturbation on simulated flow was evaluated using the Nash-Sutcliffe efficiency E (Eq. 3) (Nash and Sutcliffe 1970), the peak flow error PFE (Eq. 6) and the volume error VE (Eq. 7).

Thereafter, the identified parameters for each HR model were calibrated using the genetic multi-objective optimization algorithm NSGAII (Deb *et al.* 2002) with the sum of squared errors SSE (Eq. 5) and the linear correlation r_{QoQm} (Eq. 4) as objective functions for the sequence of selected calibration events (Table 1). Parameters that were identified to have no discernible effect on the simulated flow were set to their initially determined values. The calibrated models were then validated for the sequence of selected validation events (Table 1). Figure 1 illustrates the steps conducted during the development of the HR models.

$$E = 1 - \frac{\sum_{i=1}^{n}(Q_{o,i}-Q_{m,i})^2}{\sum_{i=1}^{n}(Q_{o,i}-\overline{Q_o})^2} \tag{3}$$

$$r_{Q_oQ_m} = \frac{\sum_{i=1}^{n}(Q_{o,i}-\overline{Q_o})(Q_{m,i}-\overline{Q_o})}{\sqrt{\sum_{i=1}^{n}(Q_{o,i}-\overline{Q_o})^2 \sum_{i=1}^{n}(Q_{m,i}-\overline{Q_m})^2}} \tag{4}$$

$$SSE = \sum_{i=1}^{n}(Q_{o,i} - Q_{m,i})^2 \tag{5}$$

$$PFE = \frac{Q_{o,p}-Q_{m,p}}{Q_{o,p}} 100 \tag{6}$$

$$VE = \frac{V_o-V_m}{V_o} 100 \tag{7}$$

where $Q_{o,i}$ and $Q_{m,i}$ [ls^{-1}] are the observed and modelled flow values, respectively, $\overline{Q}_o$ and $\overline{Q}_m$ [ls^{-1}] are the observed and modelled mean flow values, respectively, $Q_{o,p}$ and $Q_{m,p}$ [ls^{-1}] are the observed and modelled peak flow values, respectively, V_o and V_m [mm] are the observed and modelled flow volume, respectively, and n is the number of observations.

3.3   LR models

The low resolution (LR) models in the current study were developed through truncation of the stormwater sewer network using the minimum conduit diameter d_{min} as a criterion. This truncation resulted in a reduction of sewer network inlets as inlets to conduits below the applied threshold value were not included in the associated LR model. Consequently, the contributing drainage area per inlet increased and conduit flow was replaced by surface flow where conduits were discarded in the model. Three types of LR models were developed (Figure 1): (i) low resolution with weighted average surfaces (LR WA) (Paper **II**), (ii) low resolution with individual surfaces (LR IS) (Paper **II**), and (iii) low resolution with individual surfaces using a digital elevation model (DEM) based catchment delineation (LR DEM) (Paper **III**). Compared to the HR models (Figure 4A), all LR models neglected inter-subcatchment surface flow routing as subcatchment runoff was directly routed to the receiving inlet. Thus, while for the HR models the effective impervious area (EIA) was smaller than TIA, for the LR models EIA equalled TIA. It is to be noted however, that the LR model of catchment 3 represents an exception to this principle. Contradictory to city guidelines (Lahti Aqua OY 2015b), roofs in catchment 3 are mostly (92% of the roof area in catchment 3) hydraulically not connected to the sewer network, but rather drained on adjacent pervious surfaces. This routing was implemented in the HR model of catchment 3 and also maintained for the LR models of this catchment as preliminary simulations showed an excessive over-prediction of catchment runoff when roofs were directly routed to the assigned sewer inlets. The LR WA and LR IS models were developed for three threshold diameters (d_{min} 200, 300, or 500 mm) and additionally for a resolution that neglected the entire catchment network. The LR DEM model was developed only for a d_{min} of 300 mm. While the

LR WA and LR IS models were developed for the three study catchments, the LR DEM model was developed for the entire Vesijärvi catchment including the three study catchments (Figure 1). The performance of the LR models was evaluated for the calibration and validation events (Table 2) using the Nash-Sutcliffe efficiency E (Eq. 3), the peak flow error PFE (Eq. 6), and the volume error VE (Eq. 7).

3.3.1   LR WA

The contributing drainage area of each inlet in the LR WA (low resolution with weighted average surfaces) models (Paper **II**) was based on surface flow patterns identified during the development of the HR models. Each inlet was assigned a subcatchment equal to the contributing drainage area and subcatchment runoff was directly routed to the associated inlet (Figure 4C). Hydrologic/hydraulic subcatchment model parameters were derived as the weighted average of the parameters of each HR subcatchment lying within a LR WA subcatchment. The area A and the slope S were derived from spatial data while the flow width FW was computed using Eq. 1 and alternatively Eq. 2 (Section 3.2.1).

3.3.2   LR IS

The contributing drainage area of each inlet in the LR IS (low resolution with individual surfaces) models (Paper **II**) was the same as determined for the LR WA models (Section 3.3.1). However, unlike for the LR WA models, the surface disaggregation based on surface types was maintained now resulting in a number of subcatchments per inlet (and contributing drainage area). Runoff from each surface subcatchment was directly routed to the associated drainage network inlet independent of the proximity to the inlet (Figure 4B). Spatial parameters were determined based on spatial data and Eq. 2 (*FW*). This methodology allows the direct adoption of calibrated HR model parameters, as also the LR IS models consist of subcatchments with the same homogeneous surface properties. Furthermore, the retained surface discretization allows the explicit alteration of model parameters for the hydrological assessment of LIDs.
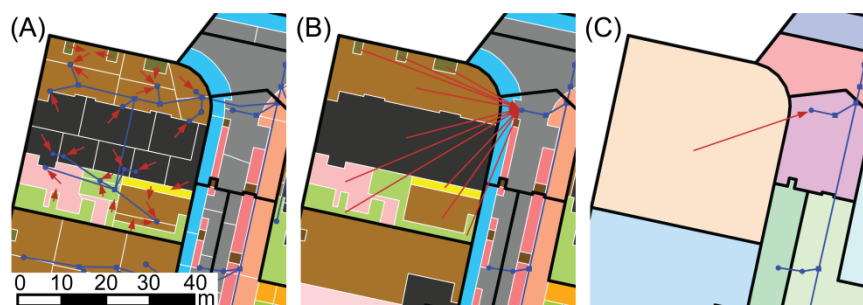
Figure 4   Surface flow routing for the HR (A), LR IS (B), and LR WA (C) models (modified from Paper **II**).

3.3.3 LR DEM

The LR DEM (low resolution with individual surfaces using DEM based catchment delineation) model (Paper **III**) followed the methodology of the LR IS models (Figure 4B, Section 3.3.2) using a conduit diameter threshold of 300 mm that was identified to sufficiently replicate the dynamics of urban runoff (Paper **II**). However, unlike the LR IS models, for which the contributing drainage areas were based on the determined HR surface flow pattern, the contributing drainage areas for the LR DEM model were based on a DEM with a resolution of 2 m. Consequently, obstacles, such as street curbs, that might influence surface flow (and thus catchment boundaries) but are not sufficiently represented in DEMs (Fewtrell *et al.* 2011, Sampson *et al.* 2012) were not taken into consideration for the determination of contributing drainage areas. Consequently, a DEM delineation affects the catchment boundaries and subsequently the catchment TIA when compared to the HR, LR WA, and LR IS models. Thus, while for the LR WA and LR IS models the alteration in EIA was purely induced by the neglecting of inter-subcatchment surface flow routing, in the LR DEM models the alteration of EIA is additionally affected by the DEM delineation induced alteration of TIA. While this simplification naturally influences the simulated flow, the automated delineation method allows the application to a large catchment. The DEM was pre-processed by burning the stormwater drainage network into the DEM surface (Gironás *et al.* 2010) using a constant depth. Thereafter, depressions were filled to allow for hydraulic connectivity. Even though only conduits with $d \geq 300$ mm were explicitly modelled, the entire available network information was used during the burning process.

3.4 Parameter regionalization

Based on the HR models of the three study catchments three parameter sets were developed (V_1, V_2, V_3; Figure 1, Paper **III**). The hydrological applicability of these parameter sets to the ungauged Vesijärvi catchment was tested by applying the parameter set of each study catchment to both the HR and LR DEM models of the remaining study catchments. Additionally, a reference parameter set V_{Ref} was compiled based on parameter values suggested in SWMM manuals (Huber and Dickinson 1988, Rossman 2010). A model parameterization based on literature is a common approach in the absence of flow data for model calibration (e.g. Huong and Pathirana 2013). Such an approach was thus used to further evaluate the performance of parameter transfer following the methodology proposed in the current study. The impact of parameter transfer as well as the performance of V_{Ref} was evaluated against monitored flow using the Nash-Sutcliffe efficiency E (Eq. 3), the peak flow error *PFE* (Eq. 6), and the volume error *VE* (Eq. 7). The impact of parameter transfer and the performance of V_{Ref} was evaluated for a total of 18 sequences (HR and LR DEM models for each catchment using three sequences each) and a total of 86 simulation events (HR and LR DEM models for the simulation events of each study catchment) (Paper **III**).

3.5 Green roof model

3.5.1 SWMM model of the test beds

Both the surface and soil layer are physically present in the monitored green roof test beds. The surface depression storage d_s that equals the berm height was set to 30 mm and the slope s was set to 8%. The remaining surface parameters (the vegetation volume fraction vvf and the Manning's roughness n_s for surface flow) were included in a sensitivity analysis (Section 3.5.2) to evaluate their influence on simulated green roof runoff. Of the soil layer parameters, only the thickness of the soil layer was assigned a fixed value (100 mm) while the remaining parameters of this layer were included in the sensitivity analysis (Table 3). The drainage mat used in the current study (Figure 3B) differs from both the conceptualized SWMM drainage mat layer and drainage mats used in earlier studies (e.g. Burszta-Adamiak and Mrowiec 2013, Vesuviano and Stovin 2013). While the mat provides storage for water, the cups are not hydraulically connected and thus drainage does not occur via the mat but rather on top of the thin textile layer that separates the drainage mat from the soil layer (Figure 3C). Thus, the parameters used to define the SWMM drainage mat layer rather represent a virtual drainage layer than a physical drainage mat. Potential evapotranspiration (PET) is the main parameter controlling the green roof retention and water losses (e.g. Palla *et al.* 2008b, Kasmin *et al.* 2010, Stovin *et al.* 2013). In the current study PET rates were computed using the Hargreaves' method (Hargreaves *et al.* 1985). The computed PET time series was scaled using a coefficient C_{PET}. The calibration (2013) and validation (2014) sequence shared only one common month (August) with the remaining calibration events occurring in September and October while the remaining validation events took place in May-July. Thus, even though a monthly C_{PET} could give a more accurate representation of PET rates, due to the limited possibility of validation, a constant scaling factor for the entire growing season (May-October) was selected. This coefficient was, additionally to the selected green roof module parameters, included in the sensitivity analysis.

3.5.2 Sensitivity analysis, calibration, and validation

Prior to calibration a model sensitivity analysis was conducted to identify the key parameters controlling simulated green roof runoff (Paper **IV**). The analysis followed the Generalized Likelihood Uncertainty Estimation (GLUE) methodology (Beven and Binley 1992) that has been applied in numerous hydrological model applications (e.g. Beven and Freer 2001, Koivusalo *et al.* 2008, Laine-Kaulio *et al.* 2014). Within the GLUE procedure, randomly generated parameter sets are used to conduct a large number of model runs. Each parameter set is considered equally likely to be a simulator of the modelled system (Beven and Binley 1992). The result of each simulation is evaluated using so-called likelihood measures or goodness of fit criteria. Parameter sets that fulfil the predefined criteria form the pool of behavioural parameter sets. The model sensitivity to a parameter can thereafter be evaluated by a comparison of the posterior

(behavioural) parameter distribution with the prior parameter distribution that was randomly generated. If the prior and posterior distributions of a parameter are similar, the model is insensitive to this parameter whereas a significant difference in the distributions indicates the model sensitivity to the parameter. The model sensitivity to each analysed parameter was evaluated using (i) cumulative distribution plots and (ii) the statistical Kolmogorov-Smirnov test (KS-test, e.g. Beven and Binley 1992). The KS-test evaluates the statistical difference D_{stat} between two distributions against a critical value D_{crit} that defines the threshold of statistical difference. In the current study the Nash-Sutcliffe efficiency E (Eq. 3) and the volume error VE (Eq. 7) (Section 3.2.2) were adopted to define the goodness of fit criteria. A total of 50000 simulations with randomly generated parameter sets were conducted and parameter sets that achieved both $E \geq 0.7$ and $-20\% \leq VE \leq 20\%$ formed the pool of behavioural parameter sets. The model sensitivity was analysed for all SWMM green roof module parameters except for those three parameters that were fixed to their physically measured values: (i) the depression storage d_s (30 mm), (ii) the slope s (8%), and (iii) the soil thickness t (100 mm) (Table 3). Consequently, including the evapotranspiration scaling coefficient C_{PET}, the model sensitivity was analysed for a total of 12 model parameters. Initial parameter values and ranges used during the GLUE analysis and the model calibration were adopted from the literature (Rossman 2010, Roehr and Kong 2010) with the aim of them being both realistic and non-restrictive (Table 3). The parameter sensitivity of the model was analysed for the sequence of calibration events (C1-C11, Table 2).

Subsequently, the identified key parameters were calibrated using NSGAII (Deb *et al.* 2002) for the calibration sequence (C1-C11, Table 2). Parameters that were identified to have no effect on simulated green roof runoff were fixed to their initial values. The sum of squared errors SSE (Eq. 5) and the volume error VE (Eq. 7) (Section 3.2.2) were used as objective functions. Commonly, the parameter set that produces the smallest SSE does not necessarily produce the smallest VE and vice versa. Thus, the selection of the optimal parameter set depends on the modelling objective and in this study the parameter set that produced the smallest SSE and a volume error $-5\% \leq VE \leq 5\%$ was defined as the optimal parameter set. The calibrated model was thereafter validated for the validation sequence (V1-V13, Table 2). The steps conducted during the parameterization of the green roof model are illustrated in Figure 1.

4 RESULTS

4.1 HR models

The most sensitive model parameters for the most urbanized catchment 1 were the surface depression storage D and the Manning's roughness n_c for conduit flow while the remaining parameters were identified to have very limited effect on the simulated flow (Paper **I**). This result can be attributed to both the high spatial resolution of the model resulting in small subcatchments of homogeneous surface properties and the high degree of urbanization in catchment 1. Furthermore, the high fraction of impervious surface limits the importance of runoff processes on pervious surfaces thus resulting in the model insensitivity to soil infiltration parameters. The high spatial resolution allows the accurate estimation of the imperviousness I, the flow width FW, and the slope S within narrow parameter ranges. As a consequence perturbations within the defined parameter boundaries had very little effect on the simulated runoff. The high degree of urbanization associated with an effective artificial drainage network results in very limited overland flow. Consequently, the model was insensitive to perturbations of the Manning's roughness (n_o). While the sensitivity analysis of catchments 2 and 3 also revealed D and n_c as the key parameters, additionally n_o and I affected simulated runoff (Paper **II**). This result can be attributed to the lower degree of urbanization in these two catchments that results in longer overland flow paths. Furthermore, street curbs are not present for the majority of catchment 2 and they are entirely absent for catchment 3 allowing runoff from street and pavement surfaces to partly drain on adjacent surfaces where it can infiltrate. This process can be accounted for with the parameter I, as a reduction of I increases the loss from an otherwise impervious surface. Due to the low fraction of impervious cover, runoff processes on pervious surfaces have an increased effect on catchment runoff in catchment 3. However, due to their limited effect in the more urban catchments 1 and 2, also in catchment 3 these parameters remained uncalibrated.

The calibration was conducted for each catchment for the parameters identified to affect the simulated flow while insensitive parameters were set to their initial values. The applied surface-type based catchment subdivision resulted in a total of 8, 23, and 25 calibration parameters for the catchments 1, 2, and 3, respectively (Table 3 in Paper **II**). The best model performance was achieved for catchment 2 with a Nash-Sutcliffe efficiency E of 0.97 (range of 0.68-0.98 for individual events) for the calibration sequence (Figure 5B, Paper **II**). For the

same sequence the HR model of catchment 1 reached an E of 0.88 (0.60-0.94) (Figure 5A, Paper **I**) while the performance of catchment 3 was generally lower with an E of 0.80 (0.42-0.81) (Figure 5C, Paper **II**). The performance for the validation events using AP rainfall data (VAL AP) was slightly lower with the best efficiency in catchment 2 (0.94 for the validation sequence, 0.78-0.96 for individual events), followed by catchment 1 (0.85, 0.62-0.95), and catchment 3 (0.66). It is to be noted that, due to the relatively large distance between the AP rainfall station and catchment 3 (4.9 km), fewer suitable events were identified for calibration (3 events) and validation (1) in this catchment. The model efficiency for the validation sequence using rainfall data from LSB (VAL LSB) was lower than for VAL AP for catchment 1 (0.84, 0.64-0.88) and catchment 2 (0.61, 0.58-0.68) while it was higher for catchment 3 (0.81, 0.53-0.83). This can be attributed to the fact that LSB is closer to catchment 3 (2.3 km) than AP, while the distances between AP and catchments 1 (1.0 km) and 2 (0.0 km) are smaller than distances between LSB and catchments 1 (1.7 km) and 2 (2.7 km). Comprehensive lists on model performance statistics for the sensitivity analysis, model calibration, and validation are given in Paper **II**. The alternative computation of the parameter FW using Eq. 2 had only negligible effect on the simulation results indicating that this approach that allows an automated determination of the flow width provides a sufficiently accurate estimation for this parameter value (Paper **II**).
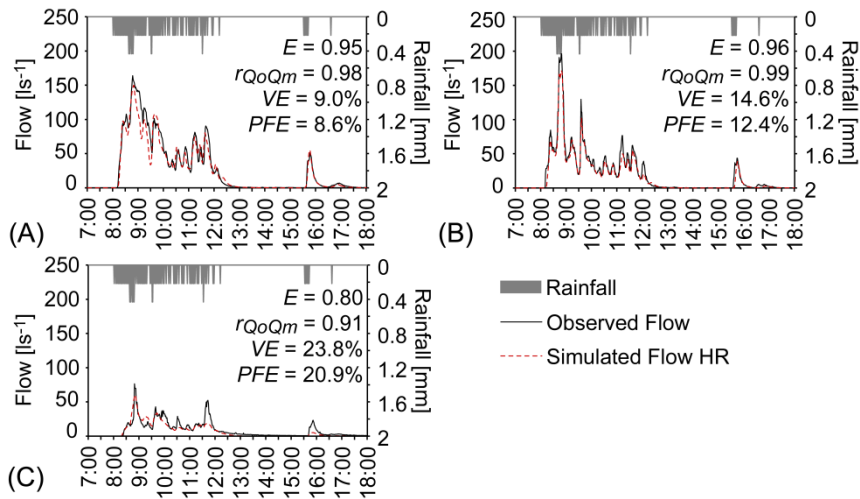
Figure 5 Observed and HR simulated flow for catchment 1 (A), 2 (B), and 3 (C) and the achieved efficiency E, the linear correlation r_{QoQm}, the volume error VE, and the peak flow error PFE (Event rainfall depth 22.0 mm, peak intensity 1.73 mm/5 min) (modified from Paper **II**).

4.2 Impact of spatial model resolution (LR WA and LR IS)

Truncation of the sewer network resulted in a reduction of network inlets and consequently a coarser surface resolution. While the HR models of catchments 1, 2, and 3, comprised of 160, 188, and 90 inlets, respectively, the truncation using e.g. $d_{min} \geq 300$ mm (LR 300) resulted in a reduction to 28, 47, and 78 inlets,

respectively (Paper **II**). As the LR WA and LR IS models were based on the HR catchment delineation, TIA remained the same for the LR WA and LR IS models when compared to the HR models. Direct routing of surface runoff to the sewer inlets (thus neglecting inter-subcatchment surface flow) altered EIA which equalled TIA for all LR models. This alteration, however, remained constant for all diameter thresholds. The change of EIA was smallest for catchment 1 where most of the catchment is hydraulically effective also in the HR model (TIA 5.04 ha, EIA 5.02 ha). A larger impact was seen for the LR models of catchment 2 with an increase in EIA of 0.34 ha compared to the HR model (TIA 3.56 ha, EIA 3.22 ha). As stated above, the roof runoff routing of the HR model was maintained for the LR models of catchment 3. Roofs in this catchment (TIA 2.37 ha) account for 1.36 ha of which 1.26 ha are hydraulically not connected to the drainage network. The direct surface flow routing to the inlet of all other impervious surfaces than roofs increased EIA from 0.89 ha (HR) to 1.01 ha (LR WA and LR IS).

The smallest impact of spatial resolution perturbations on simulated runoff was observed for the most urbanized catchment 1, which can be attributed to the very limited alteration of EIA for this catchment (Paper **II**). The simulated runoff volume was rather insensitive to spatial resolution perturbations for all three study catchments besides the impact of the EIA alteration that however remained constant for all conduit diameter thresholds. The simulated peak flow, on the other hand, was the most sensitive performance criterion to spatial resolution perturbations (Paper **II**). Disregarding the entire network left naturally no inlets as the entire catchment runoff was directly routed to the catchment outfall (LR 1). This lowest resolution resulted in a degradation of model performance for both LR WA and LR IS models that was seen as a very rapid catchment response with steep and short runoff peaks (Figure 6, Paper **II**). This effect was even more pronounced for the LR IS models. With the lowest model resolution including a network section (d_{min} 500 mm) the LR WA models were already reasonably well replicating the temporal dynamics of the monitored runoff while the LR IS models showed an over-prediction of runoff peaks. At the resolution using a d_{min} of 300 mm both LR WA and LR IS models provided sufficient simulation results (Figure 7, Paper **II**) and a further increase of spatial resolution to the threshold diameter of 200 mm resulted in only minor improvement. A comprehensive list on model performance statistics for the LR WA and LR IS models of each catchment is given in Paper **II** for all diameter thresholds.
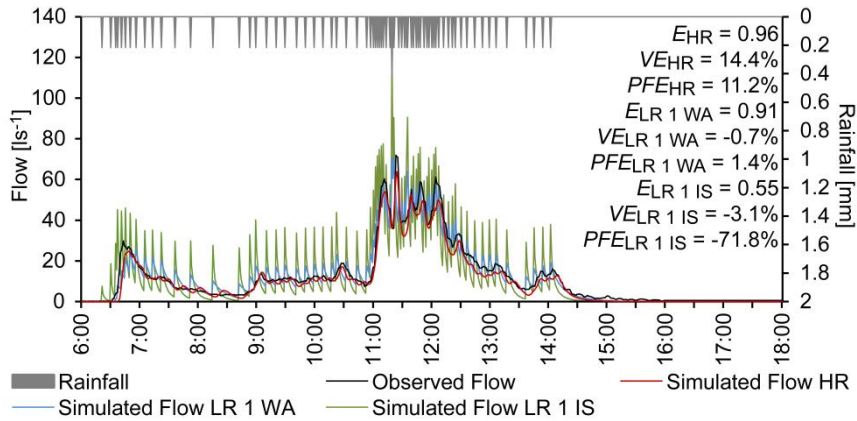
Figure 6   Observed and HR, LR 1 WA, and LR 1 IS simulated flow for catchment 2 and the achieved efficiency E, the volume error VE, and the peak flow error PFE (Event rainfall depth 15.8 mm, peak intensity 0.86 mm/5 min) (modified from Paper **II**).
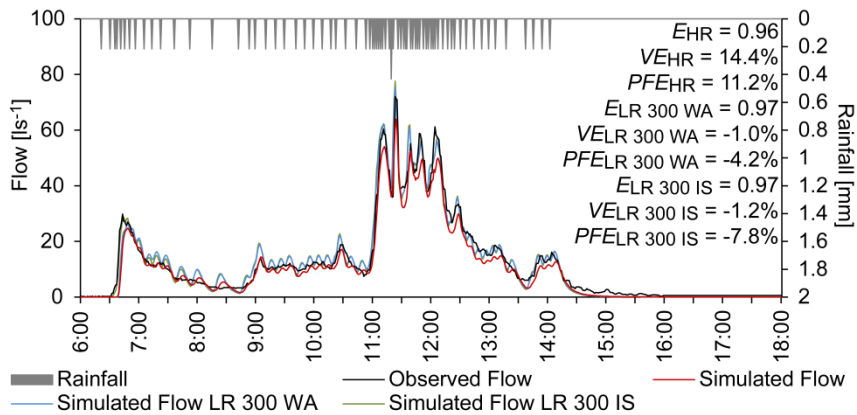
Figure 7   Observed and HR, LR 300 WA, and LR 300 IS simulated flow for catchment 2 and the achieved efficiency E, the volume error VE, and the peak flow error PFE (Event rainfall depth 15.8 mm, peak intensity 0.86 mm/5 min) (modified from Paper **II**).

4.3   Impact of DEM delineation (LR DEM)

The catchment delineation based on a DEM affects the catchment boundaries when compared to the HR models of the three study catchments (Figure 8, Paper **III**). Consequently, the area of the three study catchments differs between the HR and LR DEM models; while the area of catchment 1 and 3 decreased by 8% and 10%, respectively, it increased by 2% for catchment 2. The ability of the DEM based delineation to correctly represent the study catchments was evaluated using the overlapping surface (OS) and excessive surface (ES). The first is the fraction of the HR catchment that is also included in the LR DEM catchment and the second is defined as the fraction of the LR DEM catchment that is not included in the HR catchment.
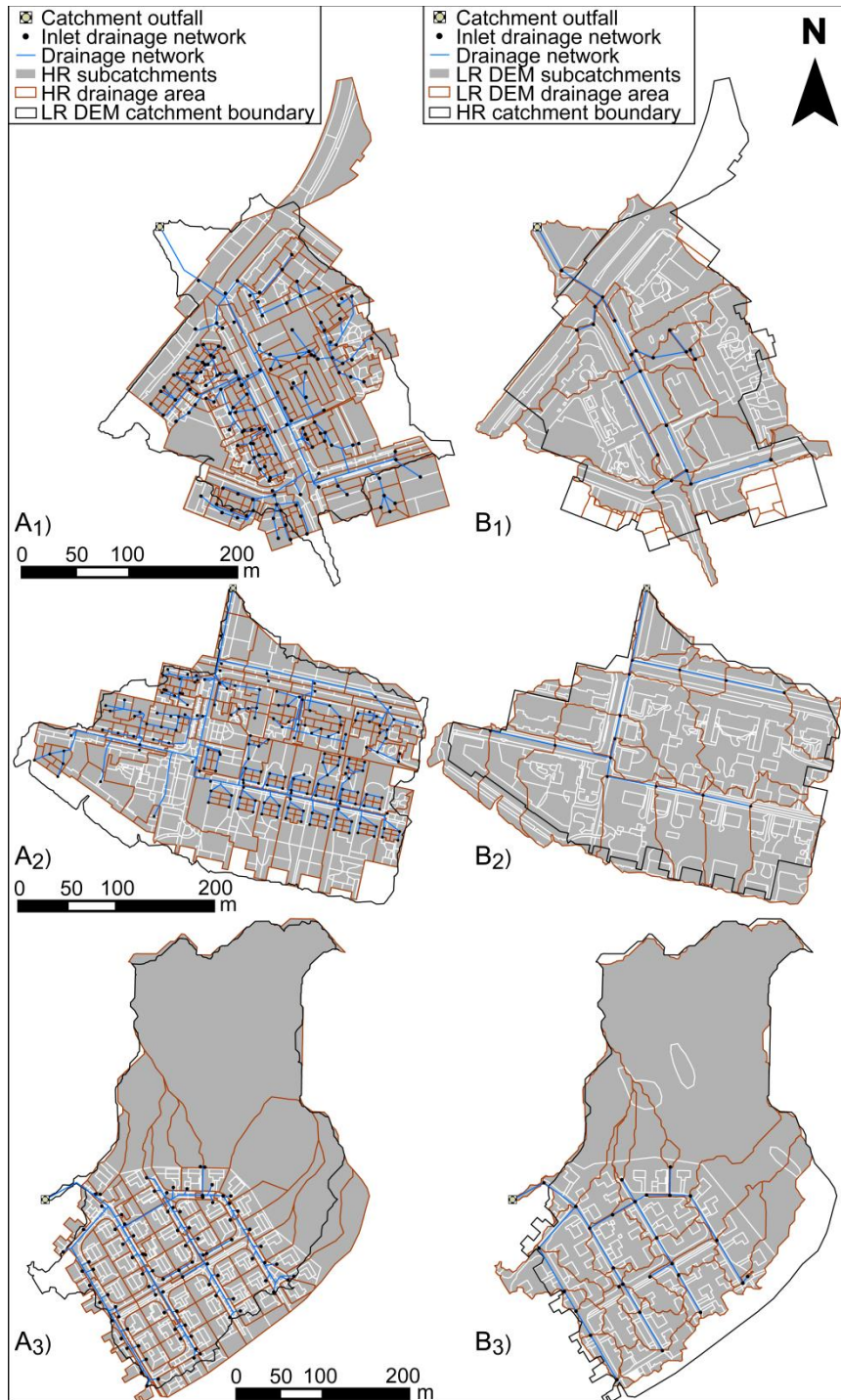
Figure 8 Surface discretization for the HR model (A_1, A_2, A_3) with the boundaries based on DEM delineation and the surface discretization for the LR DEM model (B_1, B_2, B_3) with the determined HR catchment boundaries for the catchments 1, 2, and 3 (modified from Paper **III**).

The best correspondence between HR and LR DEM catchments was found for catchment 2 where 97% (OS) of the HR catchment were also included in the LR

DEM catchment. For the same catchment the DEM based delineation resulted in an excessive surface (ES) of 5% (Figure 8A$_2$ and B$_2$). The ability of the LR DEM delineation to correctly represent the HR catchments was lower for catchment 3 (OS 89% and ES 3%, Figure 8A$_3$ and B$_3$) and catchment 1 (OS 80% and ES 13%, Figure 8A$_1$ and B$_1$). While TIA for the LR WA and LR IS models remained the same when compared to the HR models, the variation in catchment area in the LR DEM models also alters the catchment TIA. The DEM delineation induced alteration of catchment area resulted in a reduction of TIA for catchment 1 (LR DEM 4.79 ha, HR 5.04 ha) and catchment 3 (LR DEM 2.13 ha, HR 2.37 ha) while TIA increased for catchment 2 (LR DEM 3.74 ha, HR 3.56 ha) (Paper **III**). The alteration of EIA between the HR and LR DEM models is affected by both the neglecting of inter-subcatchment surface flow routing and the DEM delineation induced alteration of TIA. For catchment 1 EIA decreased by 5% (LR DEM 4.79 ha, HR 5.02 ha) while it increased by 16% and 35% for catchment 2 (LR DEM 3.74 ha, HR 3.22 ha) and catchment 3 (LR DEM 1.20 ha, HR 0.89 ha), respectively. It is to be noted that, as for the LR WA and LR IS models of catchment 3, also for the LR DEM model of this catchment the roof surface routing of the HR model was maintained.

The alteration in catchment area, TIA, and EIA naturally affects the simulated runoff. The smallest impact of the simplifications on simulated runoff induced by the LR DEM methodology was found for catchment 1 (Figure 9A) where the LR DEM model yielded a similar efficiency E (0.87) as the HR model (0.88) for the calibration sequence. For VAL AP a similar minor degradation in efficiency was observed with E of 0.83 for the LR DEM model compared to 0.84 achieved by the HR model. For VAL LSB the reduction in efficiency was slightly larger with E of 0.81 for the LR DEM model compared to 0.85 achieved by the HR model. While the LR DEM model performance with respect to the simulated runoff volume was similar to the HR model in catchment 1 (*VE* of 3.7-7.0% for the HR model compared to 1.4-6.5% for the LR DEM model for the three simulation sequences), the LR DEM methodology clearly affected the simulated peak flow. The absolute mean peak flow error (*PFE*) was 12.4%, 8.1%, and 13.7% for CAL, VAL AP, and VAL LSB, respectively and increased to 23.9%, 26.0%, and 25.3% for the same sequences using the LR DEM model (Paper **III**). The overall performance of the LR DEM model was lower for catchment 2 compared to catchment 1 (Figure 9B). However, the performance remained acceptable for both CAL (E 0.82) and VAL AP (0.90). The performance for VAL LSB (E 0.53) was lower, but it is to be noted that already the HR model of this catchment produced a relatively low efficiency (0.61). This can be attributed to the increasing distance between catchment 2 and the LSB rainfall station. While the impact of the LR DEM methodology on the simulated peak flow was lower than for catchment 1, the degradation in the volume error (*VE*) was larger (Paper **III**). The results obtained for catchment 3 were similar to catchment 2 (Figure 9C). The LR DEM model achieved an E of 0.70 (HR 0.80), 0.56 (HR 0.66), and 0.75 (HR 0.81) for CAL, VAL AP, and VAL LSB, respectively. For catchment 3 the impact on *PFE* was the smallest among all three study catchments except for VAL AP that comprised only one rainfall event for catchment 3. In terms of *VE*

the LR DEM and HR models performed equally well with identical or very similar errors for CAL and VAL LSB, while a larger change was found for VAL AP (one event only in catchment 3) (Paper **III**). A comprehensive list on model performance statistics for each catchment is given in Paper **III** for both simulation sequences and individual rainfall events.
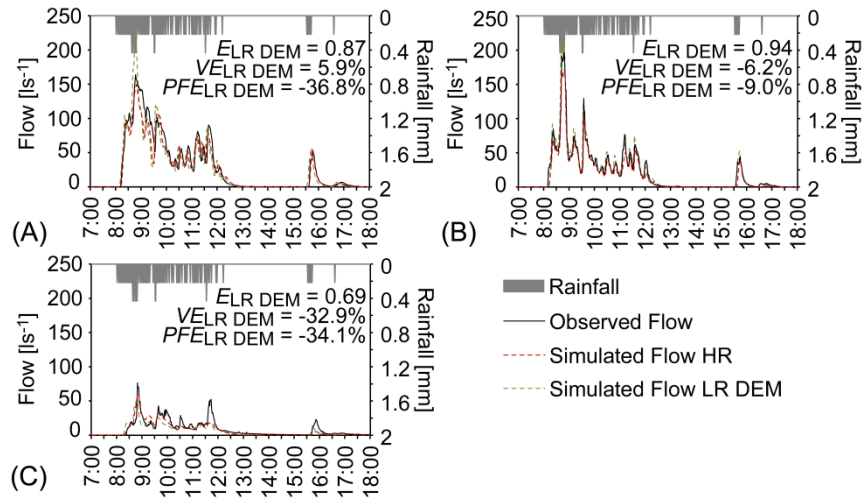
Figure 9   Observed and simulated (HR and LR DEM) flow for catchments 1 (A), 2 (B), and 3 (C), and the model efficiency *E*, the volume error *VE*, and the peak flow error *PFE* (Event rainfall depth 22.0 mm, peak intensity 1.73 mm/5 min) (modified from Paper **III**).

4.4   Parameter regionalization

Based on the HR catchments three parameter sets were developed (V_1, V_2, and V_3) (Table 3, 4 in Paper **III**). The applicability of these parameter sets to the ungauged Vesijärvi catchment was evaluated by inter-changing them between the three study catchments. The inter-change was conducted for both the HR and LR DEM models. While the HR models served as a source for the parameter sets themselves the LR DEM model methodology was applied to the Vesijärvi catchment. Additionally, the compiled parameter set V_{Ref} was applied to both HR and LR DEM models to evaluate the performance of the proposed regionalization methodology (Table 3, 4 in Paper **III**).

For 13 of the 18 evaluated sequences the specifically calibrated (site-specific) parameter set achieved the best model efficiency *E* and while for five sequences a transferred set outperformed the site-specific set, V_{Ref} did not achieve the best efficiency for any of the evaluated sequences. For the simulation events, the site-specific parameter sets achieved a mean efficiency *E* of 0.76. While the transferred sets yielded a mean *E* of 0.70, the parameterization using V_{Ref} yielded a lower mean efficiency of 0.52. The best efficiency was achieved by the site-specific parameter sets for 62% of the events and while for 35% of the events a transferred set produced the best *E*, V_{Ref} yielded the highest efficiency for 3% of the events. While the efficiency of V_{Ref} was inferior to both transferred sets for

70% of the events, it outperformed both transferred sets for 9% of the events (Paper **III**).

   The monitored runoff volume was overall better replicated by transferred parameter sets compared to site-specific parameters. While the best volume replication was achieved by the site-specific parameter sets for seven of the 18 sequences, for nine sequences the best volume simulation was achieved using a transferred parameter set and two sequences were best replicated using V_{Ref}. Overall, the best volume replication was achieved by the parameter set V_1, which produced the smallest volume error (*VE*) for all sequences of catchment 1 (for which it was calibrated) as well as for all sequences of catchment 3. When looking at simulated events, however, the site-specific parameter sets achieved the smallest mean absolute volume error (17.8%). Transferred sets yielded a mean absolute *VE* of 21.9% while V_{Ref} produced a larger volume error (33.9%). The smallest *VE* was produced for 40% of the simulation events using a site-specific parameter set, while a transferred set performed best for 49% of the events; V_{Ref} produced the smallest *VE* for 11% of the events. While V_{Ref} produced a larger *VE* than both transferred sets for 72% of the events, it outperformed the transferred sets for 13% of the events (Paper **III**).
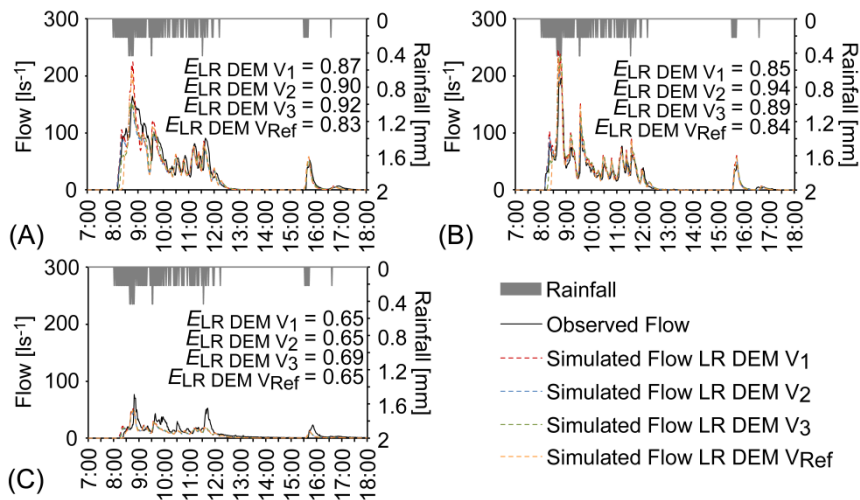
Figure 10   Observed and simulated (LR DEM) flow for catchments 1 (A), 2 (B), and 3 (C) with the parameter sets V_1, V_2, V_3, and V_{Ref}. The model efficiency *E,* the volume error *VE*, and the peak flow error *PFE* (Event rainfall depth 22.0 mm, peak intensity 1.73 mm/5 min) (modified from Paper **III**).

The performance of parameter sets with respect to the simulated peak flow was similar than found for the runoff volume; for the majority of sequences (ten) the smallest mean peak flow error (*PFE*) was achieved by a transferred set while the site-specific sets performed best for six sequences. V_{Ref} produced the smallest *PFE* for two sequences. For eleven sequences V_{Ref} produced a larger *PFE* than both transferred sets while it outperformed them for four sequences. Also the results for simulation events were similar to what was observed for the simulated runoff volume; 34% of the events had the smallest *PFE* using a site-specific set, while for the majority of events (56%) the smallest *PFE* was achieved by a

transferred set and V$_{Ref}$ achieved the best results for 10% of the events. However, while the transferred parameter sets were clearly superior to V$_{Ref}$ with respect to *E* and *VE*, the results concerning *PFE* are more vague; while V$_{Ref}$ was inferior to both transferred sets for 38% of the events, the reference set performed better than both transferred sets for 29% of the simulation events. Also the difference in mean absolute *PFE* was smaller than found for the *VE*; the site-specific parameter sets achieved a mean absolute *PFE* of 21.7% compared to 24.6% for the transferred sets and 29.2% achieved by V$_{Ref}$ (Paper **III**). An example of the ability of V$_1$, V$_2$, V$_3$, and V$_{Ref}$ to replicate the monitored flow in the three study catchments is shown in Figure 10 and a comprehensive list on model performance statistics for each catchment and each parameter set is given in Paper **III** for both simulation sequences and individual rainfall events.

4.5   Green roof model

A total of 50000 model simulations with randomly generated parameter sets were performed; 11790 of these fulfilled the defined goodness of fit criteria and thus formed the pool of behavioural parameter sets (Paper **IV**). The most sensitive parameters were the soil porosity *p* and the PET rate scaling factor *C$_{PET}$*. While *p* defines the total water holding capacity of the green roof, *C$_{PET}$* controls the restoration of green roof retention capacity during inter-event periods. Consequently both parameters directly affect the simulated runoff volume generated by the green roof. Furthermore the model was sensitive to the void fraction (*vf*) and the thickness of the drainage mat (*dmt*), the saturated soil hydraulic conductivity (*con*), and the conductivity slope (*con s*). Lower sensitivities were found for the soil field capacity (*fc*) and wilting point (*wp*) as well as for the Manning's roughness *n* of the drainage mat (Figure 12 and Table 3). Surface model parameters (the vegetation volume fraction *vvf* and the Manning's roughness *n$_s$*) and the soil suction head (*sh*) had no effect on simulated green roof runoff (Paper **IV**).
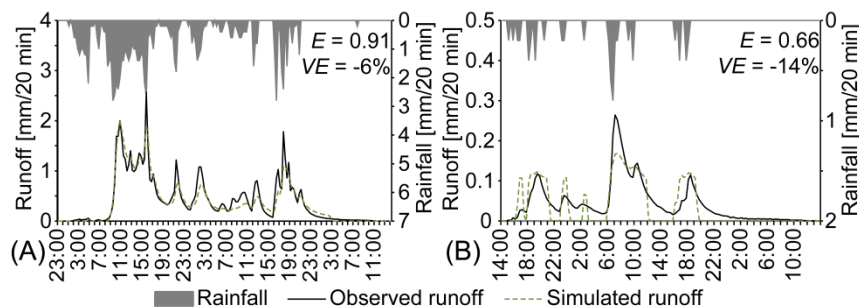
Figure 11   Observed and simulated green roof runoff for (A) an exceptionally large (89 mm) and (B) an average (6.4 mm) calibration event and the associated performance statistics *E* and *VE* (modified from Paper **IV**).

The sensitivity analysis identified nine calibration parameters that were subsequently optimized using the continuous sequence of 11 calibration events (Table 2). The optimal parameter set (Table 3) replicated the monitored green roof

runoff well both in terms of the hydrograph shape and runoff volume with a model efficiency E of 0.93 and a volume error VE of -4.7% (Paper **IV**). For four events E was above 0.80 (0.81-0.92) (Figure 11A), for two events above 0.70 (0.70-0.75) and for two events E was 0.52 and 0.66 (Figure 11B). However, the model failed to properly reproduce the monitored runoff of three events (C1, C4, and C5). These three events are characterized by a small rainfall and runoff depth and a low runoff coefficient. For C1 the model did not produce any runoff (VE -100%) indicating that the model result was actually similar to the observation that recorded a very small runoff volume (0.24 mm). For C5 the model was reasonably replicating the monitored runoff volume (VE -5%) but the monitored and simulated hydrographs show a time lag of one hour resulting in a negative model efficiency E. While the model showed an overall good ability to replicate runoff peaks and volumes, the prediction of hydrograph recession limbs was mostly unsatisfactory. For most events they were too steep compared to observed data (Figure 11B).

Table 3 The parameters analysed during the green roof model sensitivity analysis, their lower and upper boundaries (min-max), the statistical difference D_{stat} from the KS-test (sensitive values in bold font), the p-value from the KS-test, and the calibrated (bold) and fixed parameter values after optimization (PV) (modified from Paper **IV**).

Parameter	SWMM object	Description	min	max	D	p-value	PV
d_s [mm]	LID surface	Depression storage	n.a.	n.a.	n.a.	n.a.	30
vvf [-]		Vegetation volume fraction	0	0.4	0.008	5.5E-01	0.1
n_s [-]		Manning's roughness	0.01	0.6	0.005	9.6E-01	0.168
s [%]		Slope	n.a.	n.a.	n.a.	n.a.	8
t [mm]	LID soil	Thickness	n.a.	n.a.	n.a.	n.a.	100
p [-]		Porosity	0.35	0.7	**0.221**	2.2E-16	**0.41**
fc [-]		Field capacity	0.11	0.34	**0.049**	2.2E-16	**0.29**
wp [-]		Wilting point	0	0.1	**0.050**	2.2E-16	**0.02**
con [mmhr^{-1}]		Conductivity	0.25	120	0.056	2.2E-16	37.9
$con\ s$ [-]		Conductivity slope	0.1	40	**0.119**	2.2E-16	**40**
sh [mm]		Suction head	49	320	0.007	6.8E-01	61.3
dmt [mm]	LID drainage mat	Thickness	1	10	**0.074**	2.2E-16	**3.8**
n [-]		Manning's roughness	0.01	2	**0.019**	2.7E-03	**0.01**
vf [-]		Void fraction	0.01	0.8	**0.130**	2.2E-16	**0.41**
C_{PET} [-]	Climatology	Potential evaporation coefficient	0.25	1	**0.188**	2.2E-16	**0.48**

n.a. not analysed during the sensitivity analysis

The model performance for the validation sequence (V1-V13) was overall lower than for the calibration sequence, particularly in terms of the simulated runoff volume, with E of 0.82 and VE of -15% (Table 2). Lower efficiencies and higher volume errors were produced for small events characterized by a low runoff coefficient. High volume errors were found for the validation events in June 2014. This month was not included in the calibration sequence (August-October 2013) as the validation events took place May-August 2014. The generally higher volume errors indicate that one single PET scaling factor cannot sufficiently represent the seasonal influence of vegetation growth on evapotranspiration rates (Paper **IV**).
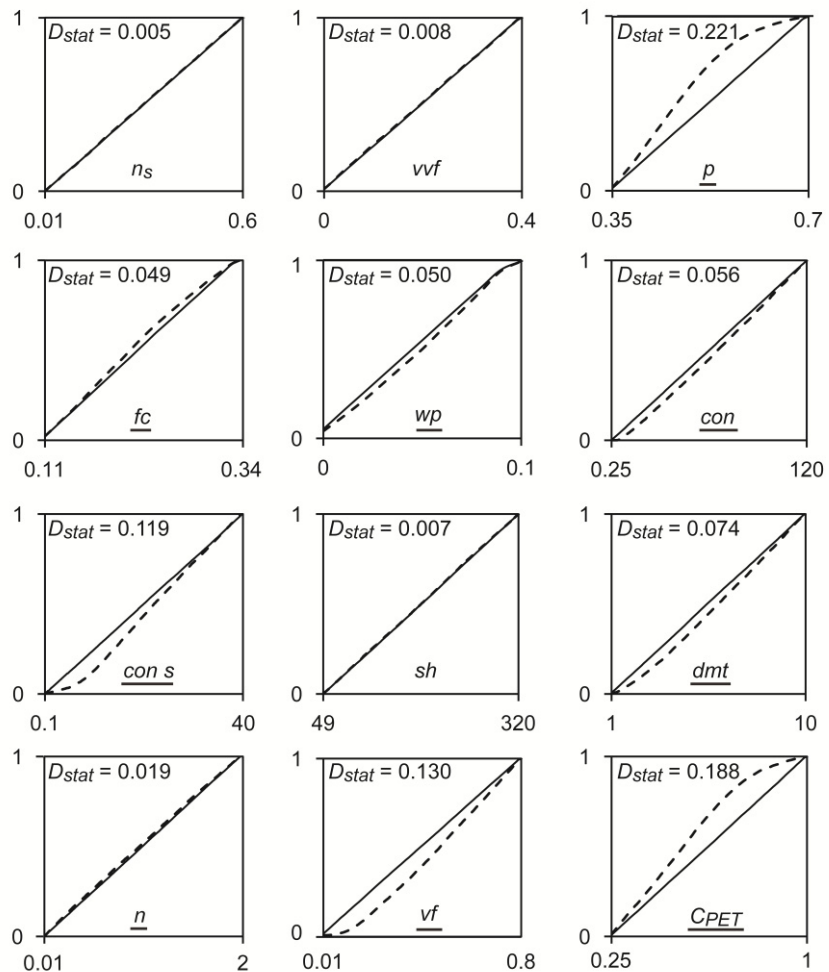
Figure 12 Cumulative frequency for the prior (solid line) and posterior (dashed line) parameter distributions produced during the green roof model sensitivity analysis. Furthermore, the statistical difference D_{stat} of the KS-test is given for each parameter and sensitive parameters are underlined (modified from Paper **IV**).

4.6 Vesijärvi catchment

The entire Vesijärvi catchment of the city of Lahti was parameterized using the LR DEM methodology (Section 3.3.3) and the parameter sets V_1, V_2, V_3, and V_{Ref} (Section 3.4) (Paper **III**). The largest fraction of the catchment is covered by forested areas (37.2% or 1108 ha) followed by other green areas (33.4% or 995 ha) that comprise parks, private and public yards. The impervious cover (27.3%) comprises rooftops (203 ha) and traffic related areas (611 ha). The catchment discretization resulted in 56037 subcatchments with homogeneous surface types (Table 1, 3 in Paper **III**) that are drained through a drainage network of 144.4 km. The network includes 115.8 km stormwater sewers, 28.6 km open streams, and 5574 inlet nodes. The network drains into Lake Vesijärvi via 71 outfalls. A section of the Vesijärvi catchment model is shown in Figure 14.
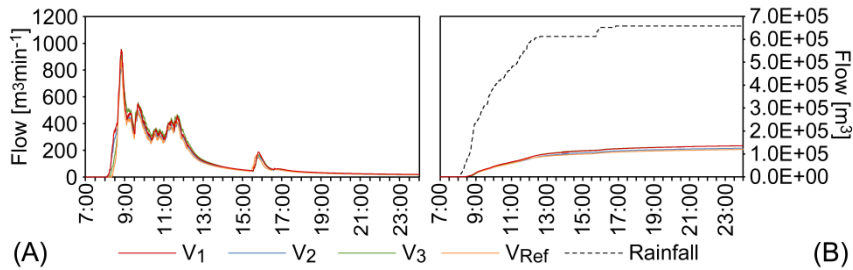
Figure 13   Simulated flow time series (A) and flow accumulation (B) for the Vesijärvi catchment for the parameter sets V_1, V_2, V_3, and V_{Ref}. (Event rainfall depth 22.0 mm, peak intensity 1.73 mm/5 min) (modified from Paper **III**).

Simulation results showed that the temporal dynamics of urban runoff are less pronounced for the Vesijärvi catchments when compared to the study catchments. This can be attributed to the catchment size differences (~0.06-0.12 km² for the study catchments compared to ~30 km² for the Vesijärvi catchment) and associated longer response times for areas more remotely situated from the catchment outfalls to Lake Vesijärvi. Nonetheless, a comparison of hydrographs for the Vesijärvi catchment (Figure 13) and HR and LR DEM hydrographs of the study catchments (Figure 9 and Figure 10) indicates a similar shape of the hydrograph (event rainfall depth 22.0 mm, peak intensity 1.73 mm/5 min).
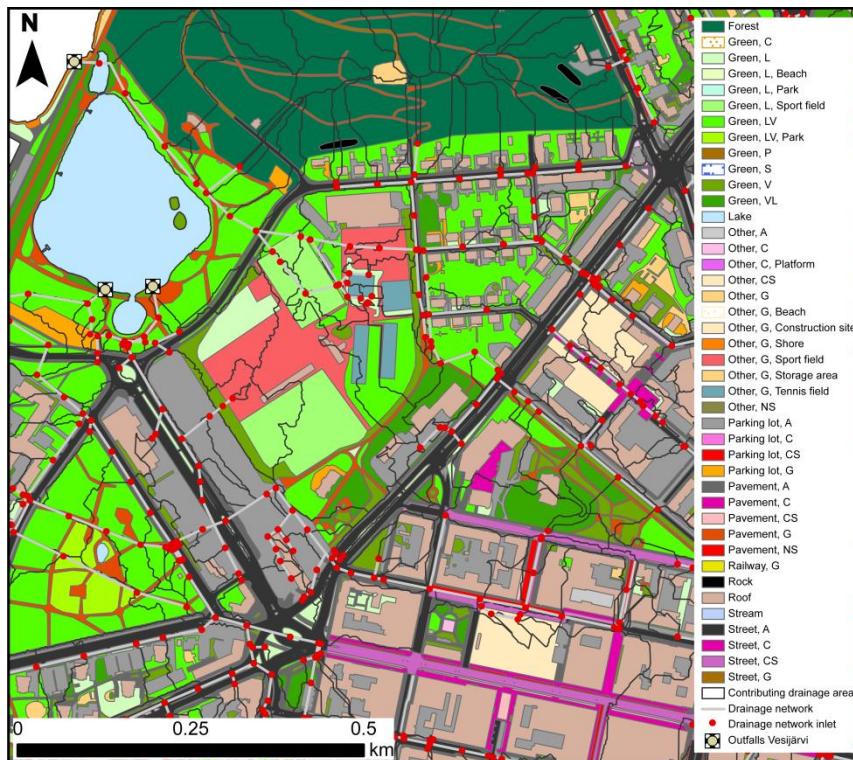
Figure 14   A section of the Vesijärvi catchment model showing the surface discretization, the drainage network and inlets along with their corresponding drainage areas (black boundary lines) (modified from Paper **III**)

5 DISCUSSION

The environmental impacts of urbanization have been widely researched and documented (see Section 1.1.1). To mitigate these impacts, a wide range of LID tools has been developed and applied (see Sections 1.1.2 and 1.1.3). The hydrological performance of LID tools to reduce stormwater runoff is widely recognized (Palla and Gnecco 2015). Hydrological modelling provides a tool to evaluate potential LID benefits prior to installation (see Sections 1.1.3 and 1.1.5) but the evaluation at the catchment scale remains difficult due to the high spatial model resolution required (Amaguchi *et al.* 2012, Palla and Gnecco 2015) and the limited availability of spatial data (e.g. Cantone and Schmidt 2009, Gironás *et al.* 2010, Jankowfsky *et al.* 2013, Salvadore *et al.* 2015). Thus, while such an evaluation would be valuable to develop sustainable, city-wide, stormwater management strategies, only few recent studies have evaluated the benefits of LID tools at the catchment scale (see Section 1.1.3). Furthermore, these model applications remained restricted to relatively small catchments (5.5-550 ha) (e.g. Amaguchi *et al.* 2012, Palla and Gnecco 2015, Rosa *et al.* 2015, Versini *et al.* 2015, 2016). Large scale model applications are further hampered by the lack of runoff data for model calibration (e.g. Rodriguez *et al.* 2005, 2013, Kay *et al.* 2007, Cantone and Schmidt 2009). Thus, there is a need to develop new methodologies to parameterize large urban catchments to support the evaluation of potential LID benefits for stormwater management at the city scale. In the current study, several aspects of urban hydrological modelling were investigated to provide a methodology to assess large scale urban areas for LID performance evaluation: (i) implications of surface discretization approaches, (ii) impact of spatial resolution on simulated runoff, and (iii) the impact of an automated DEM-based delineation approach on catchment properties and simulation results. Finally, a green roof model was parameterized to allow its implementation into a large scale urban catchment model.

5.1   High resolution modelling

The high spatial resolution used for the HR models (Paper **I**, **II**) has a number of advantages over a catchment discretization using a less detailed surface description. First, the approach allows a direct explicit simulation of LID tools for performance evaluation in stormwater management. Second, the use of subcatchments with homogeneous surface properties allows a rather accurate initial estimation of parameter values that reduces the parameter sensitivity which in

turn reduces the number of parameters that require calibration. And third, the number of calibration parameters remains low, as the number of different surface types is typically also quite low. The number of subcatchments can, however, be high due to the detailed catchment discretization. However, as same parameter values can be applied to all subcatchments sharing the same surface type the number of calibration parameters is greatly reduced. The HR model of catchment 1, for example, was calibrated using only 8 calibration parameters despite the catchment subdivision into 690 subcatchments. The obvious downside of the high resolution approach is the time required to acquire, complement, and prepare data for model development. At the same time the catchment discretization using surface types provides an avenue for the parameterization of larger, ungauged areas. When using land-use types for catchment discretization, one should acknowledge that their hydrological properties may vary substantially (e.g. the impervious cover of a residential area may be 40% or 50%). This hampers the regionalization of calibrated model parameters from gauged to ungauged catchments. On the other hand, the variation in hydrological properties of surface types is very small (e.g. an asphalt surface responds similar to rainfall independent of the land-use type).

In terms of the Nash-Sutcliffe efficiency E and according to typical ratings of E for hydrological models (Moriasi *et al.* 2007, Ritter and Muñoz-Carpena 2013), the HR models of catchments 1 (E 0.88) and 3 (0.80) performed well and the performance of the HR model of catchment 2 can be classified as very good (0.97) for the respective calibration periods (Section 4.1). As to be expected the performance for the validation sequences was lower for all catchments except for the validation period using LSB rainfall data of catchment 3 (0.81). However, E remained above 0.80 for all model runs except for the AP validation sequence of catchment 3 (0.66) and the LSB validation sequence of catchment 2 (0.61). It is to be noted that the distance between the AP rainfall station and catchment 3 (4.9 km) and the LSB station and catchment 2 (2.7 km) is relatively large. An increasing distance between rainfall and runoff measurement station results in decreasing consistency between monitored rainfall and runoff dynamics. In other words, the dynamics of the monitored rainfall (used as model input) and the rainfall that actually triggered the monitored runoff show inconsistencies. This is further indicated by the overall lower performance of catchment 3 that is rather remote from both LSB (2.3 km) and AP (4.9 km) rainfall stations.

The parameter sensitivity of the model depends on the catchment characteristics (Section 4.1). For the most urbanized catchment 1 only the depression storage D and the Manning's roughness n_c for conduit flow affected the simulated runoff, while other model parameters, such as the imperviousness I and the Manning's roughness n_o for overland flow had no or very limited effect on the simulated runoff. While the model insensitivity to I can be explained by the high spatial resolution and the surface-type discretization that allows an accurate initial estimation of this parameter value and the definition of narrow parameter ranges, the model insensitivity to n_c is due to the high degree of urbanization of catchment 1. Highly urbanized areas are drained through a dense drainage network for efficient stormwater removal from the site. The associated dense grid of

stormwater sewer inlets implies that the distances for overland flow are very short, thus resulting in the model insensitivity to this parameter. On the other hand, for the less urbanized catchments 2 and 3, that are drained through a less dense stormwater network, n_o was found to affect the simulated runoff. Similarly, the imperviousness I affected simulated runoff in catchments 2 and 3. In less urbanized catchments, street curbs that prevent runoff to leave street and pavement surfaces are often absent. Consequently, runoff does not necessarily follow the flow path to the dedicated inlet but may partly drain to adjacent pervious surfaces where it is subject to infiltration. This potential loss of surface runoff can be simulated by a reduction of the imperviousness I. Even though this simplified compensation does not exactly replicate that surface flow partly drains to adjacent pervious areas, it does reduce the surface runoff by infiltration through the generating surface itself. For both catchments 1 and 2 the Green-Ampt infiltration parameters did not affect the simulated runoff due to the high degree of catchment imperviousness. On the other hand, the sensitivity analysis showed that infiltration is a relevant factor also in urban hydrological applications when assessing less urbanized areas, such as catchment 3. The sensitivity of runoff simulation to SWMM model parameters has been analysed in earlier studies (Barco *et al.* 2008, Goldstein *et al.* 2010, Beling *et al.* 2011). Barco *et al.* (2008) used automatic calibration to parameterize SWMM to a large urban catchment (217 km²) and identified the depression storage D and the imperviousness I as key model parameters. Goldstein *et al.* (2010) reported a high sensitivity for the same SWMM parameters (D and I) during the parameterization of a small urbanized catchment (2.66 ha). Beling *et al.* (2011) applied SWMM to four peri-urban catchments (0.39-4.95 km²) in Brazil and concluded that parameter sensitivity depends on both the objective function and the catchment characteristics. Similar conclusions can also be drawn based on the results of the current study.

5.2   Reductions in spatial resolution

A reduction in spatial resolution (in the current study accomplished by truncating the drainage network using the conduit diameter as a threshold) naturally affects the simulated flow as conduit flow (in reality) is replaced by surface flow when conduits of smaller diameters are discarded in the model (Section 3.3) (Paper **II**). Furthermore, the neglecting of inter-subcatchment surface flow alters the catchment EIA as all runoff is directly routed to the stormwater sewer inlet. Commonly, when a reduction in the spatial resolution is conducted, small subcatchments are aggregated into larger ones and parameters are lumped over the larger subcatchment area (e.g. Ghosh and Hellweger 2012). The LR WA models in the current study follow this common approach of spatial resolution reduction. While this approach can be suitable when a lower model resolution is needed (e.g. due to limited data availability or a large target area), the explicit simulation of LID tools is no longer possible. Consequently, while it is acknowledged that LID tool simulation requires a spatially distributed and explicit modelling strategy (Amaguchi *et al.* 2012), LID characteristics are commonly aggre-

gated in a large scale model (Eric *et al.* 2012). In the current study, a novel approach was evaluated to reduce the spatial model resolution (LR IS). Unlike for the LR WA models, the larger subcatchments resulting from the reduction of the drainage network were only used to define the contributing drainage area for a stormwater sewer inlet and instead of subcatchment aggregation, the surface-type subcatchment discretization was maintained. This approach allows the explicit simulation of LID tools also for lower resolution models. However, the retained surface description results in a flashier simulated response to rainfall since also more remotely located surfaces within the contributing area of an inlet are directly routed to the drainage network. The effect on the simulated runoff can be seen in the excessively fast catchment response for the lowest resolution models (LR 1 IS and LR 500 IS). Furthermore, the LR IS approach requires a higher spatial resolution than the common LR WA approach. While the LR 500 WA (d_{min} 500 mm) was already sufficiently replicating the dynamics of monitored runoff, a 300 mm threshold was required to achieve similar results in the LR IS approach.

In the current study, the reduction in spatial resolution implied an alteration in EIA for the LR models when compared to the HR models. This alteration was correlated to the degree of urbanization. The smallest change in EIA was found for the most urbanized catchment 1 (0.02 ha or 0.3%) followed by catchment 2 (0.34 ha or 10.6%). This can be explained by the dense drainage network commonly existing in highly urbanized areas where most impervious surfaces are directly connected for efficient stormwater removal from the site. With a decreasing degree of urbanization also the network density and subsequently the directly connected imperviousness decreases. As mentioned in Section 3.3 catchment 3 represents an exception to the applied methodologies for LR models. Results presented in Paper **II** show that the direct routing of surface runoff to the drainage network inlet results in a dramatic increase of EIA (1.48 ha or 166%) due to the alteration of roof runoff routing. Unlike suggested by authority guidelines (Lahti Aqua OY 2015b) roof runoff in this catchment drains on adjacent pervious surfaces and is not directly connected to the stormwater sewer network. Consequently, all LR models of this catchment showed very poor performance, and the roof runoff routing to adjacent pervious surfaces had to be maintained to achieve acceptable simulation results. This indicates the importance of correct roof runoff routing for hydrological assessments in urban areas. Such information is required for model development independent of the spatial resolution and negligence could result in large errors of simulated runoff. A smaller impact of spatial resolution perturbations on simulated flow was found for the most urbanized catchment 1 than for the less densely built catchments 2 and 3. This can be attributed to the fact that the fraction of hydraulically connected imperviousness (EIA) highly affects urban runoff (Sillanpää 2013); runoff from impervious surfaces that drain to adjacent pervious areas is reduced through infiltration.

The impact of spatial resolution on model simulations has been the focus of several earlier studies. Zaghloul (1981) investigated the relation between surface discretization and simulated runoff applying SWMM to one hypothetical and

four real catchments in the United States, Canada, and Australia. Stephenson (1989) studied the dependency of model parameter values on the detail of surface discretization for a residential catchment (0.74 ha) in South Africa. The impact of spatial model resolution on simulated pollutant loads was studied by Park *et al.* (2008) for an urban catchment in South Korea. Elliott *et al.* (2009) applied the stormwater model MUSIC to a residential catchment (0.84 km²) in New Zealand to study the effect of spatial aggregation of stormwater control devices. Ghosh and Hellweger (2012) applied SWMM to a residential catchment (3.7 km²) in the United States to evaluate the impact of spatial discretization on simulated runoff. In the current study, the simulated peak flow was the most sensitive performance criterion for both approaches of spatial resolution reductions. A coarser model resolution resulted in larger simulated peak flows. The sensitivity of simulated peak flows to the spatial model resolution was also reported by earlier studies (Zaghloul 1981, Stephenson 1989, Elliott *et al.* 2009, Ghosh and Hellweger 2012). However, while Stephenson (1989) and Elliott *et al.* (2009) reported increasing peak flows with increasing catchment aggregation (as was observed in the current study), Zaghloul (1981) and Ghosh and Hellweger (2012) observed both an increase and decrease in peak flow rates for lower catchment resolutions. While the variations reported by Zaghloul (1981) were observed for same storms but different catchments, Ghosh and Hellweger (2012) reported the variation for the same catchment using different storms. These results indicate that the sensitivity of simulated peak flow rates to the spatial model resolution depends on both the catchment and storm characteristics. In the current study, however, no such indications were observed, as an increasing catchment aggregation induced similar effects for all study catchments and rainfall events. The alteration in EIA of the LR models when compared to the HR models affected the simulated runoff volume. However, EIA remained constant for all LR diameter thresholds. Thus, while this EIA alteration affected all LR WA and LR IS models similarly, perturbations in spatial resolution did not significantly affect the simulated runoff volume. Similar observations were reported by Park *et al.* (2008) and Ghosh and Hellweger (2012). Stephenson (1989), however, reported a reduction in the simulated runoff volume with increasing subcatchment aggregation.

5.3   Implications of the DEM delineation

A DEM usually provides sufficient information for catchments where surface flow is mainly affected by topography, as it is the case for natural catchments. In urban areas, however, surface flow is affected by obstacles, such as street curbs (Smith and Vidmar 1994). Through the recent advances in LIDAR technologies, high-resolution DEMs have become available for many urban regions and have been used for a variety of hydrological assessments (Brown *et al.* 2007, Mason *et al.* 2007, Fewtrell *et al.* 2008, Neal *et al.* 2009, Daniel *et al.* 2010). However, small details affecting urban surface runoff remain unsatisfactorily represented even in high-resolution terrain models (Gironás *et al.* 2010, Fewtrell *et al.* 2011, Sampson *et al.* 2012). In the current study, the impact of this lack of information

on catchment delineation and subsequently simulated runoff was evaluated (Paper **III**).

   A correlation between the error in the catchment area when delineating using a DEM and the degree of urbanization was not found. The catchment area of the most (catchment 1) and the least (catchment 3) urbanized catchments decreased by 8% and 10%, respectively. The change in the catchment area for the intermediate catchment 2 was much smaller (2%). The correspondence (in terms of overlap and excessive surface) between LR DEM and HR catchments, however, was correlated to the degree of urbanization, as a better correspondence was achieved for the less developed catchments 2 and 3 than for the highly urbanized catchment 1. Jankowfsky *et al.* (2013) studied different automated delineation methods for a peri-urban catchment in France in comparison with an approach where topographic data was complimented by field measurements. They reported overlaps of 85-98% with the reference catchment depending on the method used and corresponding excessive surfaces of 1-15%. The results produced in the current study are in accordance with the findings of Jankowfsky *et al.* (2013) with overlaps between 80-97% and excessive surfaces of 5-13%. It is to be noted however, that a high resolution DEM as available for the current study (2 m) was available only for a fraction of the study catchment of Jankofwsky et al. (2013) while the remaining catchment was covered only by a lower resolution DEM (25 m).

   The alteration in catchment properties induced by the DEM based delineation (such as area, boundaries, and imperviousness) naturally affects the simulated runoff. As discovered for the spatial resolution perturbations already (Section 4.2), the simulated peak flow was the most sensitive criterion to simplifications in catchment delineation and the simulated runoff volume was clearly less affected. These results indicate that the simulated peak flow is more sensitive to accurate catchment delineation and surface flow routing than the other model performance criteria studied here. Consequently, the selection of the spatial resolution and the accuracy required for catchment delineation depend on the objective of the hydrological assessment. An accurate peak flow prediction necessitates a more precise model description than a simulation of runoff volume. As for the spatial perturbations already (Section 4.2), a smaller impact of DEM delineation on simulated flow was found for the most urbanized catchment 1 than for the less densely built catchments 2 and 3. The alteration in EIA between LR DEM and HR models was smallest for catchment 1 where the LR DEM model performed almost equally compared to the HR model. The EIA alteration for the catchments 2 and 3 was clearly higher which was also seen in the model performance. It is to be noted that the difference in EIA between the LR DEM and HR models is not purley induced by the DEM delineation (and thus the alteration of TIA) but also the direct surface flow routing to the inlet, which was already applied for the LR models (Section 3.3).

5.4   Model regionalization

Several studies have addressed model parameterization of ungauged areas where a direct calibration of model parameters is not possible (e.g. Sefton and Howarth 1998, Seibert 1999, Kokkonen *et al.* 2003, Merz and Blöschl 2004, Parajka *et al.* 2005, Kay *et al.* 2007). The approach to parameterize an ungauged urban catchment proposed in the current study (Paper **III**) is based on the regionalization of model parameter values that were calibrated for intensively monitored study catchments with detailed spatial model descriptions (Paper **I, II**). This approach relies on catchment discretization that uses surface types and produces subcatchments with homogeneous hydrological properties. In comparison to earlier studies the proposed approach can be classified as site-similarity (e.g. Kokkonen *et al.* 2003, Parajka *et al.* 2005, Kay *et al.* 2007). However, the site-similarity in the proposed approach is independent from the actual surface structure of the catchment (i.e. the degree of urbanization or the land-use) but it is based on the high-resolution discretization of the catchment surface. Assuming that the same surface type (e.g. a stretch of asphalt) responds hydrologically in a similar way, all subcatchments sharing the same surface type should also have the same model parameter values independent of their location. And as the discretization produces same surface types for both the gauged and ungauged catchments, calibrated parameter values from the gauged catchments can be transferred to the ungauged area for model parameterization.

Several studies reported that a high spatial resolution, as used in this study, can improve simulation results (e.g. Lee and Heaney 2003, Gironás *et al.* 2010, Zhou *et al.* 2010). On the other hand, a detailed spatial discretization can also produce a large number of calibration parameters implying a model over-parameterization. In that case parameters remain not identifiable and the impact of an inappropriate parameter value may be compensated by an inappropriate value of another parameter. This results in a poor predictive model capability (Petrucci and Bonhomme 2014) and reduces the model reliability and robustness (Perrin *et al.* 2001). The spatial discretization used in the current study produces a large number of subcatchments; however, the use of surface type specific subcatchments that are characterized by homogeneous hydrological properties, helps to keep the number of calibration parameters relatively low (8-25 parameter depending on the study catchment) reducing the risk of model over-parameterization. Furthermore, the identifiability of calibration parameters is indicated by (i) similar parameter values for same surfaces in the three study catchments despite the independent calibration (Paper **I, II**), (ii) good performance of transferred parameter sets in all three study catchments despite the variation in catchment characteristics (e.g. imperviousness as well as the composition of impervious cover) (Paper **III**), and (iii) good model performance for a large number of rainfall events with varying intensity, depth, and duration (Paper **I, II**).

The high correlation of model parameter values between the independently calibrated catchments 1, 2, and 3 is in contrast to earlier studies (Sefton and Howarth 1998, Seibert 1999, Merz and Blöschl 2004) that reported low parameter correlations. Sefton and Howarth (1998) used the IHACRES model for 60

catchments in the UK to derive a set of dynamic response characteristics that were then related to physical catchment descriptors. Seibert (1999) obtained regional parameter sets for the HBV model based on eleven Swedish catchments. The studies of Kokkonen *et al.* (2003) and Merz and Blöschl (2004) concluded that the mean of available calibrated parameter values produced poor results and that hydrological differences in catchments need to be accounted for (Merz and Blöschl 2004). While Merz and Blöschl (2004) used the HBV model to evaluate regionalization approaches for 308 Austrian catchments, the study of Kokkonen *et al.* (2003) was based on the IHACRES model and 13 catchments in the Coweeta basin in the United States. Parajka *et al.* (2005) evaluated several regionalization approaches (e.g. parameter mean, spatial proximity, regression, and site-similarity) using the HBV model for 320 Austrian catchments. They achieved the best simulation results using a kriging approach or a site-similarity using a donor catchment with hydrologically similar properties. Similarly, Kokkonen *et al.* (2003) reported that parameters transferred from hydrologically similar catchments produced simulation results that were not much inferior to the ones produced by the specifically calibrated parameter set. However, while these studies were based on a large number of different catchments they were not specifically focusing on urban areas. The urban setting, where surface runoff modelling is more straightforward than in natural areas, together with the high spatial model resolution and the physical basis of parameters are the key explanatory factors for the relatively high parameter correlation between the three study catchments discovered in the current study. To further evaluate the applicability of the identified parameter values to an ungauged area, the parameter values were inter-changed between the three study catchments; the performance of transferred parameters was additionally evaluated against a reference parameter set V_{Ref} that was compiled based on literature suggestions. With respect to both the shape of the hydrograph and the simulated runoff volume, transferred parameter sets performed better than the reference parameter set. While transferred sets achieved a mean efficiency E of 0.70 and a mean absolute volume error (VE) of 21.9%, the V_{Ref} parameterization yielded both a lower E (0.52) and a larger VE (33.9%). While a better performance of transferred sets (PFE of 24.6%) compared to V_{Ref} (PFE of 29.2%) was also found with respect to the simulated peak flow, the advantage of calibrated and subsequently transferred parameters over a literature based parameterization was less clear. Overall, the results show that while site-specific parameter sets achieve an overall better simulation performance, calibrated and subsequently transferred parameters produce a reasonable replication of urban runoff.

5.5   Green roof modelling

In the sensitivity analysis of the SWMM green roof LID module the soil porosity p and the PET rate scaling coefficient C_{PET} were identified to have the largest influence on the simulated green roof runoff (Paper **IV**). While p determines the overall water retention of the green roof, the PET rate defines the pace of green roof retention capacity restoration during inter-event periods. Evapotranspira-

tion is a key process controlling the green roof retention (e.g. Palla *et al.* 2008b, Kasmin *et al.* 2010, Stovin *et al.* 2013). While most analysed parameters affected the simulated green roof runoff, the model was entirely insensitive to parameters related to the surface flow on the roof. This can be explained by the high permeability of soils commonly used for green roof substrates (Kasmin *et al.* 2010, Stovin *et al.* 2012) that prevent the occurrence of surface flow. Absence of surface flow was also confirmed during on-site visits at the test beds during intense rainfall events (Paper **IV**).

The optimized parameter set was replicating the monitored test bed runoff with an efficiency of 0.93 and a volume error of -4.7%. However, for small events characterized by a low rainfall intensity or a small runoff-rainfall ratio, the model did not perform well. Furthermore, it was noted that the replication of the observed runoff recession was not satisfactory. Compared to the measurements, the simulated recession limbs were too steep. The model performance for the validation period was, as to be expected, lower than for the calibration period with an efficiency of 0.82 and a volume error of -15%. Also for the validation sequence, the model failed to properly replicate the monitored runoff for small and less intense events. The lower validation performance can also partly be attributed to the way of calibrating C_{PET}. Validation (2014) and calibration (2013) periods shared only one common month. Thus, to allow for an independent validation of the modelling results, a single C_{PET} value was used instead of an individual value for each month. High volume errors in the validation period, especially in June, indicate that a single PET scaling factor is insufficient in representing the variation in evapotranspiration rates throughout the year. Different values for individual months or even for shorter periods could improve the predictive accuracy of the model (see Allen *et al.* 1998). Several studies have reported the influence of the current soil moisture content on actual evapotranspiration rates (e.g. Lazzarin *et al.* 2005, Voyde *et al.* 2010b, Sherrard Jr and Jacobs 2012, Stovin *et al.* 2013) but it is neglected in the SWMM green roof LID module. However, a comparison of the simulated and monitored initial soil moisture contents (Paper **IV**) shows that, despite this limitation, the SWMM green roof LID module replicated the dynamics in the soil moisture content with a reasonable accuracy. This implies that the influence of the current soil moisture content on the actual evapotranspiration rates has a limited effect on the green roof retention capacity. The 20 minute recording interval of green roof runoff data did not affect the model performance (Paper **IV**). Even though the model parameters were calibrated to 20 minute data, the model achieved good efficiencies also when tested against 1 and 10 minute data where available. Earlier green roof modelling studies have reported varying success. Burszta-Adamiak and Mrowiec (2013) applied the SWMM bio-retention LID module to replicate the runoff monitored at three intensive green roof test beds (2.9 m²) in Poland. They concluded that the model had limited capabilities in simulating green roof runoff. Alfredo *et al.* (2010) calibrated SWMM using the "curve number" and "storage node" approaches to three intensive green roofs (substrate depth 2.5-10.0 cm) in New York City, USA, and achieved reasonable results. They confirm the observations of this study about the need for a thorough calibration to

achieve reliable results. It is to be noted that neither Burszta-Adamiak and Mrowiec (2013) nor Alfredo *et al.* (2010) considered inter-event evapotranspiration during their simulation efforts. Evapotranspiration is a key driver for green roof retention and an accurate simulation of this process is required to evaluate the long-term performance of green roofs for stormwater management purposes. She and Pang (2010) coupled SWMM with a evapotranspiration-infiltration module that was calibrated against runoff data from an intensive green roof (area 240 m², substrate depth 10 cm) in Portland, USA. They reported a model performance comparable with results of the current study. Hilten *et al.* (2008) applied HYDRUS-1D to a green roof test bed (area 37 m², substrate depth 10 cm) in Athens, USA, and concluded that while the model accurately predicted small runoff events, it tended to overestimate large events. No similar correlation between the event size and the model performance was found in the current study. Instead, the SWMM green roof LID module showed a lower performance for low intensity events and events characterized by a small runoff-rainfall ratio. Palla *et al.* (2011) parameterized SWMS-2D for a full size green roof (monitored area 170 m², substrate depth 20 cm) in Genova, Italy, achieving a good performance for all simulated events with the lowest efficiency yielding 0.81. Even though the SWMM green roof LID module in the current study performed overall well with an efficiency of 0.92 for the best event, there was clearly a wider variation in model performance for all simulated events. This indicates that the more detailed process description in SWMS-2D results in a more consistent and better performance across a range of event sizes. Similar conclusions can be drawn from results presented by Palla *et al.* (2012) where a the performance of a conceptual linear reservoir model and the mechanistic model HYDRUS-1D was evaluated.

6 CONCLUSIONS

This thesis presents a methodology to parameterize a large urban catchment for the hydrological assessment of LID strategies. Implementation of such LID strategies in urban stormwater management requires evaluation of potential benefits, optimal placement, and most effective tool selection at the city scale. Simulation of LID processes requires an explicit and highly distributed modelling strategy. The parameterization of a hydrological model following such a strategy for a large urban catchment is hampered by the limited availability of both spatial and hydrometeorological data. While these limitations can be compensated for small urban areas by intensive measurement campaigns and data complementation, different strategies are required for the assessment of larger urban areas. The methodology presented in this thesis is based on three intensively monitored study catchments that are located within the targeted large urban area. The developed high resolution parameterizations of these catchments provided the basis for investigations of the impact of limited data availability on the simulation results and the model regionalization to the large Vesijärvi catchment.

The HR models of the study catchments show an overall good performance regarding the replication of the monitored runoff volumes and peak flows (Paper **I**, **II**). The lower performance of the HR model of catchment 3 indicates the importance of having rainfall data available in close vicinity to the assessed area. With an increasing distance between the assessed catchment and the rainfall measurement station the temporal dynamics of monitored rainfall and runoff become less consistent. Furthermore, the results show that the drainage of suburban areas (such as catchment 3), where surface flow patterns are less clearly defined than in highly developed areas (such as catchment 1), needs to be properly considered during model development to allow for reliable simulation results. Despite the rather laborious data acquisition, a high spatial model resolution has two main advantages over lower model resolutions. First, the detailed surface discretization supports the explicit simulation of various LID strategies, as model parameters (e.g. for a roof or a street section) can be directly manipulated or the runoff routing modified (e.g. for the disconnection of a roof area). Second, the surface-type based catchment discretization reduces the number of calibration parameters when compared to lower model resolutions. Lower model resolutions commonly comprise subcatchments that are characterized by different hydrological properties. The surface-type based discretization applied in the current study, on the other hand, produces a large number of subcatch-

ments, but only a limited number of calibration parameters as surfaces of the same type are assigned with identical hydrological properties.

A reduction of spatial model resolution is in most cases unavoidable for the assessment of large urban areas. Such a reduction, that implies the neglecting of detail concerning both the urban surface and the drainage network, naturally affects the simulated runoff due to (i) the replacement of conduit flow with overland flow implied by the omission of conduits and (ii) the alteration of EIA implied by the neglecting of surface flow routing. The results presented in Paper **II** show that while the simulated runoff volume was affected by the alteration in EIA due to the modified surface flow routing, spatial resolution perturbations based on the diameter thresholds have a negligible effect on the simulated runoff volume. The simulated peak flow, on the other hand, proved to be more sensitive to the reduction in the spatial resolution. Thus it can be concluded that the appropriate spatial resolution depends on the objective of the model application. While a lower resolution can be appropriate for a sufficient replication of the runoff volume, a higher spatial resolution can be required when the runoff peak flow is the main interest, e.g. for urban flooding assessments. Furthermore, the presented results (Paper **II**) underline the importance of EIA in urban runoff modelling. The degradation in model performance for LR models was correlated to the induced alteration of EIA. While the smallest degradation was observed for the most urbanized catchment 1, the roof runoff routing to pervious areas in catchment 3 had to be maintained for catchment 3 to achieve reasonable simulation results with the LR models. Low model resolutions commonly cannot support the explicit simulation of LID processes, as areas in question (e.g. a roof) are embedded within larger subcatchments described by lumped parameter sets. In the current study, a novel approach for a reduction in model resolution retaining the ability for explicit LID simulation (LR IS, Paper **II**) was presented. This approach has similar requirements on the detail of spatial input data when compared to the lumped LR WA models (i.e. a surface map of the catchment). However, while for the LR WA models surface properties were lumped into aggregated subcatchment parameter set, the LR IS approach retained the detailed surface discretization. Thus, the contributing drainage area of each inlet comprises a number of subcatchments. The surface runoff from each subcatchment was directly routed to the assigned inlet independent of the spatial proximity resulting in an overall flashier runoff response. Consequently, a higher spatial resolution was required for a sufficient replication of monitored flow. The results show that this surface discretization in combination with a conduit diameter threshold of 300 mm provides modelling results that do not differ much from the results provided by the HR models while requiring significantly less detailed information (and thus requiring less manual work on data).

Delineation of large areas requires automated methods (e.g. DEM based). Such methods, however, neglect details of the urban surface that are not well represented even in high resolution terrain models. Thus, an automated DEM based delineation affects the shape of the subcatchments when compared to manual delineation methods that consider small details affecting the surface flow in urban areas. The LR DEM approach presented in the current study is an exten-

sion of the LR IS approach and it was applied to the three study catchments to evaluate the impact of this further simplification on the simulated runoff. The results presented in Paper **III** indicate that the effect on catchment properties induced by the DEM delineation is smaller for less urbanized catchments than for highly impervious catchments. Obstacles, such as street curbs, exist to a smaller degree (or are completely absent) in less urbanized areas compared to densely built urban catchments. Thus, the neglecting of such details has less influence on the delineation results for suburban areas. As for the LR IS and LR WA models, the LR DEM model performance was correlated to the increase of catchment EIA; the best LR DEM model performance was achieved for catchment 1 and a lower performance was achieved for catchments 2 and 3. While the simplifications applied to the LR DEM model affect the simulated runoff, it can be concluded that the LR DEM model provided a sufficient simulation performance for all three study catchments indicating the applicability to a larger urban catchment for the evaluation of stormwater strategies.

Parameterization of large, commonly ungauged urban catchments is challenging. The independent calibration of the three study catchments yielded similar parameter values for the same surface types. While methods to conduct a so-called model regionalization have been investigated in numerous studies, commonly only low parameter correlations have been reported. However, to the author's knowledge none of the earlier studies was specifically addressing parameter regionalization for urban areas. Due to the high fraction of impervious surfaces in combination with an efficient drainage system, the hydrological behaviour of urban catchments is more straightforward than what it is in natural areas. The urban setting, the high spatial resolution and the physical basis of parameters established by the linkage to surface types are the reasons for the high parameter correlation found in the current study (Paper **II**). The high parameter correlation is further supported by good quality hydrometeorological data that needs to be available at high temporal resolution for the catchments serving for model calibration. The applicability of the study catchment parameter values to the ungauged Vesijärvi catchment was further investigated by interchanging parameter values between the three study catchments (Paper **III**) as well as against a model parameterization using literature based parameter values. The results show that parameters that were calibrated to high resolution catchments, where flow data are available, and subsequently transferred using the proposed methodology, produce superior simulation results when compared to a literature based model parameterization. However, while this conclusion is clear concerning the shape of the hydrograph and the simulated runoff volume, the interpretation is more vague concerning the simulated peak flow rates. Furthermore, it can be concluded that the performance of transferred parameter sets is not much inferior to the ability of catchment specific calibrated model parameters to replicate monitored stormwater runoff (Paper **III**).

The green roof test bed simulation results presented in Paper **IV** indicate that the SWMM green roof LID module provides a proper tool to evaluate the performance of green roofs for stormwater management. Evapotranspiration during inter-event dry periods is a key process determining the green roof retention

capacity at the beginning of a rainfall event. Thus, correct simulation of these periods is a requirement in assessing the long-term performance of green roofs for stormwater management. Based on the presented results, it can be concluded that, even though SWMM does not consider the influence of current soil moisture content on actual evapotranspiration rates, the parameterized model produces reasonable results concerning initial soil moisture content, runoff volume, and runoff peak flows for the vast majority of monitored runoff events. However, a rather poor performance was observed for events with a low runoff-rainfall ratio and low runoff intensities. Such events, however, represent only a very small fraction of annual runoff based on the available two year data, limiting their importance for stormwater management. Furthermore, replication of hydrograph recession limbs, that were too steep for most events, is not satisfactory. However, the correct simulation of runoff volumes and peak flows is only negligibly affected by this limitation. It is to be noted however, that, as the green roof module was parameterized to small scale test beds only, possible scaling issues require careful consideration.

This thesis presented a methodology to parameterize a large scale urban catchment for explicit LID simulation. The impact of limitations concerning data availability on simulation results was thoroughly evaluated. While all limitations and associated simplifications (such as a reduction in spatial resolution) naturally affect the simulated runoff to some degree, the presented results show that the suggested methodology provides an avenue to develop a model parameterization for a large, ungauged urban catchment that can provide a sufficient replication of urban runoff dynamics to evaluate the benefits of various LID tools at the city scale.

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