Department of Civil and Environmental Engineering

Effects of suburban development on runoff generation and water quality

Nora Sillanpää

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 160/2013

Effects of suburban development on runoff generation and water quality

Nora Sillanpää

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall R1 of the school on 10 January 2014 at 12.

Aalto University
School of Engineering
Department of Civil and Environmental Engineering
Water and Environmental Engineering

Supervising professor
Prof. Harri Koivusalo

Thesis advisor
Prof. Emer. Pertti Vakkilainen

Preliminary examiners
Prof. Robert Pitt, University of Alabama, USA
Dr. Jiri Marsalek, National Water Research Institute (NWRI), Canada

Opponent
Prof. Maria Viklander, Luleå University of Technology, Sweden

Aalto University publication series
DOCTORAL DISSERTATIONS 160/2013

ISBN 978-952-60-5373-8
ISBN 978-952-60-5374-5 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-5374-5

Unigrafia Oy
Helsinki 2013

Finland

A! Aalto University

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Nora Sillanpää

Name of the doctoral dissertation
Effects of suburban development on runoff generation and water quality

Publisher School of Engineering

Unit Department of Civil and Environmental Engineering

Series Aalto University publication series DOCTORAL DISSERTATIONS 160/2013

Field of research Water Resources Engineering

Manuscript submitted 8 May 2013 **Date of the defence** 10 January 2014

Permission to publish granted (date) 9 August 2013 **Language** English

☒ **Monograph** ☐ **Article dissertation (summary + original articles)**

Abstract

Urbanization leads to changes in natural catchment characteristics by increasing the impervious coverage and drainage efficiency, which enhance flooding, erosion and water quality problems in the receiving waters. Year-round monitoring of catchment-scale hydrological and water quality variables is needed to produce data resources for the development of urban drainage design principles for various management purposes in cold climate. The aim of this thesis was to investigate the impacts of urbanization on runoff generation and water quality at residential catchments in southern Finland. The study included a five-year monitoring period at three catchments: low- and medium-density residential catchments and a developing catchment under construction. A snow study was conducted during one winter period.

In the study catchments, urbanization resulted in significant increases in runoff depth, peak flows, and mean runoff intensities and reduced catchment lag during the warm period of the year. Urbanization did not cause notable changes in total runoff generation during the cold period despite the observed changes in the areal distribution of snow. However, the snowmelt period became separated into more numerous runoff events of a shorter duration and with smaller runoff volumes. Large seasonal variations existed in pollutant concentrations, which at residential catchments depended on the catchment imperviousness and the type of pollutant; yet, no single season was responsible for a notably higher proportion of annual pollutant export. In the event scale, the frequent summer storms were associated with the highest event mean concentrations, but the cold period runoff events with the largest event loads. Construction works had a profound adverse impact on water quality depending on the ongoing construction activities. Thresholds of concentration criteria were exceeded particularly in summer or spring, during all phases of construction works, and in winter for ploughed snow.

The results provide a basis for strategies aiming to reduce the adverse impacts of urbanization in the local climate. A statistically significant change in the runoff response to rainfall occurred when event rainfall depths exceeded an approximate threshold of 17-20 mm indicating a change in the extent of runoff-contributing area. Urbanization caused the greatest changes in the runoff response during frequently occurring summer storms. Hence, the infiltration and the treatment of common small storms seem to be a promising approach to maintaining the predevelopment hydrology and water quality. The runoff coefficients in Finnish stormwater design manuals at present are too high in comparison to the observed coefficients for most rainfall events. Both construction and post-construction phases should be taken into account in water quality protection. In the cold period, the focus should be aimed at reducing the wintertime pollution sources and the appropriate storage and treatment of snow.

Keywords construction, hydrology, urban snow, urbanization, water quality

ISBN (printed) 978-952-60-5373-8 **ISBN (pdf)** 978-952-60-5374-5

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2013

Pages 226 **urn** http://urn.fi/URN:ISBN:978-952-60-5374-5

A! Aalto-yliopisto

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Nora Sillanpää

Väitöskirjan nimi
Rakentamisen aiheuttamat muutokset valunnan muodostumiseen ja veden laatuun asuinalueilla

Julkaisija Insinööritieteiden korkeakoulu

Yksikkö Yhdyskunta- ja ympäristötekniikan laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 160/2013

Tutkimusala Tekninen vesitalous

Käsikirjoituksen pvm 08.05.2013 **Väitöspäivä** 10.01.2014

Julkaisuluvan myöntämispäivä 09.08.2013 **Kieli** Englanti

☒ **Monografia** ☐ **Yhdistelmäväitöskirja (yhteenveto-osa + erillisartikkelit)**

Tiivistelmä

Kaupungistuminen muuttaa merkittävästi valuma-alueiden ominaisuuksia ja luonnollista vedenkiertoa. Muutosten seurauksena aiheutuu mm. tulva-, eroosio- ja vedenlaatuongelmia. Ongelmien ehkäisemiseksi tarvitaan hydrologista ja veden laadun tutkimustietoa, jonka perusteella suunnitteluperiaatteita voidaan uudistaa tukemaan sekä valunnan määrään että laatuun liittyviä hallintatavoitteita. Kylmissä ilmasto-olosuhteissa tämä edellyttää valuma-aluemittakaavan ympärivuotista monitorointia. Väitöskirjan tavoitteena oli tutkia kaupungistumisen vaikutuksia valuntaan ja veden laatuun kolmella asuinalueella Espoossa: pientalo- ja kerrostaloalueella sekä rakennettavalla asuinalueella. Viiden vuoden tutkimusjakso käsitti valunta- ja vedenlaatuaineiston sekä lumiaineiston yhdeltä talvelta.

Tutkimusalueilla kaupungistuminen kasvatti lämpimänä vuodenaikana valunnan määrää, ylivirtaamia ja valunnan keskimääräistä intensiteettiä sekä pienensi valuma-alueen kertymisaikaa. Kylmän vuodenajan kokonaisvalunnassa ei havaittu merkittäviä muutoksia huolimatta lumen alueellisen jakauman muuttumisesta. Lumen sulantajakso näytti kuitenkin pilkkoutuvan useampiin, lyhytkestoisempiin valuntatapahtumiin. Haitta-ainepitoisuuksissa havaittiin suurta vuodenaikaisvaihtelua, joka valmiilla asuinalueilla riippui haitta-aineesta ja läpäisemättömien pintojen määrästä. Pitoisuuksien vuodenaikaisvaihtelusta huolimatta vuosikuormitus ei pitkällä aikavälillä näyttänyt keskittyvän tiettyihin vuodenaikoihin. Valuntatapahtumatasolla korkeimmat tapahtumapitoisuudet osuivat kesäaikaisiin sadetapahtumiin, mutta korkeimmat tapahtumahuuhtoumat kylmän ajan valuntatapahtumiin. Rakennustyöt heikensivät vedenlaatua merkittävästi riippuen käynnissä olevista rakennustyövaiheista. Pitoisuusraja-arvot ylittyivät erityisesti kesällä tai keväällä, kaikissa rakennustyövaiheissa ja auratussa lumessa.

Tutkimuksen tulokset luovat pohjan strategioille, joiden tavoitteena on vähentää kaupungistumisen aiheuttamia hydrologisia ja veden laadun muutoksia paikallisessa ilmastossa. Tilastollisesti merkitsevä muutos sadetapahtumien valuntavasteessa tapahtui n. 17-20 mm sademäärän jälkeen, mikä indikoi muutosta valuntaa tuottavan alueen laajuudessa. Suhteellisesti suurin muutos tapahtuu usein toistuvien sateiden valuntavasteessa. Näiden sateiden aikaisen valunnan imeyttäminen ja käsittely vaikuttavat lupaavalta lähestymistavalta luonnollisen vedenkierron ylläpitoon ja hajakuormituksen hallintaan. Suomalaisten mitoitusoppaiden valuntakertoimet ovat korkeita verrattuna mitattuihin valuntakertoimiin useimpien sadetapahtumien yhteydessä. Vedenlaadun hallinnassa tulisi huomioida sekä rakennusvaihe että rakentamisen jälkeinen vaihe. Kylmänä vuodenaikana on tärkeää kiinnittää huomiota talviaikaisten päästölähteiden pienentämiseen sekä lumen asianmukaiseen käsittelyyn ja säilytykseen.

Avainsanat rakennustyömaa, taajamahydrologia, lumi, kaupungistuminen, veden laatu

ISBN (painettu) 978-952-60-5373-8 **ISBN (pdf)** 978-952-60-5374-5

ISSN-L 1799-4934 **ISSN (painettu)** 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2013

Sivumäärä 226 **urn** http://urn.fi/URN:ISBN:978-952-60-5374-5

Author's contribution

The author is responsible for the manuscript and the collection of runoff monitoring data during the years 2004-2006. The instructor and the supervisor of the thesis have commented on the manuscript and the methods used in the study. Owing to the large monitoring work presented in the thesis, the help of the field and laboratory personnel of the Helsinki University of Technology (TKK) was needed in all practical aspects of the study. The author was responsible for a considerable part of the field work, but did not conduct the laboratory analyses of water quality samples. The author also acted as an instructor to several undergraduate students, who helped in the preparation of the data.

Jyrki Kotola and Jyrki Nurminen (TKK) were responsible for the data collection for the years 2001-2003: they also published some results from the first monitoring year, 2001-2002 (Kotola and Nurminen, 2003). These results were recalculated and reanalyzed by the author. The author also conducted the detailed mapping of the changes occurring in the impervious areas as the construction works progressed in the developing study catchment. The author was responsible for the adjustments made to improve the accuracy of the monitoring data including the change of the monitoring interval from ten to two minutes and the changes in the precipitation correction based on on-site reference rainfall measurements. The flume measurements for the verification of the stage-discharge curve of the medium-density study catchment were initiated by the author's idea, but the practical work was conducted by the laboratory personnel and as student work.

The gamma unit hydrographs in Chapter 5 were determined using a model code written by Harri Koivusalo and Teemu Kokkonen and the model runs were conducted together with Professor Koivusalo. The author was solely responsible for the preparation of the data and the interpretation of the results.

The snow study was planned by the author and the research plan was commented on by the instructor and the supervisor. An undergraduate student at TKK helped in the collection of the snow observations and conducted the laboratory analyses of snow quality samples. She also determined the surface areas for different snow types, which have been utilized in Chapter 4 and were presented in her Master's thesis (Samposalo, 2007). The snow results were recalculated and reanalyzed for this dissertation by the author. A part of the snow study was published in Sillanpää and Koivusalo (2013), Catchment-scale evaluation of pollution potential of urban snow at two residential catchments in southern Finland, *Water Science and Technology* (in press). This content was reprinted in the thesis with permission from IWA Publishing. The author was responsible for writing the article and preparing and interpreting the data. Prof. Koivusalo commented on the manuscript.

Acknowledgements

I started my doctoral studies in 2004 at the Helsinki University of Technology (TKK) under the supervision of Professor Pertti Vakkilainen, and after a rather long period as a full-time and part-time student, I conclude my journey under the supervision of Professor Harri Koivusalo at the Aalto University, created by the merger of three universities, TKK, Helsinki School of Economics, and School of Art and Design in 2010. I am grateful to Emeritus Professor Pertti Vakkilainen for the opportunity to pursue a doctoral degree in the most inspiring field of hydrology, his broad expertise and support during my studies, even after his retirement. Although Professor Koivusalo came along as my supervisor not until the last stage of my studies, I have benefited a lot from his advice and comments. I am also very grateful that Cudworth Professor, Dr. Robert Pitt from the University of Alabama and Dr. Jiri Marsalek from Environment Canada took the time for the pre-examination of my thesis, and Professor Maria Viklander from the Luleå University of Technology for accepting the invitation to act as my opponent.

During the years 2008-2010 before my maternity leave, I worked as a project manager at the University of Helsinki, in a stormwater project led by Professor Heikki Setälä. Although this period probably delayed my doctoral studies considerably, it offered me an excellent opportunity to broaden my perspective over numerous aspects involved in the urban runoff management, both from the science and practice points of view. I kindly thank Professor Setälä for his support and interest towards my field of research.

For the financial support, I wish to thank Maa- ja Vesitekniikan tuki ry. (MVTT), the Academy of Finland, the European Regional Development Fund (ERDF, the funding received from the Regional Council of Päijät-Häme), the ENARCH Doctoral Programme of Aalto University, Sven Hallin Research Foundation, and Tekniikan edistämissäätiö (TES). I also wish to acknowledge the travel grants from MVTT, which enabled me to participate in several international conferences during my doctoral studies.

I highly appreciate the help received from several people at TKK during the field studies. Most importantly, Jyrki Kotola introduced me to the field work and measurement stations. From the Water Engineering Research Group, thanks are also due to Matti Keto for the field work and Erja Salermo and Aino Peltola for the laboratory analyses. I also want to acknowledge the help received from other TKK personnel, particularly Jyrki Nurminen and Antti Louhio. Many former students at TKK have helped with the preparation of the monitoring data: Juha Seppinen, Katri Leino, Susanna Immonen and Sari Samposalo. I especially want to acknowledge the work done by Sari for conducting the laboratory analyses of snow quality samples, and for determining the surface areas for urban snow calculations. Regarding my final manuscript, I wish to acknowledge the advice given by the Lecturer of Statistics

Ilkka Mellin from the Department of Mathematics and Systems Analysis (Aalto University) about the statistical methods used in my study, and the comments by Dr. Juha Järvelä from the Water Engineering Research Group for select parts of the manuscript.

I also wish to thank the several companies, institutes, and people, who provided additional materials concerning the study catchments and other research tasks. Espoo Water provided the ortophotos for the developing study catchment. Plan drawings for different plots within the developing catchment were afforded by the construction companies NCC, YIT and LVI-Toimisto Haapalainen Oy. Workers from Peab Seicon helped to clean up and repair the monitoring station after wastewater discharges in the developing study catchment in 2004. Sewer pipes for the flume measurements were sponsored by Uponor and Espoo Water. Jukka Järvinen and Timo Nieminen from the Finnish Environment Institute provided me runoff monitoring data from small agricultural catchments to be used as a reference for the study catchments. Anas Altartouri from the Aalto University kindly provided me the figure illustrating the locations of the monitoring stations.

Finally, I owe warm thanks to my former and present colleagues at TKK, the University of Helsinki, and the Aalto University (both in Espoo and Lahti). Especially I wish to thank Dr. Hanne Laine-Kaulio for her help and friendship throughout my studies. Above all, I wish to thank my husband, Mikko, for his patience and continuous support.

In Hollola on 15 September 2013,

Nora Sillanpää

Contents

List of Symbols

α	Shape parameter of the gamma distribution
A, A_{TOT}	Catchment area [*ha*]
A_{DCIA}	Area of directly connected impervious surfaces [*ha*]
A_{SCA}	Snow covered area [*ha*]
A_{snow}	Surface area of a particular snow type [*ha*]
β	Scale parameter of the gamma distribution
β_i	Regression coefficient for variable *i*
C	Runoff coefficient, [-]
C_i	Pollutant concentration of i^{th} runoff sample [*mg/l*]
C_{snow}	Pollutant concentration in snow [*mg/l*]
C_t	Observed or interpolated pollutant concentration at time *t* [*mg/l*]
COD, COD_{Mn}, COD_{Cr}	Chemical oxygen demand
COV	Coefficient of variation, calculated as a ratio of standard deviation to average [-]
C_{VOL}	Volumetric runoff coefficient, [-] or [*%*], determined as an event ratio of accumulated direct runoff and event precipitation
D_i	Discriminant function
DA	Discriminant analysis
DAYS	Antecedent dry period [*d*]
DCIA	Directly connected impervious area
EC	Electrical conductivity, [*mS/m*]
EIA	Effective impervious area, [-] or [*%*]
EMC	Event mean concentration, [*mg/l*]
EML	Event mass load, [*kg*]
FMI	Finnish Meteorological Institute
HCA	Hierarchical cluster analysis
i	Design storm intensity [*l/s/ha*], [*mm/h*]
IDF	Intensity-duration-frequency curve for rainfall
IQR	Interquartile range
IUH	Instantaneous unit hydrograph
L	Pollutant load [*kg*]
LID	Low impact development
LL	Laaksolahti study catchment, a low-density residential area
ML_{snow}	Pollutant mass load in snow, [mg/m^2]
MLR	Multiple linear regression analysis
MTT	Mean transit time, [min]
P_{DUR}	Rainfall event duration, [*h*]
P_{MAX}	Maximum 10-minute rain intensity, [*mm/10 min*]
P_{MEAN}	Mean rainfall intensity, [*mm/h*]
PREC	Antecedent precipitation sum [*mm*]
P_{TOT}	Event rainfall, [*mm*]
Q	Peak discharge [*l/s*]
Q_{MAX}	Maximum instantaneous flow rate, [*l/s*], [*l/s/ha*]
Q_t	Flow rate at time *t*, [*l/s*]
r	Pearson correlation coefficient [-]
R^2	Coefficient of determination, [-] or [%]
R_{DUR}	Runoff event duration, [*h*]
R_{EFF}	Event direct runoff (total runoff minus baseflow), [*mm*]
RSUM	Antecedent runoff sum [*mm*]
R_{TOT}	Event total runoff, [*mm*]
SCA	Snow covered area, [%]
SEE	Standard error of the estimate, [-] or [%]
SMC	Site mean concentration, [*mg/l*]
SML	Areal snow mass load, [kg/km^2]
SR	Saunalahdenranta study catchment, a developing area
SUDS	Sustainable urban drainage system
SWE	Snow water equivalent (mm)
TSS, SS	Total suspended solids
TIA	Total impervious area, [%]
TP	Total phosphorus
TN	Total nitrogen
VIF	Variance inflation factor
VK	Vallikallio study catchment, a medium-density residential area
WSUD	Water sensitive urban design

List of Figures

List of Tables

1. Introduction

1.1 Historical context of urban runoff management

Already in ancient times, urban drainage played a key role either in promoting the success or the demise of societies (Burian et al., 1999). Commonly cited examples about man-made drainage systems in ancient times include those of the Minoan (3000-1000 BC) and the Mesopotamian (2500 BC) civilizations, the Greeks (Athens) and more developed Roman communities (Burian et al., 1999; Mays, 2001; Butler and Davies, 2004). Later, in Europe and the US, the failure of adequate drainage systems resulted in outbursts of water-borne diseases, such as cholera, typhoid and dysentery, as the drainage systems were intended for stormwater and did not include sanitary sewers (Walesh, 1989; Burian et al., 1999).

Although urban drainage has its roots deep in early civilization, the developments that have led to the current state of urban drainage practices have only occurred rather recently, during the past 200 years. According to Burian et al. (1999), the advancements that have created the basis for modern urban wet-weather flow management include improvements in the hydraulic efficiency of drainage systems in the early 19th century and, in the mid-1800s, the first comprehensive sewer system designs, the identification of waterborne diseases and advances in urban hydrology. In fact, the methods utilized today rely on mathematical concepts for the rainfall-runoff relationship developed already in the 19th century, such as the rational method (Mulvaney, 1851; Kuichling, 1889; Lloyd-Davies, 1906) and design storm, or the unit hydrograph developed in the early 20th century (Sherman, 1932). From the late 1870s onwards, the introduction of separate sewers and advances in wastewater treatment led to the development of urban drainage systems that are still in operation today. Since the 1960s, increasing environmental awareness and developments in technical tools, design methods and legislation have further promoted the evolution of the urban drainage regime (Burian et al., 1999); Katko et al. (2006) argue that advances in legislation, particularly legislation concerning water pollution control, constitute the most strategic decision affecting the development of water and sanitation services in Finland.

Modern approaches to urban runoff management

The conventional design of urban drainage systems has concentrated on conveying peak flows via pipe sewer systems, but during recent decades diffuse pollution from urban sources and restoring the urban water cycle have increasingly gained attention. This has led to the development of more integrated approaches to urban runoff management, which include three complementary goals of equal importance: stormwater quantity, quality and amenity management, all of which are intended to better mimic natural catchment processes (Maksimović, 2000). These systems have different names in different countries: *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, 2004). The systems usually consist of decentralized structures, which are designed to pond, infiltrate and harvest water at the source, thereby sustaining evapotranspiration, groundwater recharge and the re-use of stormwater (Roy et al., 2008). In Australia and the US, for example, WSUD and LID approaches have been actively developed at least since the 1990s (Roy et al., 2008). According to Ashley et al. (2007), in Europe stormwater management needs to take a more central role in all aspects of urban planning owing to the future uncertainties from climate change and impacts of legislation (see the Water Framework Directive in particular).

The modern, sustainable urban management approach requires the renewal of traditional design principles. Conventional design has aimed at accommodating design flows resulting from development 'as is'; the sustainable approach usually aims at preventing the changes that occur in the predevelopment stage. Several authors, for example in the US (e.g. Pitt, 1999; Roesner, 1999; Lee and Heaney, 2003) and Australia (Liu, 2011; Burns et al., 2012), have pointed out the importance of small- and medium-sized storms for stormwater runoff quality management and for managing a large spectrum of design events to restore predevelopment hydrology. Roesner et al. (2001), for instance, argue that design standards that aim only at retaining 2- to 25-year peak flows at the predevelopment stage mainly contribute to flood control and have only a limited impact on the post-development erosion caused by more frequent rainfall events.

In several countries, stormwater regulation has been extended to apply to the construction phase of development projects. In the US (e.g. Pitt et al., 2007), Scotland (SEPA, 2008) and Ontario, Canada (Toronto Water, 2006), for instance, construction activities are regulated by different means, including legislation, environmental permits and stormwater management guidance.

Present state of urban runoff management in Finland

Urbanization is a rather recent phenomenon in Finland — one third of densely populated urban areas were built during the years 1980-2000 (Ristimäki et al., 2003). These areas now cover approximately two per cent of the total land area, which may seem insignificant on a national scale. Yet, more than 80% of all Finns live in urban areas (Ristimäki et al., 2003) and are therefore directly affected by the management decisions made regarding urban water resources. Additionally, based on the global inventory of impervious surface area (Elvidge et al., 2007), Finland currently has 323 m^2 of constructed impervious surface area per person, which exceeds that of the US (297 m^2/person) and is way above the global average of 93 m^2/person. The high level of imperviousness is a characteristic of affluent countries in the northern hemisphere, but according to Elvidge et al. (2007), it also indicates a higher probability of catchments suffering from adverse hydrological and ecological effects.

Despite the obvious trend of urbanization, hydrological research in Finland has concentrated on rural land uses and published studies on urban hydrology are scarce. The most comprehensive study dates back to the late 1970s, to the Finnish Urban Storm Water Project (1977-1979) (Melanen, 1980, 1981; Melanen and Laukkanen, 1981). At that time, one of the key research questions was the choice between combined and separate sewer systems, particularly in areas with existing combined systems (Melanen, 1982). The first separate sewers in Finland were introduced in 1938 in Helsinki (Katko et al., 2006), and by the 1970s separate sewers had already been implemented in new areas for several decades (Melanen, 1982). The broad utilization of separate sewers made the treatment of wastewater technically feasible (Katko and Juuti, 2005), and developments in this sector have resulted in a considerable reduction in the amount of urban point pollution; for example, the phosphorus loading from treated wastewater was only 15% at the beginning of the 21st century compared with the situation in the early 1970s (Niemi and Heinonen, 2003). Today, approximately 90% of storm sewers within the metropolitan area of Helsinki consist of separate systems (HSY, 2011), whereas in several other European countries (e.g. the UK, France and Germany) combined systems account for as much as 70% of the total length of sewerage systems (Butler and Davies, 2004).

Melanen (1980) argued that there was no common need for the additional treatment of urban stormwater. Nevertheless, Melanen already made some recommendations for features that are nowadays a central part of the modern, sustainable urban drainage systems. He suggested that in low-density residential areas, urban runoff should be infiltrated to the maximum extent possible; for the conveyance of runoff, natural methods should be utilized and pipe sewer networks reduced to a minimum. For medium-density residential areas, he recommended using the traditional separate sewer networks, although he suggested that infiltration could be used to alleviate the capacity of pipe sewers. For city centres, Melanen (1980) recommended using combined sewer systems due to the occasionally poor runoff quality.

It was not until the 21st century that public interest in more sustainable urban drainage systems started to gain increasing attention in Finland. The academic community had been arguing that the issue needed to be studied in more depth and the former Helsinki University of Technology had recently established a new programme to monitor urban runoff (e.g. Vakkilainen et al., 2005). This thesis presents for the first time the findings from the study programme from the years 2001 to 2006. Since then, new monitoring programmes have been established (e.g. Valtanen et al., 2009; Sänkiaho and Sillanpää, 2012), the findings of which will further increase our knowledge about urban runoff management in the near future. During the last decade, several cities in Finland developed their own stormwater programmes. The aim was to achieve more integrated and sustainable urban runoff management, including on-site infiltration, detention and pollution mitigation, in addition to promoting the more conventional approach, which focuses on the safe conveyance of peak flow rates. However, a lack of sufficient data has so far delayed the further development of design criteria for local conditions (e.g. Sänkiaho et al., 2011). The inclusion of the sustainable urban runoff management approach in the national stormwater manual by the Association of Finnish Local and Regional Authorities (2012) can be considered a promising step forward in the direction of renewing urban runoff management at the national level.

1.2 Urban runoff generation

1.2.1 Impacts of urbanization on catchment hydrology

Urbanization causes drastic changes in natural catchment characteristics, notably by increasing the amount of impervious surface area and by creating a need for efficient drainage systems. The main hydrological impacts include increases in total and direct runoff volumes, higher peak flows associated with shorter times of concentration and potentially a lower baseflow (e.g. Leopold, 1968; Rao and Delleur, 1974; Ferguson and Suckling, 1990; Schueler, 1994; Arnold and Gibbons, 1996; Roesner, 1999; Liscum, 2001; Cheng and Wang, 2002; Shuster et al., 2005; Dougherty et al., 2006a; Line and White, 2007; Dietz and Clausen, 2008; Hur et al., 2008; Bedan and Clausen, 2009; Schueler et al., 2009; Burns et al., 2012). As a consequence, urban catchments and areas downstream experience flooding and erosion problems. In addition to the hydrologic alterations, other symptoms of urbanization that can be observed in urban streams include altered stream geomorphology and channel manipulation, changes in water chemistry, increased water temperature and light, reduced habitat complexity, loss of riparian habitats and increased movement barriers (Wegner et al., 2009). The impacts of urbanization on the hydrologic cycle are often generalized as a straightforward relationship between imperviousness and runoff (e.g. Shuster et al., 2005); however, examples can be found in the existing literature where the impacts of urbanization have been masked by other factors affecting runoff generation, such as weather conditions (Ferguson and Sucklin, 1990), season (Dougherty et al., 2006b), temporary changes in catchment conditions resulting from construction works (Line et al., 2002) and natural catchment features (Burns et al., 2005).

Cheng et al. (2010) describe three general approaches for identifying the effects of urbanization on catchment hydrology: i) upstream-downstream in the same watershed, ii) before and after the changes in the same watershed, and iii) paired or several watersheds. Most process-level studies have quantified the impacts of urbanization on runoff based on suburban catchments, where impervious surfaces cover a large percentage of the total catchment area; for this reason, additional studies are needed that compare the changes occurring in undeveloped catchments to the changes occurring in catchments with moderate suburban development (Burns et al., 2005). Shuster et al. (2005) noted that there seems to be a lack of controlled experiments that track the hydrological effects of an incremental increase in impervious surfaces for various land use types. Similarly, Dietz and Clausen (2008) argue that much of the recent research has focused on comparing different catchments at discrete points in time, while it would be easier to detect causality if increases in runoff during development were documented. In fact, many studies concerning urbanizing catchments only consider watersheds with areas ranging from several kilometres to several hundred square kilometres over a number of decades to reveal the changes that occur in runoff volumes, peak flows or pollutant export (e.g. Ferguson and Suckling, 1990; Changnon et al., 1996; Nelson and Booth, 2002; Beighley and Moglen, 2002; Dougherty, 2004; Dougherty et al., 2006a, 2006b) and not the exact construction process and related hydrological changes that occur in small urban catchments during development.

1.2.2 Role of impervious surfaces during rainfall events

Imperviousness is one of the most important characteristics describing the extent of urbanization and the severity of its impacts on the runoff process (Leopold, 1968; Schueler, 1994; Arnold and Gibbons, 1996; Booth and Jackson, 1997; Lee and Heaney, 2003). Often it is expressed as a percentage of *total impervious area* (TIA) of the catchment, including all impervious surfaces, such as roads, roofs and parking areas. However, it has been shown that runoff response is highly variable depending on the hydraulic connection of the surfaces to the drainage system (Shuster et al., 2008). The urban catchment, in fact, can be divided into three different surface types (Boyd et al., 1993, 1994): impervious surfaces with a direct connection to the sewer systems, other impervious areas that are not directly connected to the sewer systems and pervious surfaces consisting of lawns, gardens and parks. Shuster et al. (2008) define the *effective impervious area* (EIA) as impervious surfaces that are directly (hydraulically) connected to the drainage system, which are the main contributor to surface runoff during most events. The EIA is typically assumed to be a fixed percentage of the TIA (Brabec et al., 2002; Shuster et al., 2005; Said and Downing, 2010). Melanen and Laukkanen (1981), for instance, studied rainfall-runoff relationships in seven urban catchments in Finland and concluded that the EIA comprised about 50 to 80% of the TIA in residential catchments and 80 to 90% in the city centres. Thus, the area generating direct runoff during summer storms is often significantly smaller than the total amount of impervious surfaces within the catchment. Similar results have been reported in other countries with different climatic conditions (e.g. Radojković and Maksimović, 1986; Becciu and Paoletti, 1997; Chiew and McMahon, 1999). Often, pervious surfaces are not considered active for rain events of less than 5 to 10 mm, but in many catchments pervious areas may contribute pollutants and even the majority of runoff when the amount of rainfall exceeds approximately 20 mm (Burton and Pitt, 2002).

Sheeder et al. (2002) and Said and Downing (2010) argue that the combined impact of urban surfaces and the storm event magnitude on the urban runoff response to rainfall has not received as much attention as it should because of their important role as controlling factors. Information about the variable runoff-contributing area can aid in understanding the impact of urbanization on stormwater runoff and improve hydrologic modelling (Said and Downing, 2010). The effective impervious areas are considered the primary contributing areas for small- and medium-sized storms, which are the main points of concern in terms of water quality and pollution from urban areas, whereas the total area may be critical for large storms (Pitt, 1987; Novotny, 2003; Lee and Heaney, 2003). Lee and Heaney (2003, p. 426), for example, conclude that '*it is necessary to figure out the lower threshold of storms that initiate runoff from other than directly connected impervious areas and proportional contributions of urban runoff from different surface components to prorate the cost of the storm water system among major and minor storms, and water quality protection*'.

1.2.3 Runoff coefficient

Whether runoff is generated from pervious or impervious surfaces, some losses (or abstractions) always occur throughout the event. The losses, which need to be satisfied before surface runoff flows over-land, are called *initial losses*; they include surface wetting, depression storage, interception and evaporation (Field and Sullivan, 2003). Initial losses, together with continuous losses such as infiltration, need to be accurately estimated to calculate the runoff volumes. In event-scale urban runoff modelling, interception and evaporation are considered small in comparison with depression storage and infiltration losses and, thus, they are often ignored (Becciu and Paoletti, 1997). For long-term water balance, however, evaporation is an important factor and it has a strong influence on the infiltration capacity of soil (e.g. Arnell, 1982; Mitchell et al., 2001). A recent study in Vancouver, Canada, also shows that the interception by urban trees can be much larger than previously assumed (Asadian and Weiler, 2009). Additionally, although these losses may comprise only a small share of large events, they constitute a significant portion of the overall precipitation during small, frequent events (Field and Sullivan, 2003).

The conventional sewer design is based on the assumption that the majority of runoff in urban catchments is generated on impervious surfaces combined with some runoff from pervious areas. The widely utilized rational method uses the dimensionless runoff coefficient to express the amount of rainfall that is converted into direct runoff after losses. In its common form, it is as follows:

$$Q = CiA, \qquad (1)$$

where Q is the peak discharge determined by multiplying the design rainfall intensity, i, by the total drainage area, A, and the runoff coefficient, C. The duration of the design rainfall intensity corresponds to the catchment time of concentration, which is the travel time needed for water to reach the catchment outlet from the most remote hydraulic point within the catchment (Westphal, 2001). The runoff coefficient is assumed to be directly proportional to the total imperviousness of the catchment, except at low levels of imperviousness, where soil type and slope become the dominant factors (Schueler, 1994).

Despite the apparent simplicity of the rational method, its original three versions, proposed by Mulvaney (1850) in Ireland, Kuichling (1889) in the United States and Lloyd-Davies (1906) in Great Britain, have some fundamental differences in their underlying assumptions about the source areas of runoff generation (Lee and Heaney, 2003). Mulvaney worked in agricultural areas and considered runoff from the standpoint of the total catchment area. In contrast, Kuichling and Lloyd-Davies worked with rainfall-runoff relationships in urban areas, and the original Lloyd-Davies formula actually applies more directly to runoff-producing surfaces and not so much to runoff from the total catchment area. Thus, the Lloyd-Davies formula takes the form of $Q=iA_{DCIA}$, where A_{DCIA} is the amount of directly connected impervious surfaces. Lee and Heaney (2003) suggested that the Lloyd-Davies formula, by using a more accurate estimate for impervious surfaces, could work better for evaluating urban drainage systems than the traditional rational method with a runoff coefficient.

In addition to the runoff coefficient C, a *volumetric runoff coefficient* (C_{VOL}) is used particularly in the determination of runoff volumes for water quality design practices (e.g. Roberts, 2001) although a clear distinction between the different coefficients is not always given in the published literature. Several authors (e.g. Pitt, 1999; Roesner, 1999; Novotny, 2003) have discussed the importance of small- and medium-sized storms in stormwater runoff quality management. For these events, most of the pervious areas are not hydraulically active and a larger fraction of rainfall is extracted by rainfall losses compared with larger storms. Thus, the runoff coefficient should be smaller (Pitt, 1987; Roesner, 1999). Melanen and Laukkanen (1981) also supported a similar idea based on monitoring data from Finnish urban catchments although they did not particularly discuss water quality management. They suggested the following volumetric runoff coefficients for estimating average runoff volumes for rainfall events: 0.05-0.20 for low-density residential areas (TIA 10-30%), 0.20-0.40 for medium-/high-density residential areas (TIA 30-50%), and 0.40-0.80 for city centre-commercial areas (TIA 50-90%). It has been estimated that the use of constant, large runoff coefficients for all storm events results in runoff prediction errors greater than 25% (Pitt, 1987). Lee and Heaney (2003) even observed differences greater than 260% in peak flow rates, depending on the choice of runoff coefficient/imperviousness in the flow modelling.

1.2.4 Urban runoff generation under wintry conditions

In Finland, approximately 40% of the annual precipitation falls in the form of snow (Kuusisto, 1986a). The local climate has a profound impact on seasonal runoff patterns, particularly in rural areas; for example, in agricultural catchments in Finland, often more than 90% of annual runoff is produced outside the growing season (Vakkilainen et al., 2010). Also in urban areas, the runoff process is complicated by freezing temperatures and the lengthy accumulation of snow within the catchment. However, the lack of studies focusing on urban runoff generation and snow properties under cold conditions has been recognized by several authors (e.g. Semádeni-Davies and Bengtsson, 1999; Bengtsson and Semádeni-Davies, 2000; Thorolfsson, 2000; Matheussen, 2004; Ho and Valeo, 2005). One reason for ignoring the cold conditions is that researchers commonly focus on high intensity rainfall events as the key contributor to flooding in urban areas (Ho and Valeo, 2005). Nevertheless, Thorolfsson and Brandt (1996) observed that owing to decreased evaporation, the runoff volume was twice as high during the winter season (November-April) as during the summer months (May-October) in a 20 ha residential catchment (30% impervious) in Trondheim, Norway, despite the fact that there was an equal amount of precipitation during both seasons. They also discovered that the maximum runoff volumes occurred during rain-on-snow events during winter, although the highest peak flows occurred during summer storms. Semádeni-Davies and Bengtsson (1999) examined the monthly water balance in the city of Luleå, Sweden and discovered a bimodal runoff pattern with high runoff volumes during spring and autumn: these seasons were important periods for groundwater recharge, even though frozen soil can limit infiltration. The seasonal runoff conditions affect, for example, the design and performance of stormwater management structures in cold climate conditions (Semádeni-Davies, 1999b; Bengtsson and Semádeni-Davies, 2000; Thorolfsson, 2000; Oberts, 2003; Semádeni-Davies and Titus, 2003; Westerlund, 2007). The limited availability of urban snow data, such as the snow water equivalent (SWE), constricts the testing and makes it difficult to improve the urban hydrological models (Semádeni-Davies, 1999b, 2000; Matheussen, 2004; Ho and Valeo, 2005).

The areal heterogeneity and variability of the snow cover affect melt rates and runoff generation in urban areas (Semádeni-Davies, 1999b, 2000) in addition to the reduced wintertime evapotranspiration (Thorolfsson, 2000). Snow conditions in urban areas are strongly influenced by the handling of snow: snow is either removed from streets and parking lots, stored along roadsides and in separate snow deposits, or left untouched (e.g. Semádeni-Davies and Bengtsson, 1999; Semádeni-Davies, 1999a;

Matheussen, 2004; Valeo and Ho, 2004). Laiho (1983) concluded that the transport of snow outside the catchment boundaries reduced event runoff volumes in two city centres in Finland during snowmelt. Additionally, urbanization affects radiation fluxes, especially because of buildings, impervious surfaces and the lower albedos of urban snow, which results in increased melt rates, particularly at the beginning of the spring snowmelt (Buttle and Xu, 1988; Bengtsson and Westerström, 1992; Semádeni-Davies and Bengtsson, 1998; Semádeni-Davies et al., 2001; Ho and Valeo, 2005). For example, snow on roofs melts quickly due to the free exposure to solar radiation and the heat flux from the roofs (Buttle and Xu, 1988). As a consequence, most of the impervious surfaces are actually snow free at the onset of the spring snowmelt; thus, the hydrologically active area for urban snowmelt is not the same as for summer rainfall.

Westerström (1984) monitored snowmelt runoff for one spring season at a small residential catchment (30% impervious) in Luleå, Sweden. At the beginning of the melt, 68% of the total catchment area had a snow cover that corresponded well with the extent of pervious surfaces. The proportion of the area contributing to runoff increased from 48% at the onset of the spring snowmelt to 85% towards the end of the melt period. Thus, the hydrologically active area exceeded the extent of impervious surfaces during the early melt period and the area of pervious surfaces during the later spring melt. These results are supported by equal overland flow rates observed by Bengtsson and Westerström (1992) for grassed, gravel and asphalt surfaces during the later stages of snowmelt in Luleå. Similar findings about seasonal increases in the runoff-contributing area in urban areas during winter have been observed in Canada (Taylor, 1977, 1982; Buttle and Xu, 1988; Ho and Valeo, 2005), Sweden (Bengtsson and Westerström, 1992) and Norway (Thorolfsson and Brandt, 1996). Because of these changes, the common assumption that runoff in urban areas can simply be predicted as functions of the extent of the impervious surfaces can be misleading in cold climate conditions (Taylor, 1977).

The seasonal differences in runoff intensities and in the runoff-contributing area also affect the duration of the runoff events: runoff events that last less than an hour are rare (Bengtsson, 1984). For example, in a 320 ha urban catchment with a mixed land use in Växjö, Sweden, the runoff induced by winter and spring rain events lasted for as long as 12 hours, whereas the runoff induced by the summer storms lasted for only two to three hours (Semádeni-Davies and Titus, 2003). Despite the low intensity of the snowmelt, the long duration of the snowmelt and the large area of contributing surfaces must be considered when designing, for example, retention/detention storage structures in urban catchments (Bengtsson and Westerström, 1992).

Although it is well known that there are large seasonal variations in the hydrology of urban catchments, conflicting results have been reported regarding the type and extent of changes caused by urbanization on runoff response under wintry conditions. Several studies deal with the hydrological impact of urbanization in the Kawarta Heights catchment in Peterborough, Ontario, Canada (Taylor 1977, 1982; Buttle and Xu, 1988; Buttle, 1990). Taylor (1977) compared seasonal variations in runoff behaviour between rural (1.14 km^2) and urban catchments (0.70 km^2, TIA 38%, including also a construction site). According to his results, the contrast between the two catchments was the largest during the springtime in terms of both direct runoff volumes and peak flow rates. Taylor (1977) concluded that urban development appeared to have a larger impact on runoff during snowmelt than during summer and autumn rainfall conditions. Additionally, Buttle and Xu (1988) concluded that suburban development increased direct runoff during snowmelt and rain-on-snow events because of the lowered infiltration capacity of impervious surfaces, the disturbed soil surfaces at construction sites and some urban lawns (Buttle and Xu, 1988). Later on, however, Buttle (1990) reported that significant increases in event direct runoff volumes or peak flow rates could not be observed based on the data for individual snowmelt events from 14 years of suburban development. As a result, Buttle (1990) noted that urbanization does not cause such pronounced changes during cold period runoff events as it does during summer rainfall events, although urbanization clearly affected, for example, the runoff response during rain-on-snow events and increased the number of runoff events during winter. In a more recent modelling study conducted in Trondheim, Norway, Matheussen (2004) concluded that the most distinct change in urban runoff generation during the cold period was the result of earlier snowmelt and the enhanced melt rates during the early phase of the spring thaw.

1.3 Impacts of urbanization on runoff quality

1.3.1 Urban runoff pollution and pollutant sources

Urban runoff constitutes a diffuse pollution source, as do agricultural and silvicultural runoff. According to Campbell et al. (2004), urban runoff pollution originates from land use activities, is intermittent and occurs mostly during meteorological events, but the discharge itself is often observed through a well-defined outlet or at an overflow point. Thus, urban runoff pollution has features of both non-point and point source pollution, but the pollution generation process is by nature a stochastic phenomenon and is not analogous to the most common example of urban point source pollution: municipal wastewater.

The link between an increasing TIA and pollutant loads has been reported many times (Sonzogni et al., 1980; Melanen, 1981; Hatt et al., 2004; Wollheim et al., 2005; Dougherty et al., 2006a; Dietz and Clausen, 2008; Bedan and Clausen, 2009). The sources of urban pollutants are numerous; they include wet and dry atmospheric deposition, litter, animal faeces, fallen leaves and grass residues, soil erosion, road traffic, fertilizers, pesticides and illicit wastewater connections, combined with more winter-specific pollutant sources, such as de-icing chemicals and the salt and sand used for traffic safety (Novotny and Chesters, 1981; Malmqvist, 1983; Marsalek et al., 2003; Burton and Pitt, 2002). Many pollution sources are intensified during the cold period, such as emissions resulting from heating and the less efficient operation of motor vehicles, tyre wear emissions, the deterioration of road surfaces as a result of maintenance work, the ploughing of snow and the use of studded tyres (Viklander, 1997; Bäckström et al., 2003; Hallberg et al., 2007). The most common pollutants in urban runoff include total suspended solids (TSS), nutrients (P and N), heavy metals (Cu, Pb, Zn) and faecal bacteria (e.g. Roesner et al., 2001). Runoff quality can also be classified based on land use type. Melanen (1980), for instance, classified two land use groups for Finnish catchments: suburban residential and other areas (city centres, traffic areas and industrial areas), of which the latter had poorer water quality.

Harremoës (1988) divides urban pollution problems into two groups, *acute* and *cumulative*, based on their type of impact. Acute effects are caused by high pollutant loads or concentrations in the receiving water. Examples of acute effects include high levels of bacteria in the vicinity of bathing beaches after rainfall or oxygen depletion followed by combined sewer overflows. Acute contamination is always short-term in nature. Nevertheless, the contamination may have long-term effects, e.g. the amount of time it takes a fish population to recover after acute oxygen depletion. Cumulative effects are caused by a long-term, gradual build-up of pollutants in the receiving water, such as the accumulation of nutrients in lakes or metals in the bottom sediments. The effects are often realized when a certain threshold concentration is exceeded. Since the exposure time for acute effects can be only a few hours, cumulative effects build up over the course of months (nutrients) or even decades (metals). The associated timescale for receiving water impacts may also depend on the type of receiving water, ranging from a matter of hours for small ponds and streams to weeks, seasons or even years for lakes and bays (WEF-ASCE, 1998).

Due to the unique characteristics of urban water quality problems, different approaches are required for their assessment. Acute effects have to be evaluated based on the statistics for individual events (Harremoës, 1988) by utilizing probabilistic distributions of concentrations or loads, e.g. for assessing water quality criteria violations (Marsalek, 1991). Even though urban runoff can cause acute impacts on receiving waters, the typical levels of conservative contaminants are usually well below the acute toxicity levels and the receiving water responds to the pollutant mass flux rather than to the varying concentrations of the contaminants during a single event (Novotny, 1992). In most cases, therefore, it is more important to know the total pollutant load of a runoff event than to examine the individual concentrations within each particular event (Marsalek, 1991; Novotny, 1992).

Several methods exist for calculating urban diffuse pollution loads. The methods can be divided into three categories: i) transfer of runoff quality data to unmonitored sites, ii) runoff monitoring, and iii) runoff quality simulation (Marsalek, 1991). The choice of method depends on the type of pollution problem and the available resources. Reliable monitoring requires extensive field measurements: in a typical case, the flow is measured continuously and water quality is sampled for a number of events (Marsalek, 1990, 1991). The measurements can also be used for model calibration; however, the complexity and difficulties with using physically based formulas for assessing urban water quality have led to a preference for statistical approaches (Van Buren et al., 1997).

A unit pollutant load (e.g. $kg/km^2/a$) expresses the pollutant mass generated from a unit area during a certain time period (Novotny, 1992), also called *pollutant export rate* or *yield*. For Finnish urban catchments, Melanen (1981) reported a wide range of annual values: 10000-100000 $kg/km^2/a$ for suspended solids (SS), 10000-50000 $kg/km^2/a$ for chemical oxygen demand (COD_{Cr}), 20-200 $kg/km^2/a$ for total phosphorus (TP), and 200-1000 $kg/km^2/a$ for total nitrogen (TN). Large variations in export rates are caused by factors such as seasonal and meteorological variations, geographical and land cover differences, heterogeneity in soil characteristics and the reliability of measurements (Novotny, 1992). If the uncertainties related to unit loads are recognised, they provide an easy and simple tool for planning-level pollution analysis. However, it is difficult to assess the errors in load calculations (Marsalek, 1991). Only a few published export rates include all flow phases, such as snowmelt, which can have major effects on receiving waters (Burton and Pitt, 2002). Shaver et al. (2007) proposed that by establishing ranges of unit loads, some measure of uncertainty in the estimates can be achieved. This includes estimating the minimum and maximum values together with a mean or median for each pollutant in order to evaluate how the observed range affects conclusions based on unit load calculations.

The unit loads were used to compare different sites, especially in the investigations done in the 1960s and 1970s (WEF-ASCE, 1998). In more recent studies (e.g. U.S. EPA, 1983; Brezonik and Stadelmann, 2002; Westerlund et al., 2003; McLeod et al., 2006; Hallberg et al., 2007; Liu, 2011), water quality is often presented by means of event mean concentrations (EMCs). The lognormality assumption regarding EMCs has generally been accepted, at least between the 5th and 95th percentiles (Maestre et al., 2005). Site mean concentration (SMC) is a representative measure of the distribution of EMCs for a particular pollutant and catchment (Mourad et al., 2005). There is substantial guidance on experimental design to help determine the number of samples needed for water quality characterization (e.g. Burton and Pitt, 2002). Usually, several dozen events are required to estimate the representative SMC for one site depending on the pollutant; for example, Shuster et al. (2008) referred to an Australian study (Francey et al., 2004) in which sample sizes of 50, 30 and 25 events were required for the TSS, TP and TN, respectively, in order to determine the SMC with a reasonable amount of confidence (so that the 95% confidence interval is no greater than 50% of the mean).

At ungauged sites, water quality assessments can be made with the help of runoff quality databases if updated values from appropriate catchment/land use types are available. It should be noted, however, that land-use-based models relying on constant concentrations and runoff coefficient/imperviousness estimates can cause great uncertainties in the estimation of pollutant mass loads (Park et al., 2009). A common example of an urban water quality database is one compiled by the United States EPA in 1983 as part of the NURP study, during which time 28 urban sites were monitored throughout the US (as cited in Marsalek, 1990). The data from different land use types were combined, because no significant statistical difference between event mean concentrations (EMCs) was found between the three studied land use types: residential, mixed and commercial (Table 1). This, however, is not a common outcome in all studies. For example, in a study conducted in Minnesota based on 21 sites, Brezonik and Stadelmann (2002) observed that EMCs were better explained by land use groupings than by pooling all of the data together. In Finland, seven urban catchments were studied during the late 1970s as part of the Finnish Urban Storm Water Project (e.g. Melanen, 1980, 1981) and statistically significant differences were observed in the EMCs from suburban residential and city centre areas. Additionally, Melanen (1980) presented separate values for rainfall and snowmelt-induced runoff events (Table 1). The NURP study still remains an important reference for stormwater management planning purposes in North America, even though the study was conducted between 1978 and 1983. Studies with more recent monitoring data from the US have suggested lower median EMC values for several water quality constituents (Smullen and Cave, 2003; Park et al., 2009). Yet, trends in EMCs are not observed in all studies or for all pollutants, except for lead (Pitt and Maestre, 2005). Like the NURP study, the Finnish Urban Storm Water Project is still an important reference for stormwater research in Finland.

Table 1. Event mean concentrations (EMCs) for select water quality parameters in the US and Finland. If the two studies are compared, the average values without parenthesis should be used.

	NURP study[1]		Finnish Urban Storm Water Project[2]			
EMC (mg/l)	Median urban site	90th percentile urban site	Suburban residential	City centre, commercial	Traffic	Industrial
TSS	141-224 (100)	424-671 (300)	90-200 (50-150)[3]	200-250 (300-700)	250-350 (250-350)	300-500 (300-500)
COD[1], COD_{Cr}[2]	73-92 (65)	157-198 (140)	80-120 (70-110)	120-150 (150-300)	150-200 (200-300)	100-120 (100-300)
TP	0.37-0.47 (0.33)	0.78-0.99 (0.70)	0.2-0.3 (0.2-0.4)	0.3-0.4 (0.4-1.2)	0.3-0.4 (0.3-0.5)	0.4-0.5 (0.4-0.6)
TN[4]	2.44-3.08 (2.18)	5.65-7.14 (5.05)	1.3-1.9 (3-4)	1.5-2.2 (3-6)	1.5-2.5 (3-5)	1.5-2.2 (3-5)

1) Mean EMC values recommended for pollutant load estimations to receiving waters, the median EMC values in parenthesis are recommended for planning purposes as the best description of the quality of urban runoff (U.S. EPA, 1983; as cited in Novotny, 1992)

2) Mean value recommended for urban runoff calculations (Melanen, 1980)

3) Mean values for snowmelt runoff in parenthesis (Melanen, 1980)

4) TN shown as a sum of TKN + NO_{2+3}-N for the NURP study

1.3.2 Construction sites

Construction sites have been considered the type of urban land use with the highest pollution potential, especially due to the erosion of exposed soil surfaces (Wolman and Schick, 1967; Sonzogni et al., 1980; Harbor, 1999; Burton and Pitt, 2002; Hur et al., 2008; Maniquiz et al., 2009). If receiving waters are severely impacted during the construction phase, even an extensive, post-construction stormwater management programme cannot meet its goals (Shaver et al., 2007). In the US, developing areas can have a soil erosion rate ranging from 2 to 40,000 times greater than in preconstruction conditions (Harbor, 1999), and the sediment yields from construction sites are typically ten to twenty times greater compared with agricultural areas and 1000 to 2000 times greater than those from forested areas (U.S. EPA, 2000). In Exeter, England, Walling (1973) observed that building activity increased sediment concentrations fivefold and sediment loads five- to tenfold in comparison to the pre-development land used as permanent pasture. In addition to sediment, the US EPA (2000) lists typical pollutants discharged from construction sites as solid and sanitary wastes, nutrients from fertilizers, pesticides, oil and grease, concrete truck washout, construction chemicals and other construction debris.

Information about the magnitude of the pollutant loads during the actual construction period is largely based on research conducted in the US in the 1960s and 1970s; more recent studies are scarce, especially outside the United States. Oftentimes, construction practices occupy only a small fraction of the catchment under observation, and the reported unit loads decline with increasing catchment area due to a dilution effect caused by runoff from areas without construction activities (Wolman and Schick, 1967). For suspended sediments, annual loads ranging from 6500 to 30000 kg/ha/a in Wisconsin (Daniel et al., 1979; Sonzogni et al., 1980) and North Carolina (Line et al., 2002) have been observed. Ellis (1996) reported a median sediment loading rate of 67415 kg/ha/a with a typical range of 22000 to 84,000 kg/ha/a, whereas a higher range (45,000-450,000 kg/ha/a) was given by Burton and Pitt (2002) for construction sites in most locations in the US. Wolman and Schick (1967) even reported a 550,000 kg/ha/a annual sediment yield for a small construction site in Baltimore, Maryland. For nutrients, annual loads of 8-23 kg/ha/a and 15-63 kg/ha/a have been estimated for total phosphorus and total nitrogen, respectively (Daniel et al., 1979; Sonzogni et al., 1980). More recently, Line et al. (2002) reported annual loads of 1.3-3.0 kg/ha/a for phosphorus and 8.3-36.3 kg/ha/a for nitrogen. Clearly the export rates reported for developing urban areas vary widely; for example, the three construction sites studied by Daniel et al. (1979) shared similar land uses, slopes, storm intensities and ground cover, but large differences in annual loads between the sites were observed.

In the UK, Ellis and Mitchell (2006) classified the construction industry as an important source of sediment, a documented source of nitrogen and a possible source of phosphorus and metals. However, previous studies on construction sites focus mainly on sediment export, whereas other pollutants, such as nutrients and metals, have not been studied as widely (Phillips et al., 2003). Additionally, studies on the importance of construction activities as a source of nutrients, especially phosphorus, have yielded contradictory results (e.g. Cowen and Lee, 1976; Line et al., 2002; Ellis and Mitchell, 2006). Waller and Hart (1986), for instance, did not consider construction sediment a significant source of nutrients. Cowen and Lee (1976), in contrast, observed the highest range of particulate P concentrations (0.365 to 2.850 mg/l) at construction sites in Wisconsin as opposed to other urban land use types (residential, institutional and commercial), and Sonzogni et al. (1980) observed that urban construction sites yielded more phosphorus than agricultural, forested and urban land use types. Line et al. (2002) reported finding higher TP concentrations in a residential area rather than a construction site in North Carolina. However, the TP export from the construction site exceeded that from the residential area during the initial earth-moving works, despite the lower average concentrations.

Factors affecting pollution generation from a developing area include (e.g. Overton and Meadows, 1976; Novotny and Chesters, 1981; Burton and Pitt, 2002) local rainfall characteristics, soil conditions (the removal of vegetation, soil erodability and the extent and duration of soil exposure), catchment topography (slope and distance of the construction works from watercourses) and management conditions (the type of drainage systems and ongoing construction activities). According to Overton and Meadows (1976), a construction project can be divided into two phases. The first phase, site preparation, involves clearing and grubbing a new site, rock blasting, the possible demolition of existing structures, excavation work, grading, the compaction of the foundation and the transportation of excess materials. The second phase involves constructing the desired end-product with a variety of building materials and machinery. Pollutants generated during the process can be linked to the ongoing construction activities. During the site preparation phase, the existing soil surfaces are disturbed, leading to soil erosion and high sediment loads. Examples of pollutants generated during the second construction phase include oils and lubricants from machinery, metals and inorganic substances leached or corroded from building materials, and organic substances originating with litter and food waste.

Topsoil disturbance may also lead to an increase in more soluble pollutants, such as nitrate, which can easily leach into groundwater (Wakida and Lerner, 2002). Wakida and Lerner (2002) estimated that the average nitrate leaching from soil is 65 kg N ha^{-1} based on soil samples for one year taken from three different construction sites in Nottingham, England. They also concluded that the potential nitrate leaching is affected by the high variability in infiltration rates and soil density, which is caused by high soil disturbance. The most important factors affecting nitrogen loss at a construction area are the predevelopment land use, the remaining quantity of total nitrogen after topsoil stripping and the seasonal timing of the construction work (Wakida and Lerner, 2005).

It is not often mentioned that construction activities, in fact, share similarities with activities typical for both rural and urban land uses. During the initial period of construction, the clear-cutting of construction sites may include a total removal of native vegetation, well beyond the extent of normal silvicultural operations. Construction can even alter the landscape to a greater degree than intensive agriculture; for example, subsoil is often exposed down to the C-horizon (Wolman, 1975). Erosion and sedimentation problems are related to the time at which the greatest soil disturbing activities occurred. Early results from the US in the 1960s showed significant increases in sediment yields from construction sites into the receiving waters during the construction period, followed by a decrease in the yield upon completion of the development (Wolman, 1975). Thus, the erosion impacts caused by any specific construction site are relatively short term in nature (Burton and Pitt, 2002). Flooding problems, however, appear during later stages or after the completion of the project due to newly constructed impervious surfaces (Walesh, 1989). Post-construction erosion problems are often associated with high flow rates and channel enlargement (Leopold, 1968), and on-site erosion may be minimal due to the paving of surfaces and the presence of mature vegetation on pervious surfaces. According to Novotny (2003), an area can be considered fully developed and established one year after the completion of the development.

Even though the ongoing construction activities may have their own distinct pollution features, the majority of researchers have not discussed their results according to different construction phases. One example can be found in a study by Line et al. (2002), who studied water quality and pollutant export rates in a small, 4-ha construction site in North Carolina. They divided their monitoring results into two phases: the first phase included earth-moving works, while the second phase included the building construction and the installation of roads and a storm drain infrastructure. Mean EMCs and the annual mass TSS and TP loads decreased after the first period of construction, which was attributed to the stabilization of soil surfaces. Total nitrogen EMCs and mass loads, however, increased during the second construction period and were also the highest of all the studied land use types, including residential and industrial areas, a golf course, a pasture and a wooded area. Line et al. (2002) attributed the high nitrogen export to a combination of enriched topsoil, mulch, fertilizer, pet waste and immature vegetation in the drainage area. The two construction phases also had quite different rainfall-runoff ratios: runoff comprised 52% of rainfall during the first construction period, including the rough grading phase, and increased to 70% during the second construction period. The higher runoff ratio was explained by the lack of established vegetation and the compaction of soil surfaces by heavy machinery. Although the construction site did not have as high an impervious coverage as the other urban land use types in the study, it still produced the highest runoff ratio. Line and White (2007) completed the analysis by reporting the results for the entire 5.6 years of monitoring the site, including a period of 3.5 years following the construction period. They compared the pollutant loads of the finished development to a nearby undeveloped site of forest and cropland. The annual pollutant loads after the development were 95%, 74% and 69% larger than at the undeveloped site for TSS, TP and TN, respectively. The ratio of runoff to rainfall was 0.55 at the end of the monitoring period. The corresponding ratio of the undeveloped site was only 0.21.

Pollutant concentrations and loads also depend on the characteristics of individual rainfall-runoff events. Daniel et al. (1979) found that sediment yield was best explained by the total runoff volume. At three construction sites in Wisconsin, the concentrations of suspended solids ranged from a few mg/l during small events to 60,000 mg/l during the events responsible for the major loads, with 15,000-20,000 mg/l being common concentration range for moderate events (Daniel et al., 1979). Walling (1974) concluded that sediment concentrations and loads were best explained by either the kinetic energy or the maximum intensity of rainfall. More recently in the US, a positive correlation between mean TSS concentrations and event rainfall was reported by Schueler (2000) and between event rainfall intensity and TSS concentrations by Nelson (1996; as cited in Burton and Pitt, 2002). It is also worth mentioning that at construction sites studied by Daniel et al. (1979), the concentrations of the different pollutants did not behave similarly during the storm events. The concentrations of suspended solids, total phosphorus and organic nitrogen followed the changes in flow rates. However, the concentrations of dissolved nitrates and nitrites were inversely proportional to flow during runoff events — concentrations of 1.0 mg/l were the most common, but maximum values of 3.0 mg/l were observed between events.

1.3.3 Seasonal variations in urban runoff quality

Seasonal information about urban runoff quality is needed not only for general urban stormwater management planning, but also for those designing and operating stormwater management structures (Semádeni-Davies and Titus, 2003) and for the development of urban pollution models (Bartošová and Novotny, 1999). In cold climate, pollutants accumulate and are stored in snowpacks for long periods of time, resulting in a higher pollutant load during snowmelt rather than rainfall events (Bengtsson and Semádeni-Davies, 2000). For example, large nutrient loadings in spring are available for uptake when the growing season commences, potentially leading to eutrophication (Brezonik and Stadelmann, 2002). According to Oberts (1982; as cited in Oberts, 1990), in a typical urban site with mixed land use, approximately 65% of the annual loads of solids, COD and nutrients may occur during the winter snowmelt and early spring rainfall events. In Toronto, Ontario, a three-month cold runoff period accounted for 67 to 78% of the annual total loads for solids, phosphorus, ammonium nitrogen and COD, even though, according to Pitt and McLean (1986), the warm period generated nearly 50% of the annual runoff (as cited in Burton and Pitt, 2002). For Finnish urban catchments, Melanen (1982) reported smaller percentages: snowmelt accounted for 5-40% of annual TSS, TP and COD loads and 23-56% of the annual TN load.

Several studies investigate seasonal urban runoff quality on the scale of a road or street (e.g. Sansalone and Buchberger, 1997; Bäckström et al., 2003; Westerlund et al., 2003; Westerlund and Viklander, 2006; Hallberg et al., 2007; Helmreich et al., 2010), whereas Semádeni-Davies and Titus (2003) call attention to the lack of catchment-scale studies of seasonal water quality in cold climates. At street or highway sites, pollutant concentrations during snowmelt often exceed those observed during summer rainfall events. For example, Westerlund et al. (2003) and Westerlund and Viklander (2006) found higher concentrations of TSS and particles during snowmelt events than they did during rainfall-runoff events for road runoff in Luleå, Sweden, and Hallberg et al. (2007) observed elevated TSS EMCs in snowmelt at highway sites in Stockholm, Sweden. The number of events was rather low in both studies: Hallberg et al. (2007) had four warm period events and five cold period events and Westerlund et al. (2003) had eight warm period events and nine cold period events. However, the observed difference in the latter study was statistically significant at a 95% level of confidence.

At a catchment scale, more varied results have been reported. Brezonik and Stadelmann (2002) found significant seasonal differences in EMCs based on a review of several studies in Minnesota. They concluded that, for example, the median EMCs for TP and TN were higher in snowmelt than in rainfall runoff at most urban sites. Semádeni-Davies and Titus (2003) compared event TSS concentrations from a 320 ha catchment of industrial and residential land uses in Växjö, Sweden and found marginally higher TSS concentrations for snowmelt events. In Finland, city centres and commercial areas yielded higher TSS concentrations for snowmelt than for warm period rainfall events, whereas in suburban residential areas snowmelt had higher average concentrations only for TN (Table 1) (Melanen, 1980). However, Melanen (1981) noted that the results based on snowmelt samples should be interpreted with caution owing to the low number of sampled events. On the whole, it appears that the seasonal differences in water quality, at least to some extent, depend on land use and/or development density. Based on the Finnish study catchments, Kotola and Nurminen (2003) suggested that in catchments with a TIA of 40% or more, the quality of snowmelt (TSS, COD and TP) is often worse than that of stormwater during the summer season; the reverse holds true in urban catchments with a TIA less than 40%. Melanen (1980) also presented a similar idea, albeit he associated water quality with increasing traffic loads and land use types instead of TIA.

The importance of snowmelt- or rainfall-induced runoff events in pollutant export is affected by the seasonal changes occurring in both pollutant concentrations and runoff volumes. For example, Brezonik and Stadelmann (2002) concluded that event pollutant loads depended primarily on runoff volume and less on the type of runoff event (snowmelt or rainfall). Semádeni-Davies and Titus (2003) observed that cold period pollutant loads may be greater than warm season loads due to the long duration of runoff events, although they observed similar concentrations for both periods. Nevertheless, Westerlund et al. (2003) reported that the mass load of suspended solids was greater during snowmelt events, despite the larger amount of runoff during rainfall events: according to Westerlund (2007), key factors promoting the high concentrations of suspended solids and mass loads in snowmelt runoff from a road area included the intensity of overland flow and the amount of available material for wash off both in the snowpack and on the road surface.

Based on the previous research, it is difficult to make generalizations about the results concerning the importance of cold period runoff quality on an annual scale, as the results concerning pollutant concentrations and loads and the relationships between them vary greatly depending on the study location and the methods used. Obviously, the differences between the studies and sites demonstrate the need for local monitoring data: Oberts et al. (2000) recommended monitoring periods of several years to determine the load range and its seasonal distribution. Often monitoring covers periods from only a few months up to one year and, hence, any generalization based on such short monitoring periods should be treated with caution: for instance, according to Waller and Hart (1986), the extrapolation of data from a single season to an entire year can provide biased estimates for annual pollutant loads.

In cold climates, snow conditions need to be thoroughly investigated in order to achieve a comprehensive view of urban runoff pollution. Research on urban snow appears scarce, although the need for research has been recognized by many authors (Semádeni-Davies, 1999b; Semádeni-Davies and Bengtsson, 2000; Thorolfsson, 2000; Matheussen, 2004; Ho and Valeo, 2005). According to Marsalek et al. (2000), the pollutant accumulation in urban snowpacks cannot be generalized on a global scale due to differences in local conditions. Cold climate regions include areas with long snow accumulation periods of several months, and areas with intermittent snowmelts occurring throughout the winter months: these weather patterns affect the accumulation of pollutants in the snow (Reinosdotter and Viklander, 2005) and the release of pollutants from a snowpack (Oberts, 1994; Marsalek et al., 2000). The type of pollutant, particle-bound or soluble, affects the transport of substances from snow to the drainage system (Oberts, 1990; Viklander, 1997, 1999; Marsalek et al., 2000; Reinosdotter and Viklander, 2005). Vehicular traffic and winter maintenance activities are a major, documented source of pollution for urban snow (Hautala et al., 1995; Viklander, 1997; Sansalone and Glenn, 2002; Reinosdotter and Viklander, 2005; Reinosdotter, 2007; Engelhard et al., 2007). The quality of ploughed snow is particularly influenced by local practices regarding the use of sand and/or salt to control slipperiness (Reinosdotter and Viklander, 2005).

Snow provides temporary detention/retention storage for pollutants within a catchment. Therefore, by developing management strategies for urban snow, we have the opportunity to decide where these pollutants end up after melting (Viklander, 1999). For example, Reinosdotter and Viklander (2006) developed a strategy for treating urban snow in Sweden based on daily traffic loads: polluted snow should be stored on land and snowmelt should not be conveyed directly to receiving waters. Highly polluted snow should be transported to central, land-based snow dumps, where flow control and water quality treatment can be organized during snowmelt. Oberts et al. (2000) argued that, due to the high pollutant loads released during the spring thaw, runoff pollution studies should include locally collected estimates for the input from snowmelt to aid in the development of suitable management techniques in cold climates. However, previous studies on urban snow quality (e.g. Hautala et al., 1995; Viklander, 1997, 1999; Sansalone and Glenn, 2002; Reinosdotter and Viklander, 2005; Reinosdotter, 2007; Engelhard et al., 2007) usually focused on point observations of snow quality without considering the catchment scale or monitoring runoff. This makes it difficult to evaluate the importance of snow storage in urban runoff pollution and in the development of cost-effective snow management practices.

1.4 Objectives

This thesis aims to provide a catchment-scale overview of the seasonal implications of urbanization on runoff generation and water quality in cold climate conditions. The study is motivated by the current need to develop a more sustainable approach to dealing with urban runoff and snow management in order to mitigate and prevent the adverse impacts of urbanization on water cycle and water quality.

The review of the existing literature demonstrates that several gaps exist with respect to this topic, including the scarce amount of hydrological data on local conditions as well as similar climates on a global scale, the lack of updated water quality data, the lack of catchment-scale studies on seasonal pollutant loads in cold climate conditions and the contradictory results on the impacts of urbanization on runoff generation under wintry conditions. Owing to the large temporal and spatial variations associated with urban runoff and water quality, monitoring studies should aim for year-round data collection for a period of several years. It is also important to observe changes in a wide range of events rather than just taking the traditional flood control approach. Based on the introduction, urban snow has an important role in wintertime hydrology and water quality, and urban runoff management could be improved by establishing a stronger link between the urban snow observations and the catchment-scale runoff and water quality analysis. The research so far has concentrated on the post-development phase of urban catchments, whereas developing areas under construction have remained rather inconspicuous. The construction phase, however, is of utmost importance for two reasons. First, construction sites may be a considerable source of pollution for receiving waters. Second, there is a documented lack of studies that are able to track down changes occurring in catchment hydrology based on gradual changes that occur in the impervious coverage.

The methodological approach of this thesis is observational, supported by several data processing and statistical methods. The analysis is limited to residential land use and the common water quality parameters in separately sewered areas. The results are divided in three chapters, which include an analysis of the impacts of urbanization on long-term runoff generation and water quality in Chapter 3, an analysis of urban snow properties in residential areas in Chapter 4 and an event-scale runoff and water quality analysis in Chapter 5.

The specific objectives of the long-term runoff and water quality study (Chapter 3) are as follows:

1a) *to identify and quantify the impacts of suburban development on annual and seasonal runoff generation in relation to the general theoretical principles of urban hydrology*,

1b) *to demonstrate the impacts of urbanization on long-term pollutant concentrations and export rates and their seasonal patterns*, and

1c) *to evaluate the magnitude of urbanizing and urban land uses as sources of diffuse pollution.*

The specific objectives of the urban snow study (Chapter 4) are as follows:

2a) *to collect data series for urban snow properties and show how these properties are affected by suburban development*, and

2b) *to evaluate the pollution capacity of urban snow from a broader catchment perspective.*

The specific objectives of the event-scale runoff and water quality analysis (Chapter 5) are as follows:

3a) *to examine changes in the event runoff characteristics during construction works and between the warm and cold period runoff events*,

3b) *to identify the key variables affecting the warm period runoff generation and water quality*,

3c) *to quantify the changes in runoff-contributing area and volumetric runoff coefficients and to compare the observed runoff coefficients with those used in the dimensioning of stormwater practices in Finland*, and

3d) *to demonstrate seasonal differences in event pollutant mass loads and concentrations and their exceedance probabilities between the study catchments, and to compare event water quality with the long-term average concentrations and seasonal patterns defined in Chapter 3.*

2. Methods

2.1 Study catchments

According to the Finnish Meteorological Institute (*www.fmi.fi*), all of Finland belongs to the temperate coniferous-mixed forest zone with cold, wet winters: in southern Finland, the average annual precipitation ranges from 650 to 750 mm, the average annual temperature ranges from 4 to more than 5 °C and snow cover exists from November to April (the normal period for the years 1981-2010). This thesis has to do with a five-year monitoring study from the summer of 2001 to the autumn of 2006 in three study catchments located within the city of Espoo, in southern Finland (Figure 1). The study catchments and the hydrological and water quality monitoring methods were previously described by Kotola and Nurminen (2003) for the first monitoring year and also by the author of this thesis (Metsäranta et al., 2005).

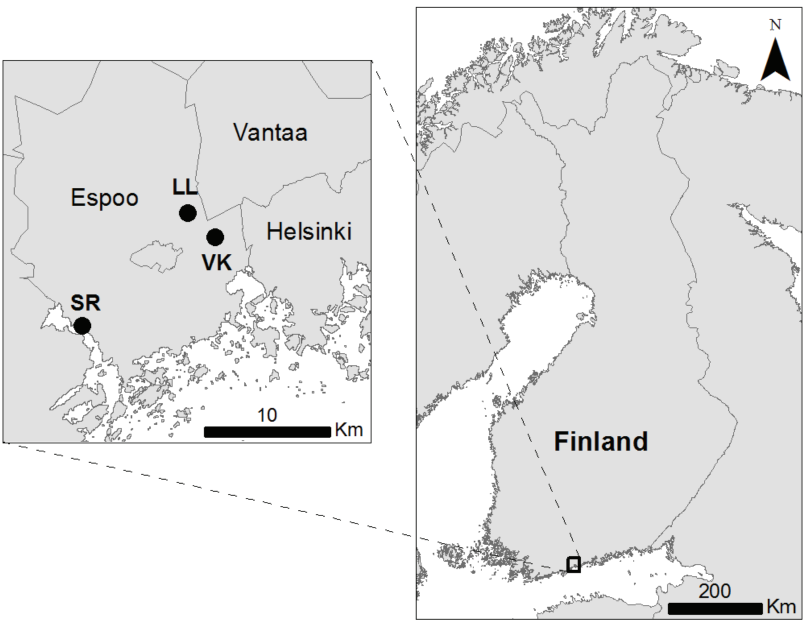


Figure 1. Locations of the study catchments: the developing SR catchment, the medium-density VK catchment, and the low-density LL catchment (© National Land survey of Finland, 2013).

The Saunalahdenranta (SR) study catchment underwent major construction activities during the monitoring period; for this reason, it is later referred to as the developing catchment. The catchment area (0.085 km^2) is characterized by rocky hillslopes with elevations ranging from 5 to 50 metres above sea level. In 2001, SR consisted mainly of coniferous forest, whereas by 2006 the catchment had been fully transformed into a medium-density residential area (Figure 2). Building types within the area range from two-storey terrace houses to six-storey blocks of flats. Stormwater runoff from SR is conveyed via a separate sewer system to a nearby small bay in the Baltic Sea.

Figure 2. Aerial photos of SR before (2001) and after (2007) construction works (aerial photos provided by the City of Espoo).

Simultaneous measurements were conducted at two urban catchments within a distance of 15 km from the SR catchment: Laaksolahti (LL) and Vallikallio (VK) (Figure 3). These catchments already represent developed urban areas and, in this study, they have been used as control sites. The use of control catchments makes it easier to distinguish hydrological changes resulting from urban development at SR from those caused by variations in the weather conditions.

Laaksolahti (LL) is a low-density residential area of mainly detached housing (0.31 km^2 with 20% impervious surfaces, 2600 people per km^2) and Vallikallio (VK) is a medium-density residential area consisting mainly of blocks of flats (0.13 km^2 with 50% impervious surfaces, 12300 people per km^2). At LL, some of the driveways still do not have asphalt paving and drainage is mainly organized using open ditches. Stormwater from rooftops is mainly conveyed to nearby lawns. At the medium-density VK catchment, all traffic-related areas have an asphalt coating. A subsurface storm sewer network covers the whole catchment area. Both the traffic areas and most of the rooftops are directly connected to the storm drainage system. Based on a study by Kotola and Nurminen (2003), the traffic loads in the study catchments are 10,200 and 1,440 vehicles/day at VK and LL, respectively. The elevation ranges from 29 to 50 m above sea level at VK and 30 to 60 m above sea level at LL. The higher elevation difference at LL is reflected by the average slope of the streets, which is 4.0% at LL and 1.9% in VK (Kotola and Nurminen, 2003). However, at LL the vegetated open ditch serving as the main drainage system 500 m upstream of the measurement station in Figure 3(b) has an approximate slope of only 0.4%.

The soils within the study catchments mainly consist of three soil types: i) bedrock with a thin (<1 m) soil layer on top, ii) till and iii) fine-grained material such as clay in the areas at the lowest elevation (digital maps by Geological Survey of Finland, *www.gtk.fi*). Owing to the different elevations of the catchments, SR consists mainly of rocky areas with a thin till layer, whereas VK consists of rocky areas and steeper layers of sandy till and LL consists of all soil types, including a clayey area alongside the main road. During the construction works, no particular erosion or sediment controls were installed at SR.

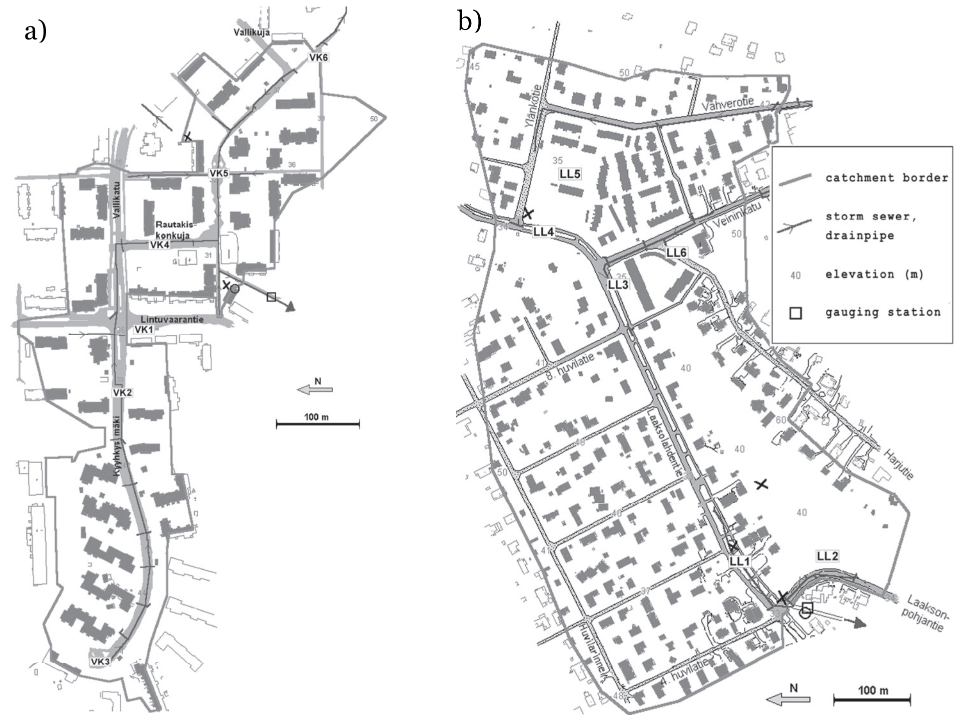


Figure 3. Illustrations of a) the medium-density VK catchment and b) the low-density LL catchment showing the locations of the main roads, buildings, pipe sewers, and the gauging stations (Sillanpää and Koivusalo, 2013, reprinted with permission from IWA Publishing). Also the locations of the snow courses used in the snow surveys are shown: the snow courses VK1-VK6 in VK and the snow courses LL1-LL6 in LL. The locations of open ditches in LL are not shown.

2.2 Summary of the construction works and data breaks in the developing SR catchment

An illustration of the general construction phases at the developing SR catchment is shown in Figure 4. During the five-year monitoring period, SR was divided into several building sites operated by different developers. Hence, construction works at the different sites progressed according to their own individual timetables, and different types of construction activities (such as site preparation or building construction works) were simultaneously carried out in different parts of the catchment. For this reason, a detailed timing of individual construction activities, other than the progression presented in Figure 4, was not available. The following section describes the main construction activities and incidents having an impact on stormwater quantity or quality during the monitoring period as well as the periods for which data are missing. A summary of the changes in the total catchment and impervious areas is provided in Table 2.

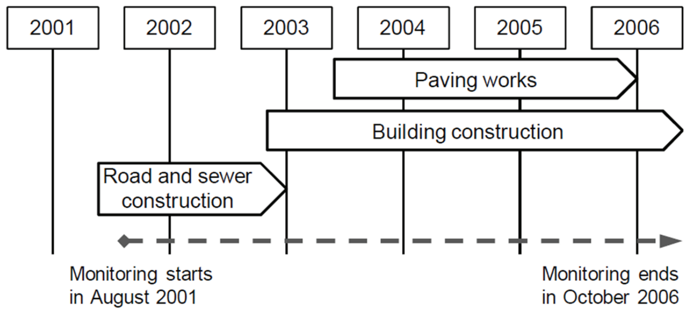


Figure 4. The main construction phases at the developing SR catchment.

Table 2. Total catchment area and the total impervious area (TIA) during the construction works at the developing SR catchment.

Catchment summary	2001-2002	May 2004	May 2005	May 2006	Oct 2006
Total area (ha)	8.5-11.5(*	13.2	13.2	13.2	13.2
Roofs (ha)	0.0	1.11	1.68	1.80	1.82
Other impervious (ha)	0.125	1.43	2.49	3.02	3.07
TIA (%)	~1.5%	19.3 %	31.6 %	36.5 %	37.0 %

*) Total catchment area determined by Kotola and Nurminen (2003)

The years 2001-2003

Construction works at the SR catchment started with the reconstruction of an existing main road together with the installation of a separate storm sewer network during the summer of 2001. For the first years 2001-2002, the catchment area (8.5 ha) was delineated based on the catchment topography and the location of the main sewer lines, as reported by Kotola and Nurminen (2003). In 2001, water quality was affected by a leaking wastewater sewer, but changing the location of the sampling tube in January 2002 minimized this effect (Kotola and Nurminen, 2003).

In early 2002, trees were felled to make room for new streets. The sewers were constructed under the main streets, which were left unpaved. The sewer works resulted in a gradual expansion of the catchment area up to 11.5 ha (Kotola and Nurminen, 2003), which is illustrated in Figure 5. Site preparation and construction works at some building sites started in December 2002. During the years 2001-2002, the greatest changes occurred in the location of the catchment boundaries, but the area of the impervious surfaces (TIA) remained low (Table 2).

During the winter and spring of 2003, monitoring data from four months was discarded owing to inaccuracies caused by freezing and a leaking measurement weir. The main streets were paved with asphalt in two phases during July and September of 2003. In autumn 2003, elevated levels of nitrogen raised suspicions about the possible presence of wastewater in the stormwater network: two temporary site huts at one building site had released their wastewater into the storm sewers instead of into the wastewater sewer. The incorrect connection had already been made at the end of March 2003. In addition to site huts, two residential buildings had been misconnected to the storm sewer system as well, but these incorrect connections did not affect water quality until new residents moved into the buildings at the end of December 2003. Starting from December 2003, the catchment area was estimated as being 13.2 ha. At the end of 2003, the TIA of the catchment was 19.3% (Table 2).

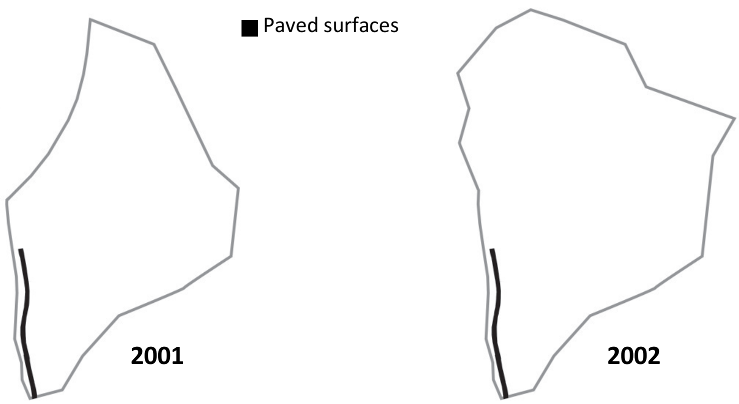


Figure 5. The SR catchment boundaries and impervious surfaces during the years 2001-2002.

The years 2004-2006

In January 2004, wastewater discharged from the two misconnected residential buildings resulted in an accumulation of solid wastes in the measurement weir and blockage of the sampler. The sewer connection was repaired by the end of the month. Yet, in the winter and spring of 2004, four months of monitoring data was rejected due to the maintenance works required after wastewater discharges, and later during the same winter, due to freezing problems and leaks from the measurement weir during the spring snowmelt. In the summer of 2004, another misconnection was discovered in a site hut on another plot, but this time the incorrect connection was noticed and repaired after only a few days.

The majority of the paving work at the building sites was performed during the years 2004-2005 (Figure 6). From May 2004 to May 2005, the TIA increased from 19.5% to 31.6% (Table 2). Data from the two-month period in October and November 2005 were not used due to errors in the data logger software, which affected the water depth records.

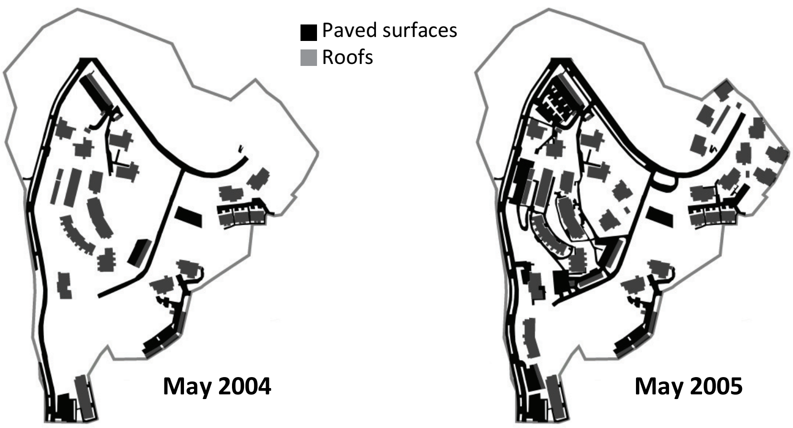


Figure 6. The SR catchment boundaries and impervious surfaces during the years 2004-2005.

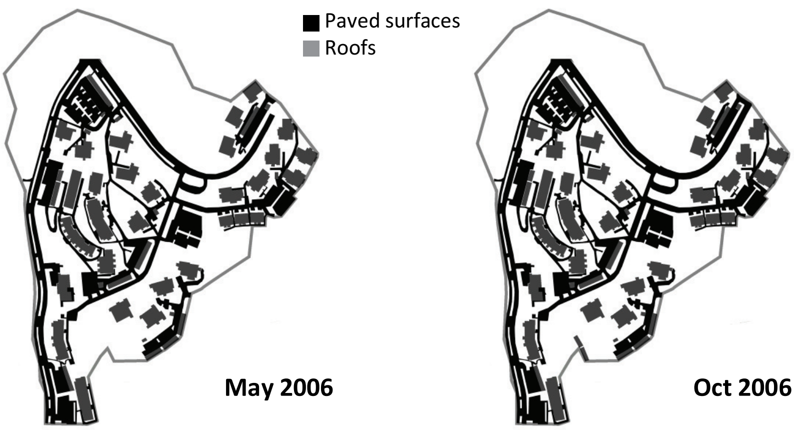


Figure 7. The SR catchment boundaries and impervious surfaces in May 2006 and at the end of the monitoring period in October 2006.

In early 2006, site preparation works at the last building site started. In March, trees were felled and road construction work started at a boundary area of the catchment, which also affected the stormwater quality. All 27 of the planned residential buildings were completed by the end of the monitoring period in October 2006, although some unfinished courtyards without protective surface cover still remained. Hence, the monitoring results reflect the conditions of a developing catchment and do not extend to the period after the construction. Only minor changes in impervious surfaces occurred during the year 2006 (Figure 7, Table 2).

2.3 Monitoring

2.3.1 Precipitation

In each study catchment, a weather station was equipped with an ARG100 tipping bucket rain gauge (Campbell Scientific Ltd, 1998), adjusted for a volume resolution of 0.2 mm. Rain gauges were located on roofs in the vicinity of the flow monitoring points: at SR and LL about 2-3 m above ground level on the roofs of the monitoring equipment shelters and, at VK, about 5 m above ground level on a building roof. The gauge locations were selected to minimize the sheltering effect by nearby buildings and vegetation. For the first four years, the data logger recorded rainfall intensity as ten-minute precipitation sums and, starting from September 2005, as two-minute sums.

If the rainfall data of a tipping-bucket gauge is recorded by registering every individual tip, an empirical, usually non-linear, calibration function can be used to correct the precipitation data (Niemczynowicz, 1996). In this case, the original data with separate tips was not recorded by the data loggers and, thus, not available. For this reason, the accuracy of the precipitation data was tested by performing reference measurements with standard precipitation gauges (Tretjakov type gauge, nominal area 200 cm^2, see e.g. Førland et al., 1996) during a period of two months in autumn 2005. The standard precipitation gauges, located close to the tipping-bucket gauges, were manually read after rainfall events and, thus, gave cumulative precipitation sums from consecutive periods lasting from three days to two weeks depending on the weather.

The uncorrected precipitation sums are presented in Table 3 for both gauge types. The tipping bucket gauge gave 3-12% larger precipitation sums than the standard gauges at LL and SR (observation periods without long data breaks) (Table 3). At VK, the difference between the gauges was not as systematic: the measured rainfall with the ARG100 equalled or exceeded the observations with the standard gauge. Based on the results presented in Table 3, all of the precipitation data collected with the tipping-bucket gauge were used without making any additional corrections because, if the commonly suggested upward correction for standard gauges (4-8%) had been applied, the volume of precipitation would have been overestimated.

In this way, the volumetric runoff coefficients determined in this thesis for planning purposes would also not be underestimated.

Table 3. Comparison of precipitation measurements between the ARG100 tipping-bucket rain gauge and the standard gauges in the autumn 2005.

	Developing SR catchment			**Low-density LL catchment**			**Medium-density VK catchment**		
Date	Standard (mm)	ARG100 (mm)	Deviation (%)	Standard (mm)	ARG100 (mm)	Deviation (%)	Standard (mm)	ARG100 (mm)	Deviation (%)
Cumulative precipitation during the event > 1mm									
29/08	49.7	52.8	-6.2	59.1	60.6	-2.5	59.8	59.6	0.3
08/09	7.1	7.4	-4.2	5.5	6	-9.1	4.8	5.0	-4.2
17/10 [1]	18.1	20.2	-12	14.6	15.2	-4.1	9.3	11.2	-20
25/10	18.7	19.8	-5.9	19.6	20.4	-4.1	21.4	21.2	0.9
19/09 [2]	8.6	8.8	-2.3	11.9	10.8	9.2	9.1	8.0	12
Cumulative precipitation during the event < 1mm									
05/09	0	0.6		0	0.2		0	0.4	
13/09	0	0.2		0.3	0.2		0.3	0.4	
26/09	0	0.4		0	0		0	0.2	

1) Break in the ARG100 data at SR from 4/10 to 5/10

2) Breaks in the ARG100 data at all study sites from 15/9 to 17/9 and from 19/9 to 20/9

During the snow measurement campaign (winter/spring 2006), the standard precipitation gauges were also used to monitor snowfall at the control catchments. Otherwise, precipitation measurements for the winter months (the months with average air temperatures below 0°C) were taken from the Finnish Meteorological Institute's Helsinki-Kaisaniemi measurement station. The Helsinki-Kaisaniemi station was selected from among three other weather stations based on the on-site precipitation measurements during the spring of 2006. The cold period precipitation data were corrected upwards using a correction factor of 1.35, which is considered a general correction factor for snowfall in Finland (Kuusisto, 1986a). It is similar to the 1.33 correction factor used by Semádeni-Davies (1999b) based on Swedish recommendations. Gürer (1975) showed that a large variation in winter correction factors for Finnish catchments exists from 1.19 to 1.44 with an average of 1.31. The constant correction factor chosen for this study may lead to an overestimation of precipitation during warm winter months, when a substantial part of the precipitation may consist of rainfall instead of snowfall.

2.3.2 Flow

The temporal resolution of the flow measurements was equal to the precipitation, ranging from two to ten minutes year-round. At each site, the flow rates were determined based on the water depth recorded using pressure transducers (STS ATM/N, see STS Sensors, 2013). In the case of equipment malfunctions, the company providing the flow monitoring equipment used also other types of pressure transducers on-site. At the SR and LL catchments, the pressure transducers were installed into a v-notch weir in an open ditch — outside the pipe sewer outlet at SR and after a road culvert at LL. The notch angles were 90° at SR and 120° at LL; the stage-discharge curves for the angles have been presented previously by Kotola and Nurminen (2003). The maximum measurable flow was 238 l/s and 297 l/s in SR and LL, respectively. In SR, the maximum capacity of the measurement weir was exceeded two times during the monitoring study.

At VK, the pressure transducer was located in the manhole of a sewer pipe (Ø 500 mm). The flow rate was calculated using a stage-discharge calibration curve (Figure 8) determined based on on-site manual calibration measurements conducted by Kotola and Nurminen (2003) as well as laboratory flume measurements with a 1:1-model of the manhole and the inlet and outlet sewer pipes. The laboratory flume had a capacity for water depths of up to 390 mm at the outlet sewer pipe. The calibration points for water depths of 0...55 mm were obtained using both on-site and flume measurements, and for water depths of 55...390 mm based on the flume measurements. For water depths below 390 mm, flow rates were linearly interpolated between the closest two calibration points. For water depths between 390 mm and 500 mm (full pipe), the Manning equation was used. The average difference between the on-site flow measurements and the flow rate, which was determined based on the calibration curve, was 2.6%, and it ranged from <1 to 27% for individual measurements.

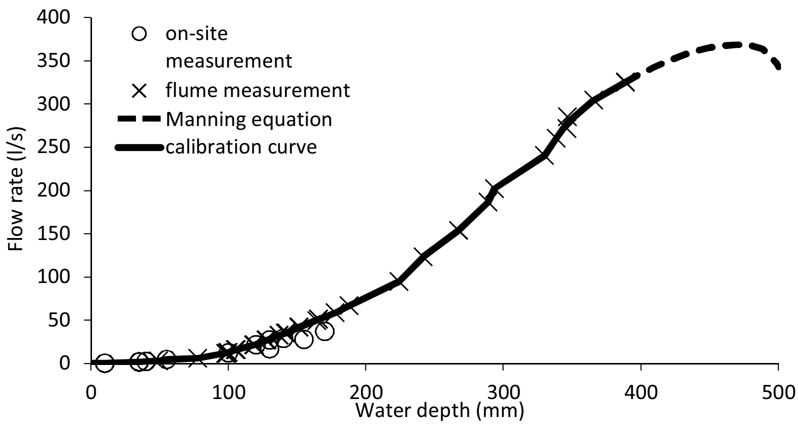


Figure 8. Calibration curve used in calculation of flow rates in the VK catchment.

During the study, the full pipe capacity was exceeded eight times at VK. The exceedances had short durations, ranging from approximately ten minutes to 20 minutes during three events. For these incidents, the flow rate equivalent of a water depth of 500 mm (342.6 l/s) has been used, unless stated otherwise. It should be noted that especially during these events, backwater from the downstream sewer conjunction may have raised the water depths, which may have affected the measured flow rates.

2.3.3 Water quality

Each study site was equipped with an automatic sampler with 24, 1,000 ml sample bottles to enable flow-weighted sampling. At the beginning of the monitoring study, the samplers included Isco 3700 (LL), Isco 2700 (VK), and Sigma Streamline 800 SL (SR), which were replaced with Isco 2700, Isco 6712, and Isco 3700, respectively, in the summer 2003 due to practical reasons. Water samples were drawn at irregular time intervals based on the accumulated runoff volume. In addition to runoff volume, samples were also taken when a predetermined rise in the flow rate was exceeded between two consecutive flow observations. This made it possible to take samples more frequently during short and intense rain events; at such times, the runoff volume might be too low to trigger the sampler, but the instantaneous flow rates and pollutant concentrations can still be high. The samples were picked up from the measurement stations at least once a week and analysed at the Water Resources Laboratory of the former Helsinki University of Technology (now Aalto University) for total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN) and chemical oxygen demand (COD_{Mn}) (Table 4). During the years 2001-2003, samples were sometimes combined and analysed as flow proportional composite samples. During the latter monitoring period, composite samples were seldom used and the emphasis was placed on the year-round determination of instantaneous concentrations.

Table 4. Water quality analyses and standards.

Pollutant	Acronym	Standard
Total suspended solids	TSS	SFS-EN 872 (1
Total phosphorus	TP	Tec. ASN 111-02/92
Total nitrogen	TN	Tec. ASN 110-03/92
Chemical oxygen demand	COD	SFS 3036 (2

1) Whatman GF-52 glass fibre filter

2) Oxidation w ith permanganate

2.3.4 Snow

A snow survey was organized during the winter and spring of 2006. The snow measurements were conducted at the low-density LL catchment and the medium-density VK catchment. The developing SR catchment was excluded from the snow study due to difficulties in maintaining regular measurement points during the construction activities and access restrictions at the construction sites. Also, reference measurements of rural snow were conducted in a forested catchment in Siuntio, 17 km west of SR: the snow conditions of this catchment were previously studied by Koivusalo (2002). The reference measurements represented both an open clearing and a mature forest dominated by Norway spruce (Picea abies).

Within the study catchments, a total of six snow courses consisting of three to six measurement points were identified. The locations of the snow courses are illustrated in Figure 3 and a detailed description of them can be found in Table 5. The snow courses included measurement points for different types of urban snow: both *untouched snow* in yards and parks and *disturbed snow*, i.e. ploughed and piled snow along roadsides and walkways. No rooftop measurements were carried out for practical as well as safety reasons. Visual observations of a *snow covered area* (SCA) were carried out during each survey.

Table 5. Descriptions of the snow courses.

Snow course	Description	Sampled snow types
The medium-density VK catchment		
VK1	Main roads	*Ploughed snow on roadsides, untouched snow.*
VK2	Residential street	*Ploughed snow on roadsides, untouched snow.*
VK3	Turnaround area	*Ploughed snow at a parking area and on roadside, untouched snow.*
VK4	Residential street	*Ploughed snow at a parking area and on roadside, untouched snow.*
VK5	Recreation area	*Untouched and ploughed snow along a walkway.*
VK6	Walkway at a forest	*Untouched and ploughed snow along a walkway.*
The low-density LL catchment		
LL1	Main road	*Ploughed snow on roadsides and along a walkway, untouched snow.*
LL2	Forest	*Untouched snow.*
LL3	Commercial building	*Ploughed snow along a walkway, untouched snow.*
LL4	Day nursery	*Ploughed snow on roadsides and along a walkway, untouched snow.*
LL5	Parking area	*Ploughed and untouched snow.*
LL6	Residential street	*Ploughed snow on roadsides, untouched snow.*

Monitoring started as soon as the permanent snow cover was established, and field surveys were carried out fortnightly during the mid-winter months and at least weekly during the spring melt; the study included a total of 14 snow surveys on both catchments during the period from 4 January to 13 April. During every survey, the snow depth and snow density were measured using a measuring rod and snow scales (ø 11.25 cm). For each measurement point, the *snow water equivalent* (SWE) was determined and a density of 900 kg/m^3 for ice was used if there was an ice layer at the bottom of the snowpack. During the snow surveys, the approach of using constant measurement points proved to be difficult to maintain. The location of the snow piles changed throughout the observation period. The snow that was supposed to remain untouched throughout the winter had suddenly been disturbed, e.g. by children or pets, between field visits. Sometimes the ploughed snow was so icy that the snow scales could not be used. In these cases, measurement points were sometimes rejected and replaced, if possible, by another measurement of the same snow type.

Samples of snow quality were collected from different snow types during 13 and 7 snow surveys at VK and LL, respectively. At LL, the snow quality observations focused on the spring melt and fewer samples were taken in mid-winter. The samples were taken as vertical profiles of the snowpack using a clean plastic shovel and stored in 10-litre plastic lidded buckets. The samples were transported to the laboratory for melting (usually over a weekend at room temperature), where analyses were done within a couple of days. In addition to analysing their pH and electrical conductivity (EC), the samples were analysed for COD_{Mn}, TP, TN and TSS according to the same standards as the runoff samples (Table 4). Some samples (1-2 samples per survey) were also analysed for dissolved concentrations (TP, TN and COD_{Mn}) starting from the middle of March.

2.4 Data processing and statistical methods

In the following section, the main methods are introduced separately for the long-term runoff and water quality analysis (Chapter 3), the snow study (Chapter 4) and the event-scale runoff and water quality analysis (Chapter 5). Statistical testing was conducted using the PASW Statistics 18 and IBM SPSS Statistics 20 software, except for the simple linear relationships established using Microsoft Excel 2010. The confidence level used for the statistical analyses is 95%. In all of the chapters, the normality testing is based on the Kolmogorov-Smirnov test with the Lilliefors correction and the Shapiro-Wilk test coupled with histograms and Q-Q plots. Skewed data were log-transformed when needed, for instance before calculating the correlations and regressions.

2.4.1 Long-term runoff and water quality analysis

For the long-term runoff analysis, temporal patterns were analysed according to annual, six-month, seasonal and monthly scales. Owing to data breaks, the number of years with full data coverage varied among the study catchments. Additionally, changes occurring in runoff and water quality during the construction works were investigated by dividing the monthly data series into three continuous periods (11…15 months) representing different construction and catchment conditions.

Long-term pollutant loads (L) were calculated using the *linear interpolation method* (Endreny et al., 2005). Thus, the missing concentration values for each flow observation were linearly interpolated between the observed concentrations. The load (*kg*) was then calculated according to Equation (1):

$$L = \sum_{t=1}^{Year} \left(Q_t C_t \Delta t \right) \qquad (1)$$

where Q_t is the flow rate at time t (*l/s*), C_t is the observed or interpolated pollutant concentration at time t (*mg/l*) and Δt is the time step between the flow observations (*s*). The advantage of the method is that it ensures objectivity when handling the concentration data; however, it does not include any correlation with flow. The method was chosen to ensure consistency with a similar method used by Kotola and Nurminen (2003), who reported results for runoff volumes and long-term pollutant loads from the first monitoring year 2001-2002. Annual, seasonal and monthly pollutant export rates (*kg/km²*) were determined as the ratios of the cumulative loads to the total catchment area, and long-term concentrations (*mg/l*) as the ratios of the loads to the corresponding cumulative runoff volumes.

Table 6 summarizes the main statistical methods used for the long-term runoff analysis. Linear regression was used to analyse the annual runoff and precipitation. The F-test indicated the statistical significance of the regression models, and the coefficient of determination (R^2-value) was used as a goodness-of-fit criterion. To test statistically significant differences between the annual regression models for the different catchments, a multiple linear regression model of a dependent variable, Y, an independent variable, x, and an error term, ε, was added to a dummy variable, z, for the two data groups and their interaction term ($x \times z$) according to Equation 2*:*

$$Y = \beta_0 + \beta_1 x + \beta_2 z + \beta_3 (x \times z) + \varepsilon \quad (2)$$

where β_i is the regression coefficient. A significant difference between the two regression models was then determined by testing the significance of the dummy variable and the interaction term. If the hypothesis H_0: $\beta_2 = \beta_3 = 0$ is accepted, then the model $Y = \beta_0 + \beta_1 x + \varepsilon$ can be applied to both groups.

Table 6. Main statistical methods used in the analysis of long-term runoff and water quality.

Purpose	Statistical method	Acronym
Identification of relationships between annual precipitation and runoff	*Simple linear regression*	
Identification of differences in annual runoff between sites	*Multiple linear regression*	
Comparison of monthly high-flows, mean flow rates, and low-flows between two periods	*Mann-Whitney U test*	
Identification of interrelationships in the temporal behaviour of pollutant concentrations	*Hierachical cluster analysis*	*HCA*
Relationships between monthly concentrations	*Pearson correlation*	
Identification of seasonal water quality patterns	*Discriminant analysis*	*DA*

Temporal patterns and their differences in monthly runoff and pollutant export were investigated using the monthly average values and their 95% confidence intervals based on the Student's t distribution. Changes occurring in the monthly high-flows, mean flow rates and low-flows during the construction works were investigated by comparing their probability plots supported by the nonparametric Mann-Whitney U test (Table 6). The

Mann-Whitney U test is recommended for the detection of change in hydrological records when the time of change is known (Kundzewicz and Robson, 2004): in this case, two year groups, 2001-2003 and 2004-2006, were used because the majority of the asphalt works were conducted after the year 2003. The Mann-Whitney U test compares the locations of the distributions of two independent groups based on the ranks of the observations. The null hypothesis to be tested is that two populations have identical medians (e.g. Yue and Wang, 2002a). The test assumes that the data are independent and that the probability distributions of the two data sets are the same and have the same variances. The test can also accommodate a moderate number of 'nondetectable' values (Burton and Pitt, 2002). Because of the artificial upper limit in the measured high-flow rates, owing to the exceedances of the maximum measurable flow rates (Chapter 2.3.2), the magnitude of the observed change in the monthly high-flows was quantified based on the 85^{th} percentile high-flow of both year groups.

Hierarchical cluster analysis (HCA) was used to investigate the relationships between the water quality variables (Table 6). The clustering method used was Ward's linkage with squared Euclidean distances as a measure of similarity, which has previously been used in multivariate statistical water quality studies (e.g. Grum et al., 1997; Zhou et al., 2007; Pejman et al., 2009). For HCA, log-transformed monthly concentrations were used owing to the skewed distributions. The HCA results were supported by Pearson correlations.

Discriminant analysis (DA) was used to study seasonal patterns in the log-transformed monthly pollutant concentrations (Table 6). DA has been previously used by Sheng (2004), who classified urban rainfall-runoff events based on their pollutant behaviour, and by Zhou et al. (2007), who investigated the temporal and spatial behaviour of monthly river water quality during a five-year monitoring period. DA indicates whether cases or observations can be classified into predetermined groups based on each case's score on one or more quantitative variables (Stern, 2010). The outcome of DA provides discriminant functions, which consist of discriminating variables and their coefficients. Each case is then classified into a group based on the highest score given by the discriminant functions. The statistical significance of the DA outcome is based on Wilk's lambda statistic. In this study, the seasonal classification of monthly concentrations was based on four seasons: September to November (autumn), December to February (winter), March to May (spring) and June to August (summer). The stepwise method was used; with this method, a variable that minimizes Wilk's lambda is added to the model at each step until an insufficient F level or tolerance for further computations is reached. DA assumes that the data are multivariate normal; however, the discriminant analysis can cope with some skewness. The test is more sensitive to outliers; hence, some observations were removed from the analysis, particularly two monthly values from the data on the low-density LL catchment during construction works at one property. Also, the heterogeneity of the variance-covariance matrices and multicollinearity should be avoided.

Because DA is based on samples for which the group membership is already known, it may overestimate the overall classification accuracy. If large sample sizes are used, one way to test the applicability of the classification is to use two sample subsets — one for deriving the discriminant functions and one for testing its accuracy for classifying cases. In this study, because of the low number of observations, validation of the sample results was conducted using a 'leave-one-out' procedure offered by PASW Statistics: this procedure repeated the classification for each case based on an equation derived with the case omitted from the data set (Stern, 2010).

2.4.2 Snow survey

Temporal patterns and differences in the snow depth, density and SWE between snow types and study catchments were investigated using the average values from each survey as well as their highest values (i.e. season maximum) at the onset of the spring snowmelt, supported by their 95% confidence intervals based on the Student's t distribution. The season maximums were also used to determine areal SWEs as area-weighted averages of the different snow types.

The differences in the snow quality between the snow types and study catchments were investigated based on survey means and their 95% confidence intervals. Snow quality was presented as pollutant concentrations and pollutant mass loads. The unit mass load of a pollutant for a certain snow type was calculated using Equation 3:

$$ML_{snow} = C_{snow}(SWE) \qquad (3)$$

where ML_{snow} is the mass load (mg/m^2), C_{snow} is the pollutant concentration in a melted snow sample (mg/l) and SWE is the snow water equivalent (mm). The areal snow mass load (SML), which describes the total amount of pollutants stored in snow within the catchment area (kg/km^2), was calculated using Equation 4:

$$SML = \frac{\Sigma[A_{snow}(ML_{snow})]}{A} \qquad (4)$$

where A_{snow} is the area of the snow type (ha), $\sum[A_{snow} \cdot ML_{snow}]$ is the sum of the pollutant mass stored in different snow types and A is either the total catchment area (*ha*) or A_{SCA}, which is determined as the snow covered area (*ha*). In the calculation for areal *SWE* and *SML*, the values of untouched snow were used for roof snow.

2.4.3 Event-scale runoff and water quality analysis

Event characteristics

As a starting point for the event-scale analysis, the event characteristics summarized in Table 7 were determined. A runoff event was defined as starting from the first precipitation observation and lasting until the flow rate had returned to the pre-event baseflow rate. If the flow rate did not return to the pre-event baseflow level, or if the event had a prolonged recession phase and the tail of an event did not have a major impact (~1%) on the event runoff coefficient (C_{VOL}), then the event was cut off earlier. The cold period events covered the period starting from the first snowfall and freezing temperatures and lasting until the end of the snowmelt in spring, usually from the end of November to late April. These events were separated from the data based only on the flow record.

In Table 7, the rainfall characteristics and C_{VOL} as a ratio of the direct runoff (R_{EFF}) to event rainfall (P_{TOT}) were only determined for the warm period rainfall-runoff events. The R_{EFF} was calculated by extracting the baseflow from the total event runoff (R_{TOT}) as a constant flow rate defined at the beginning of an event. At the medium-density VK catchment, the peak flow (Q_{MAX}) had an artificial upper limit due to exceedances of the full-pipe capacity; for these events, the variables describing runoff characteristics (R_{TOT}, R_{EFF}, C_{VOL}) were estimated based on P_{TOT} using regression equations later defined in Section 5.1.6. In Table 7, the duration of a rainfall event (P_{DUR}) was defined as the time from the beginning of an event until the last precipitation recording during the runoff event; hence, the P_{DUR} also included time steps without rain.

Event-scale water quality parameters were calculated as *event mean concentrations* (*EMC*) and *event mass loads* (*EML*) (Table 7). The method used to calculate the EML followed the principles used by, for example, Charbeneau and Barrett (1998) and Westerlund (2007). Hence, the EML was defined as the sum

$$EML = 1000 \sum_i C_i \forall_i \qquad (5)$$

where C_i is the concentration of the i^{th} sample (*mg/l*) associated with runoff volume $\forall_i$ (m^3). First, cumulative runoff volumes for each individual sample were determined for a given event, and, next, mid-sample volumes were calculated as a sum of the cumulative volume for the previous sample and one-half of the difference between the cumulative volumes for two consecutive sampling times. Then, $\forall_i$ was determined as the difference between mid-sample volumes (Charbeneau and Barrett, 1998). After this, the EMC was defined as the ratio of the EML to the R_{TOT}. *Site mean concentration* (SMC), which is less sensitive to the high concentrations associated with low runoff volumes (Mourad et al., 2005), was calculated as a volume-weighted average EMC for each catchment. Also, medians and arithmetic means are used as average EMCs in this study.

Table 7. Description of the event characteristics for the warm and cold period runoff events.

Event characteristics	Acronym	Unit	Additional remarks
Rainfall characteristics			
Event rainfall sum	P_{TOT}	*mm*	
Maximum rainfall intensity	P_{MAX}	*mm/10 min*	
Duration of rainfall	P_{DUR}	*h*	
Average rainfall intensity	P_{MEAN}	*mm/h*	Calculated as P_{TOT}/P_{DUR}
Runoff characteristics			
Total event runoff	R_{TOT}	*mm*	
Direct runoff	R_{EFF}	*mm*	Baseflow extracted as a constant rate from R_{TOT}
Event peak flow rate	Q_{MAX}	*l/s*	Also *l/s/ha* in Section 5.1.5
Duration of runoff event	R_{DUR}	*h*	
Mean runoff intensity	R_{MEAN}	*mm/h*	Calculated as R_{TOT}/R_{DUR}
Volumeric runoff coefficient	C_{VOL}	-	Calculated as R_{EFF}/P_{TOT}
Water quality			
Event mean concentration	*EMC*	*mg/l*	
Event mass load	*EML*	*kg*	
Antecedent conditions for rainfall-runoff events			
Antecedent dry period	*DAYS*	*d*	Time since the last event of at least 1 mm of rain
Antecedent precipitation sum	*PREC1/3/5/7*	*mm*	Antecedent 1, 3, 5, or 7-day cumulative rainfall
Antecedent conditions for cold period runoff events			
Antecedent dry period	*DAYS*	*d*	Time since the last event of at least 1 mm of runoff
Antecedent runoff sum	*RSUM1/3/5/7*	*mm*	Antecedent 1, 3, 5, or 7-day cumulative runoff

Two types of variables describing antecedent conditions were also determined (Table 7) by first describing the length of the dry period before an event (DAYS), and second, by summing the wetness of the preceding period before an event as the precipitation sum ranging from one to seven days (PREC1...PREC7) for the warm period events and as cumulative runoff (RSUM1...RSUM7) for the cold period events. The preceding dry period (DAYS) was calculated from the previous event of at least 1 mm of rainfall – this amount was enough to produce direct runoff at urbanized catchments.

Data analyses

To visualize the data, box-and-whisker plots were used. The box plots used in this study follow the default settings for the SPSS software and consist of a box showing the median and bordered plots at the 25th and 75th percentiles. The interquartile range (IQR) is the difference between the 75th and 25th percentiles and corresponds to the length of the box. Mild outliers are values between 1.5 IQR's and 3 IQR's from the end of the box. Values more than 3 IQR's from the end of the box are defined as severe outliers. In the figures, mild outliers were illustrated as circles and severe outliers as triangles. Probability plots were used to illustrate and identify the differences between seasons and catchments.

Table 8 summarizes the main statistical methods used in the event analysis. Statistical testing was usually performed for rainfall events with at least 1 mm of precipitation or for events producing measurable direct runoff. In the case of the cold period, all cold period events (2001-2006) or winters with a full set of events (the winters 2001-2002, 2004-2005 and 2005-2006) were chosen for the analysis.

Table 8. Main statistical methods used in the analysis of event runoff and water quality.

Event-scale analysis	Statistical method	Acronym
Identification of changes in runoff event characteristics during construction works	*Kruskal-Wallis test, Mann-Whitney U test*	
Identification of changes occuring in gamma parameters and mean transit times	*Kruskal-Wallis test*	
Relationships between gamma parameters, mean transit times, and rainfall characteristics	*Pearson correlations*	
Estimation of effective impervious area and initial losses	*Simple linear regression*	
Identification of changes in runoff generation between minor and major rainfall events	*Multiple linear regression analysis*	
Simple relationships between runoff event characteristics and event water quality.	*Pearson correlations, Spearman rank order correlations*	
Relationships between event runoff, precipitation, antecedent conditions, and catchment imperviousness.	*Stepwise multiple linear regression*	*MLR*
Relationships between event water quality, event characterics, and construction activities.	*Stepwise multiple linear regression*	*MLR*
Identification of differences between sites and seasons	*Kruskal-Wallis test, Mann-Whitney U test*	

The changes occurring in the runoff event characteristics during the construction works were studied using the box plots and the nonparametric Kruskall-Wallis test (Table 8). The Kruskal-Wallis test extends the Mann-Whitney U test to more than two groups (Landau and Everett, 2004), and it has been recommended when examining the equality of sub-period variability in hydrological records (Kundzewicz and Robson, 2004). In this thesis, first the annual groups of events in the developing SR catchment were investigated and pooled into similar continuous periods. These periods were then tested for statistically significant differences occurring in event runoff during the construction works. The analysis was repeated using the same periods for the control catchments in order to distinguish between changes caused by the changing catchment characteristics and those caused by varying weather conditions. The comparison tests were also used to detect changes in the runoff response during events of different magnitudes by dividing the rainfall events into two groups (minor and major events) based on precipitation depths. If significant differences were detected when using the Kruskall-Wallis test, the different/similar groups were further identified by making paired comparisons with the Mann-Whitney U test when needed. Previously, Burns et al. (2005) and Dougherty et al. (2007) used the Kruskall-Wallis test to compare urban catchments, whereas Brezonik and Stadelmann (2002) used it to compare water quality between seasons and sites. When the nonparametric comparison tests have been used, it should be noted that the analyses have been based on assumptions that the samples from consecutive years are independent of each other and that only a small amount of autocorrelation between events exists within the same year. In fact, not all rainfall or water quality events were used and the selected events were separated by a dry period of changing durations. Nonetheless, the results from the statistical comparison tests should be treated with caution, and in the present thesis, no conclusion is based on a single method; rather, they are always supported by other methods and results, including visual, statistical, event-scale and long-term data analyses.

The box plots, the probability plots, as well as the nonparametric comparison tests, were used to study differences in the EMCs and EMLs between seasons and catchments (Table 8). Additionally, box plots and the comparison tests were used to detect changes caused by construction works on the cold period runoff events. Other studied variables included the number of runoff events during each cold period and the end date of the last direct runoff event during the spring melt.

The Pearson correlations were calculated to identify the general tendencies and relationships between the event characteristics after the normality tests (Table 8). Also, the nonparametric Spearman correlation coefficients were checked when the log-transformation did not result in a near-normal distribution: this concerned in particular the R_{EFF} and C_{VOL} during the first years of monitoring at the developing SR catchment and the variables describing the antecedent conditions.

Instantaneous unit hydrographs (IUH), which are based on gamma distribution, were used to study the effects of urbanization on the shape of the direct runoff hydrograph and the catchment time of concentration. The two-parameter gamma distribution can be written as

$$IUH(t) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} t^{\alpha-1} e^{-t/\beta} \qquad \alpha \geq 1, \beta > 0 \qquad (6)$$

where α is the shape parameter, β is the scale parameter and Γ is the gamma function. The mean transit time (MTT), which describes the catchment lag (e.g. Hrachowitz et al., 2010), was:

$$MTT = \alpha\beta \quad (7)$$

It was used as an estimate for the time of concentration. The two-parameter gamma IUH model is equivalent to a commonly applied model by Nash (1957), where two parameters, *n* and *k*, are conceptualized as the number of linear reservoirs with storage coefficient *k* (Cheng and Wang, 2002; Singh, 2005; Rabuñal et al., 2007). The IUH method used in this study was previously described by Kokkonen et al. (2004) and the gamma parameters for each runoff event were optimized using a shuffled complex evolution method (SCE-UA) introduced by Duan et al. (1992). The sum of the squared error between the observed and calculated runoff rates was used as the objective criterion. Owing to two different monitoring intervals during the study, ten-minute IUHs were used for studying the changes during the construction works and two-minute IUHs for comparing the study catchments. The changes occurring during the construction were studied using the annual averages and the 95% confidence intervals of α, β and MTT and the rainfall event characteristics P_{TOT} and P_{MAX}. The Pearson correlations between these variables were also investigated (Table 8).

Both initial losses and the hydrologically active area in the study catchments were determined by fitting a simple linear regression equation to the plot marking event rainfall and direct runoff (e.g. Melanen and Laukkanen, 1981; Boyd et al., 1994; Chiew and McMahon, 1999). If the plot gives a straight line, the area contributing to runoff remains constant for all storms (Boyd et al., 1994). The intercept on the rainfall axis gives an estimation of the initial loss, which must be satisfied before any direct runoff occurs. The slope of the regression line describes the *effective impervious area* (EIA). Boyd et al. (1993) extended this approach to consecutive regression lines to estimate contributing surfaces for varying rainfall depths. In this thesis, the significant differences between regression lines for two rainfall event groups (minor and major storms) were tested by using multiple linear regression analysis (Table 8) by inserting a dummy variable and interaction term into the regression analysis, as described earlier in the case of annual runoff (Section 2.4.1). If a significant difference existed, a threshold precipitation was estimated as the intersection of the two regression lines.

Multiple linear regression analysis (MLR) was used to investigate the key variables affecting runoff generation (particularly R_{TOT}, R_{EFF}, Q_{MAX} and C_{VOL}) and event water quality (EMC and EML) (Table 8). In the MLR models, the independent variables included rainfall characteristics, antecedent conditions (Table 7) and catchment imperviousness. Because the water quality MLR models often resulted in smaller R^2 values than the runoff models, runoff characteristics were included as independent variables in the water quality models if they clearly improved the model performance. For the water quality models, independent variables describing the ongoing construction activities were also defined (see Section 5.1.8). Because the variables had skewed distributions, they were log-transformed, and all MLR models had the form:

$$\log(Y) = \beta_0 + \sum \left[\beta_i \log(x_i) \right] \quad (8)$$

where β_i is the regression coefficient for each explanatory variable, x_i. Variables having zero values were transformed as *log(1+x)*.

The MLR models for runoff variables were constructed both for individual catchments and as a combined model for all catchments: the data from the developing SR catchment was divided into two data sets, one representing events before major asphalt works (2001-2003) and another representing events after major asphalt works (2005-2006): the MLR models for runoff variables at SR were separately developed for both data sets, and the latter set was used in the combined models for all of the catchments. For the water quality MLR, a combined model for all catchments was not constructed and all events (2001-2006) were used for the SR catchment without splitting the data.

In MLR, the automatic stepwise method was used. The model building was repeated several times with different variable combinations based on theoretical knowledge, previous regression rounds and bivariate correlations between the variables to reach the best possible model with the minimum number of independent variables. The R^2 values and the standard error of the estimate (SEE) were reported for each model. Only variables significant at the 95% confidence level were accepted. If several variables produced similar outcomes, usually the ones which correlated most highly with the dependent were chosen. Also, explanatory variables that correlated with each other were accepted for the same stepwise regression round: variables exhibiting excess collinearity were afterwards eliminated from the regression based on the multicollinearity statistics (tolerance and VIF). The residual plots were always investigated for outliers as well as for the normality and homoskedasticity of the residuals.

3. Long-term patterns of urban runoff generation and water quality

3.1 Results

3.1.1 Annual precipitation and runoff

The monitoring period represented a range of meteorological conditions from dry to wet years (Figure 9). Compared with the 30-year average at the Helsinki-Kaisaniemi weather station (1971-2000), the annual precipitation varied from 55 to 150 per cent of the 30-year mean. Nevertheless, the average annual precipitation at the three study catchments for the whole study period (614-644 mm uncorrected, 672-702 mm with a correction for snowfall) was close to the long-term average of 624 mm (uncorrected) at the Helsinki-Kaisaniemi weather station.

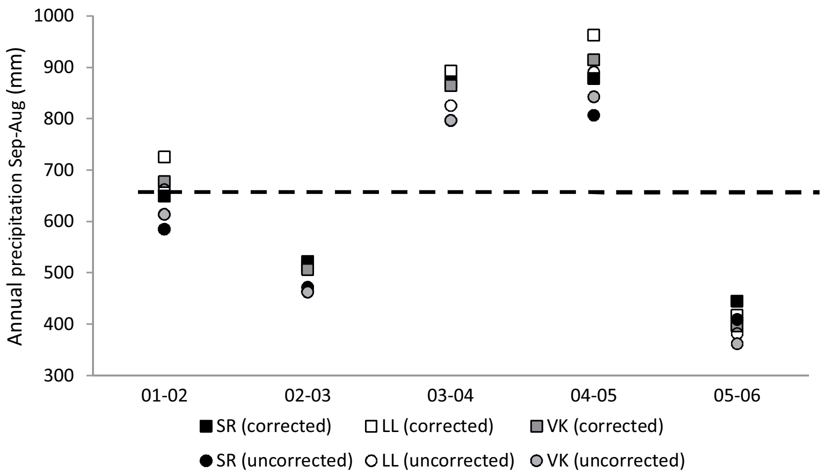


Figure 9. Annual precipitation at the developing SR catchment, the low-density LL catchment and the medium-density VK catchment. A dashed line shows the long-term average for the normal period 1971-2000 from the Finnish Meteorological Institute (FMI).

During the study period, the largest annual runoff was generated at the developing SR catchment and the smallest runoff at the low-density LL catchment. The differences in annual runoff between the catchments increased with increasing annual precipitation (Figure 10). Hence, the largest differences in annual runoff between the catchments were observed during the wet years, 2003-2004 and 2004-2005 (Figure 9).

Annual runoff at the low-density LL catchment and the medium-density VK catchment had a statistically significant linear relationship with the annual precipitation at a 95% confidence level (Figure 10). However, statistically significant differences were not found between these regression lines ($p<0.05$). A statistically significant regression line ($p=0.004$) was found by combining the annual data points of the control catchments, but it had a lower R^2 value (R^2 0.84) than the separate regression models and higher residuals, especially towards the higher precipitation levels. At SR, a direct comparison of annual runoff and precipitation is somewhat dubious, as their relationship was expected to vary not only because of the weather conditions but also because of the changing catchment characteristics. For this reason, and due to the low number of annual data pairs (n=3), a linear regression equation was not included for SR in Figure 10.

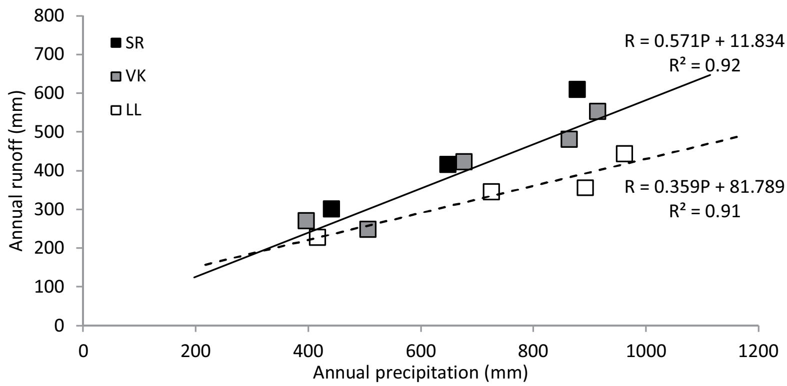


Figure 10. Scatter plot of annual precipitation (P) and runoff (R) for the monitoring years. The number of annual values was 3 for SR, 4 for LL, and 5 for VK. The regression equations are shown for LL (dashed line) and VK (solid line).

The differences in annual runoff generation during construction works were investigated based on annual runoff ratios using three continuous periods without data breaks. The periods are labelled SR1-SR3 for the developing SR catchment and LL1-LL3 and VK1-VK3 for the two control catchments (Table 9). As stated in Section 2.2, the period SR1 included mainly earth-moving activities and road construction works, with only 1.5% of the catchment area classified as impervious. SR2 covered the building construction phase, when the area of the disturbed soil surfaces was largest and the catchment experienced large changes in its TIA, from 19.3% to more than 30% (Table 2). During the construction period SR3, only one new building site was started and the main construction activities were landscaping works. It should be noted that the construction phase SR3 and its reference periods, LL3 and VK3, do not represent exactly the same time periods because monitoring ended at the end of August 2006 at the control catchments, but two months later at SR.

Table 9. Mean annual precipitation, runoff and runoff ratios for the different construction phases at SR and the reference periods at the LL and VK control catchments.

	Period	Precipitation	Mean runoff	Runoff/Precipitation
Construction phases 1-3, the developing SR catchment				
SR1	9/01-11/02	Average (600 mm/a)	372 mm/a	0.62
SR2	6/04-8/05	High (907 mm/a)	655 mm/a	0.72
SR3*	12/05-10/06	Low (442 mm/a)	300 mm/a	0.68
Reference periods 1-3, LL and VK control catchments				
LL1	9/01-11/02	Average (659 mm/a)	297 mm/a	0.45
LL2	6/04-8/05	High (968 mm/a)	454 mm/a	0.47
LL3	9/05-8/06	Low (417 mm/a)	227 mm/a	0.54
VK1	9/01-11/02	Average (610 mm/a)	377 mm/a	0.62
VK2	6/04-8/05	High (936 mm/a)	588 mm/a	0.63
VK3	9/05-8/06	Low (397 mm/a)	271 mm/a	0.68

*) For the period SR3, annual values calculated by multifying 11-month sums with a factor of 12/11

SR1: Clearing and grading, road construction

SR2: Building construction, paving works

SR3: Landscaping, new buiding construction started in spring

Because of the larger TIA, runoff ratios for the medium-density VK catchment were consistently higher than for the low-density LL catchment (Table 9). The high runoff generation at SR was illustrated by large runoff ratios (>0.60) for all of the construction periods. The construction period SR1 had already produced large runoff volumes in comparison to the control catchments, despite the low TIA of SR at that time. This can be explained by the rocky topography of the catchment: due to steeper slopes, thinner soils, and thereby, less storage capacity for soil water, more runoff was produced at SR than LL.

The annual runoff ratios for SR did not reflect the large changes that occurred at TIA during construction works. A similar finding was made when comparing SR and the control catchments: the runoff ratios for SR equalled the ratios for VK during the periods SR1 and SR3, while the ratio for SR even exceeded that of VK during the construction period SR2. At LL and VK, the annual runoff ratios behaved similarly during the three periods: the reference periods 1 and 2 (LL1 and LL2, VK1 and VK2), with average to high precipitation, had nearly equal runoff ratios, whereas the reference periods LL3 and VK3, with low precipitation, had the largest runoff ratios (Table 9). Interestingly, for the control catchments the periods with the smallest annual runoff had the highest runoff ratios.

In terms of runoff generation, the high runoff response to precipitation during the wet conditions of the building construction period SR2 was atypical compared with the other construction periods (SR1 and SR3) and the reference periods for the control catchments. The hydrological behaviour of SR was affected by the presence of disturbed soil surfaces as well as additional pumping from the constructions sites during wet weather conditions. The pumping effect was most clearly observed as a variation in the recession flow rates after rainfall events.

3.1.2 Seasonal runoff generation

Differences in long-term runoff generation during warm and cold periods were investigated using six-month total runoff ratios: the months from June to November constituted the warm period and the months from December to May constituted the cold period. On average, the cold period received 40% and the warm period 60% of the annual precipitation during the study period.

The average runoff ratios during the warm periods were notably smaller than those during the cold periods for all of the study catchments (Table 10), which is a reflection of higher evapotranspiration losses during the warm period. The warm period runoff ratio was always higher for the medium-density VK catchment than for the low-density LL catchment, but the ratios converged during the cold period (Figure 11). For the developing SR catchment, the high runoff ratios (>90%) for the cold period (Table 10) may indicate that the precipitation data from the Helsinki-Kaisaniemi weather station for the cold period was not as suitable for SR as for the other catchments owing to its more distant location (~19 km) from the weather station. In any case, a runoff ratio exceeding 100% for SR, shown in Table 10, is not realistic. The likely reasons causing the uncertainties related to high runoff ratios are discussed in Section 3.2.5.

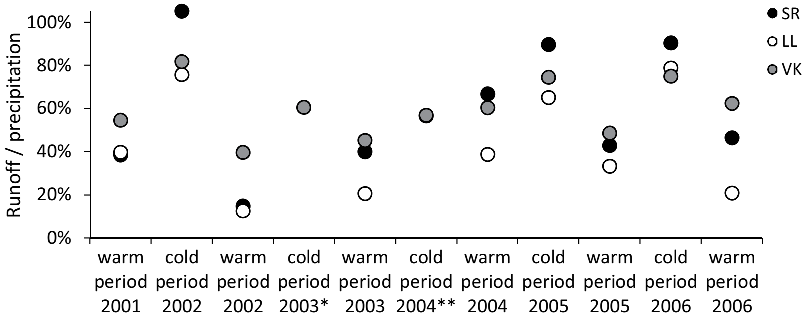
At SR, the cold period runoff ratios were consistently high throughout the monitoring period, yet the warm period runoff ratios changed during the course of the construction works (Figure 11). During the years 2001-2002, the warm period runoff ratios equalled those observed at LL, but during the later years, the runoff ratios resembled more those observed at VK. The change in the warm period runoff ratios became clear only in comparison with the control catchments; if the runoff ratios from SR were investigated without reference to the control catchments, the change would be masked by a high runoff ratio during the 2001 warm period and a low ratio during the 2006 warm period.

Based on the COV values in Table 10, the warm period runoff ratios for LL and SR had higher interannual variations than the cold period ratios. For VK, the six-month runoff ratios showed similar variations during the warm and cold periods, while the interannual variations were lower than at the other catchments. For LL, the warm period runoff ratios were affected by the long-term precipitation patterns, which can be observed as large warm period runoff ratios (>30%) during wet summers and a small ratio (12%)

during a dry summer (Figure 11). This type of weather-dependent effect was not as pronounced at VK, although the dry summer of 2002 had the smallest runoff ratio out of all the years.

Table 10. Minimum, maximum and average runoff ratios for the warm and cold periods (n = the number of periods, COV = the coefficient of variation) at the low-density LL catchment, the medium-density VK catchment, and the developing SR catchment.

		n	min	max	mean	median	COV
LL	warm perioc	6	12%	40%	27%	27%	0.4
	cold period	4	56%	79%	69%	70%	0.1
VK	warm perioc	6	39%	62%	52%	51%	0.2
	cold period	5	57%	82%	70%	74%	0.2
SR	warm perioc	6	15%	67%	41%	41%	0.4
	cold period	3	89%	105%	95%	90%	0.1



* Data from LL and SR discarded due to the freezing problems at the measurement weirs

** Data from SR discarded due to freezing problems and waste water contamination

Figure 11. The warm and cold period runoff ratios during individual study years.

The monthly runoff generation patterns are shown in Figure 12. The large 95% confidence intervals illustrate both a low number of monthly observations and large interannual variations in monthly runoff. Typically, any month could produce runoff ranging from <20 mm to more than 60 mm depending on the weather conditions. Based on average monthly runoff, VK had an even runoff distribution throughout the year, with the exception of low runoff in February (Figure 12). The most pronounced feature in the monthly runoff pattern at LL was the occurrence of the largest monthly runoff in April, during the spring snowmelt. Although VK produced more runoff than LL during summer and autumn, LL had a slightly larger mean monthly runoff in January and February.

The average monthly runoff pattern in the developing SR catchment is presented in Figure 12 for comparison purposes. The use of average values for the entire monitoring period masks the increase that was earlier observed during the warm period runoff generation (Figure 11). The average monthly runoff pattern at SR was visually similar to that at LL, with the exception of larger runoff volumes during the periods from October to March and July to August. Compared with VK, SR produced more runoff during the winter months from December to February and in April. The large confidence intervals compared to the control catchments were affected by the smaller number of months, particularly in March and April at SR.

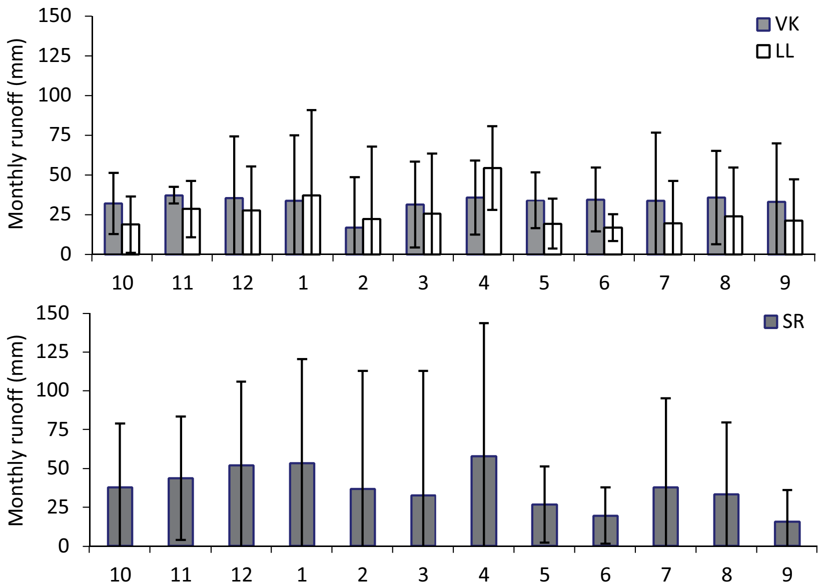


Figure 12. Average monthly runoff and their 95% confidence limits based on the Student's t distribution. The number of observations for each month: 4-6 at SR (3 observations for March and April); 5-6 observations at VK and 4-6 at LL.

During the study years, the importance of different seasons in the annual runoff generation varied greatly along with the changing weather conditions (Figure 13). The summer runoff had the largest interannual variability (COV 0.7-1.0) and the spring runoff the smallest (COV 0.1-0.3). On average, spring contributed 30%, 27% and 26% of the annual runoff at LL, SR and VK, respectively. Based on the average seasonal runoff distributions in Figure 13, runoff at LL and SR was mainly generated during the cold period of the year (on average, about 60% of annual runoff occurred during the cold period), while annual runoff at VK was rather evenly distributed throughout the year. During years with low summer precipitation (2002 and 2006), spring runoff was multifold in comparison with the summer runoff at all catchments: the ratio of spring runoff to summer runoff was 4...6 for LL, 2...3.5 for VK and 3.5...8 for SR, while during the years with high summer precipitation (2004 and 2005), the corresponding runoff ratios between spring and summer runoff volumes were 0.6...0.85 for LL, 0.5 for VK and 0.6 for SR (data for SR did not include spring 2004).

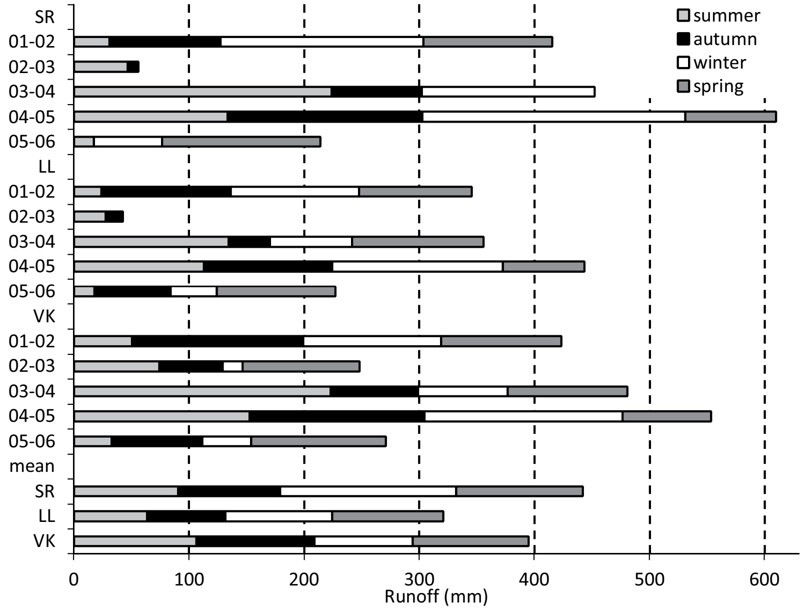


Figure 13. Seasonal runoff (mm) during individual study years and average seasonal runoff distributions for the developing SR catchment, the low-density LL catchment, and the medium-density VK catchment. Only the seasons without data breaks are included: summer (Jun-Aug), autumn (Sep-Nov), winter (Dec-Feb), and spring (Mar-May).

3.1.3 Variations in monthly flow statistics

During the years 2004-2006, the monthly high-flow rates at the developing SR catchment showed a distinct increase in their probability of occurrence compared with the years 2001-2003 (Figure 14). This statistically significant change (the Mann-Whitney test, $p<0.001$) was observed for the whole high-flow range. Significant differences in the monthly high-flow rates between the two periods were not observed at the LL and VK control catchments (the Mann-Whitney test, $p=0.656$ LL, $p=0.367$ VK).

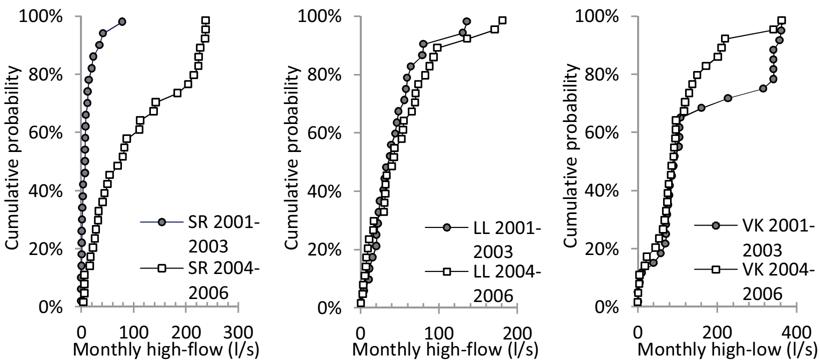


Figure 14. Probability plots of monthly high-flow rates during the years 2001-2003 (grey circles) and the years 2004-2006 (white boxes) for the developing SR catchment, the low-density LL catchment, and the medium-density VK catchment.

For the medium-density VK catchment, the probability of high-flow rates exceeding 250 l/s was higher during the years 2001-2003 owing to a larger number of rainfall events with higher intensities compared with the years 2004-2006 (Figure 14). Also at SR, the highest observed peak flow (79 l/s) during the years 2001-2003 occurred during an exceptional rainfall event: in July 2002, it rained 58 mm in 24 hours, which equals a recurrence interval of 20 years (Kuusisto, 1980). The maximum one-hour intensity of this event (37 mm/h) occurs only once in every 100 years (IDF-curves by FMI, 2006). The high-flow observations were affected by the capacity of the flow monitoring arrangements, which were exceeded two times at SR and eight times at VK; Figure 14 shows the maximum measurable flow rates for these events.

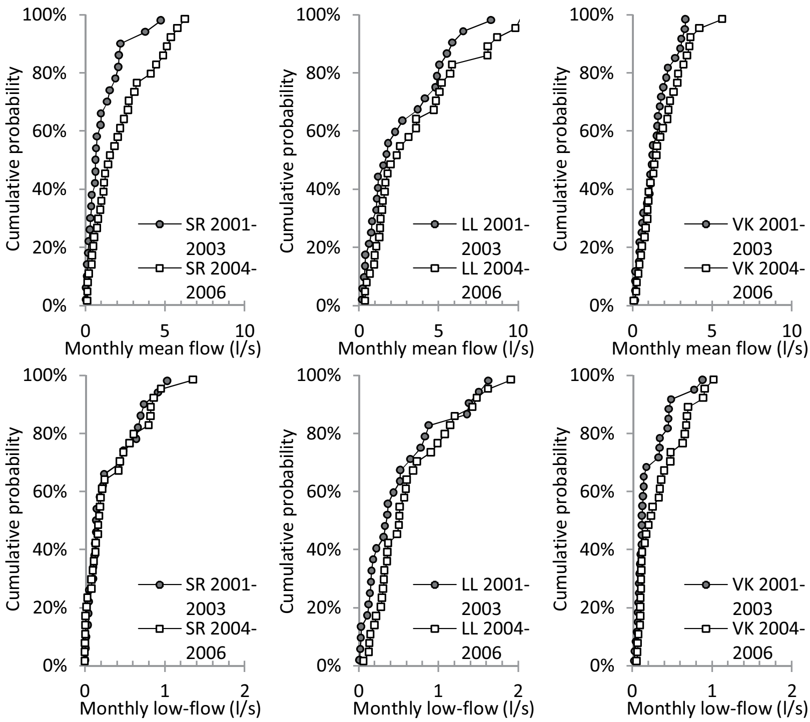


Figure 15. Monthly mean and low-flow rates during the years 2001-2003 and the years 2004-2006 at the developing SR catchment and the LL and VK control catchments.

At the developing SR catchment, monthly mean flow rates increased during the latter monitoring period, whereas the low-flow rates remained unchanged (Figure 15). Also, the LL and VK control catchments had slightly higher mean flows during the years 2004-2006 compared with the first period. Based on the Mann-Whitney test, the observed difference in monthly mean flow rates between the year groups was statistically significant for SR ($p=0.012$), but not for the control catchments ($p=0.205$ in LL and $p=0.324$ in VK). At LL and VK, the wet weather conditions during the year 2004 slightly increased low-flow rates during the years 2004-

2006. In fact, the difference in the low-flow rates between the two periods was statistically significant for VK (the Mann-Whitney test, p=0.025).

At SR, the monthly high-flow rates increased by more than 500% during the study period. At the same time, the monthly mean flow rates doubled (Table 11). The monthly mean and high-flow rates at SR during the years 2001-2003 equalled those at LL. During the years 2004-2006, the monthly mean flow rates at SR reached the level observed at VK, yet the high-flow rates still remained smaller.

Table 11. Comparison of the monthly high-flow and mean flow rates during the years 2001-2003 and 2004-2006 between SR and the LL and VK control catchments.

	Monitoring periods (SR)		Total period	
	2001-2003	2004-2006	LL	VK
Monthly high-flow (l/s/ha)*	2.7	17.0	2.7	24.4
Monthly mean flow (l/s/ha)**	0.06	0.11	0.06	0.10

*monthly high-flow as the 85th percentile of monthly values
**monthly mean flow as median of monthly values

Monthly time series revealed a cyclical pattern in the high-flow rates (Figure 16), which was pronounced in more developed catchment conditions (SR during the years 2004-2006 and VK) and during the wet summers in less developed catchment conditions (LL). Distinct temporal patterns were not observed for the monthly mean and low-flow rates. At all of the study catchments, and especially during the later monitoring years at SR, the highest flow rates occurred between June and October (Figure 17). During the first three years at SR, the high-flow rates during the winter months were comparable to the flow rates in the summer. At VK, the high-flow rates were not as affected by seasonal precipitation pattern as they were at LL; rather, they were affected by the characteristics of individual rainfall events. For this reason, the cyclical pattern appeared as higher peak flows for VK during the summers of 2002 and 2003 in Figure 16.

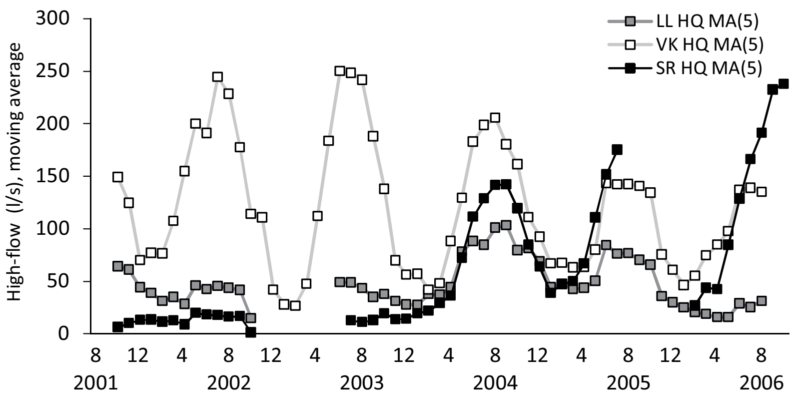


Figure 16. The five-month moving average of monthly high-flows (HQ) for the developing SR catchment, the low-density LL catchment, and the medium-density VK catchment.

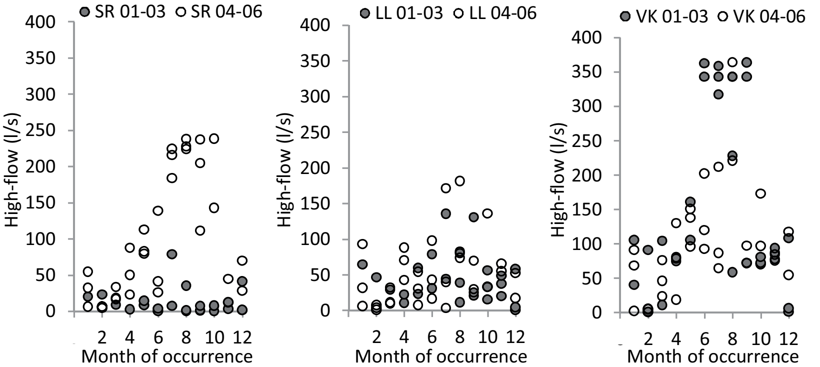


Figure 17. Occurrence of monthly high-flows during the years 2001-2003 (grey circles) and the years 2004-2006 (white circles).

3.1.4 Summary of individual water quality observations

In total, 4100 individual runoff samples were analysed during the study period, both from wet-weather and dry-weather flows. Although the average concentrations of the studied pollutants were largest at the developing SR catchment, very high concentrations were temporarily observed at all catchments (Table 12). Pollutant concentrations varied widely in all of the catchments: based on the coefficient of variation (COV), the highest variations occurred in the TSS concentrations (COV 2.2...5.0), while the smallest variations occurred in the TN concentrations (COV 0.5...0.8). Also, the large differences between the mean and median values implied highly skewed distributions of the water quality variables. The normality of concentration series for all pollutant groups was rejected at the 95% confidence level (the Kolmogorov-Smirnov test). The descriptive statistics revealed that all of the concentration data were positively skewed. Logarithmic transformation improved the symmetry of the distributions, but still the normality assumption was rejected. Due to the high degree of variability in the observed concentrations and the highly skewed distributions, the weight of the data analysis in the following chapters was not placed on assessing the individual concentrations, but on methods that reduce the high variability by using long-term averaged concentrations.

Table 12. The range of individual grab samples taken by automated sampler. n = number of the samples taken during the years 2001-2006. LL = the low-density catchment, VK = the medium-density catchment, SR = the developing catchment.

Water quality based on individual water samples (mg/l)						
		n	**TSS**	**TP**	**TN**	**COD**
LL	range	1426	0.7-11560	0.003-7.7	0.3-11.7	1.3-137
	median/mean		18.1 (68.2)	0.06 (0.11)	0.3 (1.4)	7.0 (8.6)
VK	range	1540	0.2-2540	0.010-3.8	0.2-19.2	1.2-168
	median/mean		25.7 (76.3)	0.08 (0.15)	2.2 (2.4)	6.5 (9.8)
SR	range	1135	0.2-8320	0.005-6.5	0.3-24.6	2.7-193
	median/mean		27.4 (133.6)	0.08 (0.22)	5.5 (6.6)	8.7 (11.5)

3.1.5 Annual pollutant concentrations and pollutant export

The average annual concentrations of all of the studied pollutants were largest at the developing SR catchment and smallest at the low-density LL catchment (Figure 18). Only modest year-to-year variations in the annual concentrations were observed based on the coefficients of variation (COV values ≤0.4), although the TN concentrations at SR (Figure 18b) exhibited higher annual variations in comparison with the control catchments (COV 0.6) and other pollutants. The average annual TSS concentrations were 135 mg/l, 65 mg/l, and 40 mg/l at the developing SR catchment, the medium-density VK catchment and the low-density LL catchment, respectively. Similarly, the mean concentrations for TP were 0.158 mg/l (SR), 0.122 mg/l (VK) and 0.082 mg/l (LL), for TN they were 4.7 mg/l (SR), 2.4 mg/l (VK) and 1.6 mg/l (LL) and for COD they were 10.9 mg/l (SR), 8.5 mg/l (VK) and 7.7 mg/l (LL).

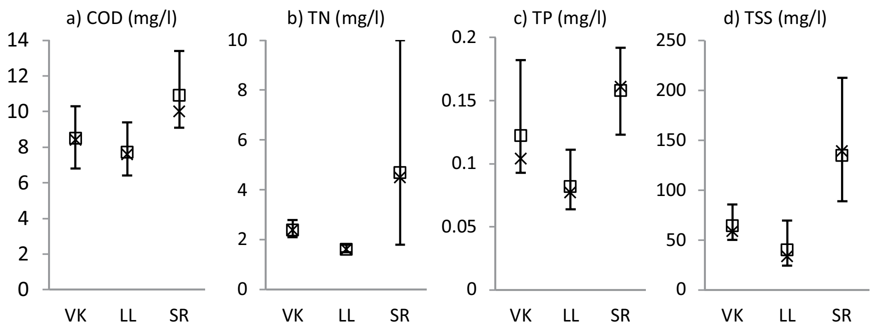


Figure 18. Mean, median and range (min-max) of annual pollutant concentrations for a) COD, b) TN, c) TP, and d) TSS. The means and medians are shown with box and cross symbols, respectively. The means and medians were determined by using the 12-month periods starting from September; four years at VK and LL, and three years at SR. The year 2002-2003 was excluded owing to insufficient water quality data (all catchments) and the year 2003-2004 (SR) owing to periods of wastewater contamination and monitoring problems. The minimum and maximum values were determined based on all available water quality and runoff data.

The annual export rates from the catchments demonstrated similar differences to those already observed in the annual concentrations (Figure 19). Yet, the differences between the LL and VK control catchments were more pronounced for the export rates since annual TSS and TP export rates did not have overlapping ranges (Figure 19c-d). At SR, interannual variations in the TN export (COV = 1.0) were high compared to those for other pollutants and the control catchments (COV ≤ 0.3). At SR, VK and LL, average annual TSS export rates were approximately 54800 kg/km²/a, 26700 kg/km²/a and 12900 kg/km²/a, respectively. Similarly, the average export rates for TP were 65 kg/km²/a (SR), 50 kg/km²/a (VK) and 26 kg/km²/a (LL), for TN they were 2290 kg/km²/a (SR), 1010 kg/km²/a (VK) and 560 kg/km²/a (LL) and for COD they were 4700 kg/km²/a (SR), 3570 kg/km²/a (VK) and 2670 kg/km²/a (LL).

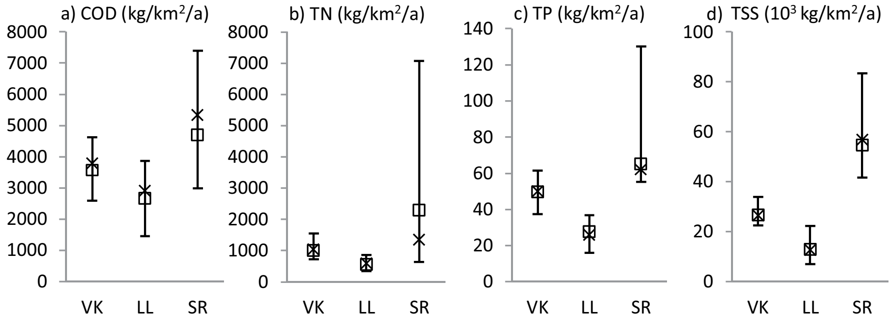


Figure 19. Mean, median and range (min-max) of annual pollutant export rates for a) COD, b) TN, c) TP, and d) TSS. The means and medians are shown with box and cross symbols, respectively. Due to missing autumn months in 2005, one year at SR corresponds to the last continuous 11-month period from December 2005 to October 2006, which has been multiplied by factor 12/11 to correspond to a full year.

The impact of the long-term weather conditions and construction activities on annual pollutant concentrations and export were further investigated based on the three construction periods SR1-SR3 and their references periods, LL1-LL3 and VK1-VK3, which were described earlier in Table 9. It should be noted that the periods SR1-SR3 were chosen so that they excluded the summer and autumn of 2003 and spring of 2004, during which time direct wastewater discharges were observed in the developing catchment (see Section 2.2). Unfortunately, some uncertainty still remains about the extent to which wastewater leaks affected runoff quality outside those periods.

In the control catchments, the largest pollutant export occurred during the periods LL2 and VK2 owing to large runoff volumes (Figure 20). During reference period 3, which had the smallest annual runoff volumes, annual concentrations of particle-bound pollutants (TSS and TP) in particular seemed less diluted compared to other periods for LL and VK. The elevated concentrations compensated for the impact of smaller runoff on annual pollutant export and explained why linear relationships similar to those between the annual precipitation and runoff discussed in Section 3.1.1 were not as distinct in the annual water quality data.

At the developing SR catchment, large changes in both runoff volumes and pollutant concentrations affected the pollutant export. Already during the construction period SR1, the export rates for TSS, TP and COD were larger at SR than at VK owing to higher pollutant concentrations (Figure 20). The main source of the higher concentrations was increased soil erosion resulting from the earth-moving works and road construction described in Section 2.2. SR had a lower TN export than VK during the first construction period owing to both smaller runoff volumes and lower pollutant concentrations. During the construction period SR2, both the large runoff volumes and the higher pollutant concentrations increased the export rates in comparison to VK: the largest difference was observed at TN, which had a 340% higher pollutant concentration and a 380% higher export rate than those observed at VK. During the period SR2, runoff generation was affected by the increasing amount of impervious surfaces, the overland flow from the disturbed soil surfaces and the pumping of drainage water from the building construction sites. The timing of the highest pollutant export during the construction works differed between TN and other pollutants, indicating different sources and transport mechanisms. The main sources of nitrogen are further discussed in the next section. During the construction period SR3, the pollutant export at SR was larger than at VK only in the case of TSS and TN.

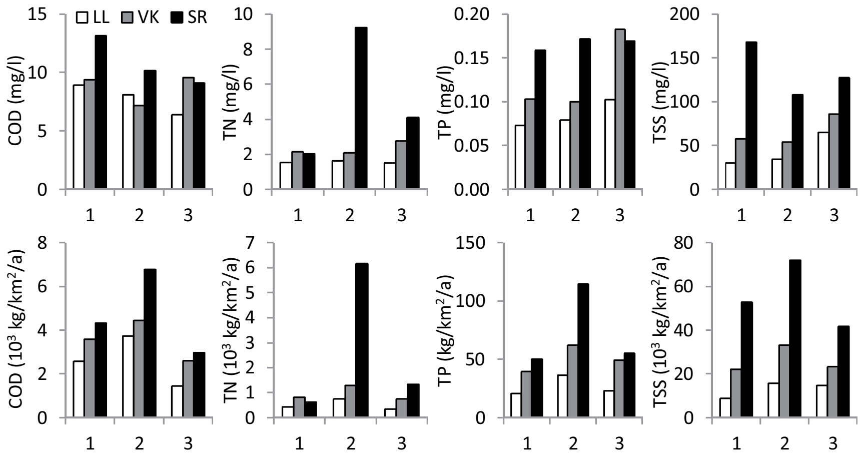


Figure 20. Annual concentrations and export rates during the three construction periods. The numbers 1-3 refer to the construction periods SR1-SR3 and the corresponding reference periods LL1-LL3 and VK1-VK3.

Compared with the low-density LL catchment, both the higher pollutant concentrations and larger runoff volumes resulted in larger pollutant export during all three construction periods at SR (Figure 20). The smallest difference between the two catchments was observed in TN export during the construction period SR1. At worst, the annual TSS export at SR was 500% larger than at LL during the earth-moving works in the construction period SR1, and annual the TN export was more than 700% larger during the construction period SR2.

3.1.6 Patterns and differences in seasonal pollutant concentrations

Hierarchical cluster analysis (HCA) was conducted using monthly log-transformed concentrations to investigate the temporal and spatial behaviour of the pollutant concentrations. The impact of season on the pollutant concentrations was investigated based on 1) an inspection of the average three-month seasonal concentrations and their 95% confidence intervals, and 2) discriminant analysis (DA) of monthly concentrations using the studied pollutants as independent variables and seasons as discriminating groups.

The HCA results are illustrated via a dendogram in Figure 21. In the dendogram, variables connected to each other within a shorter distance along the horizontal distance axis are more similar than the variables with a longer distance between them. The temporal behaviour of TSS, TP and COD was similar for all of the study catchments despite the different land use intensities and ongoing construction activities. The similarities are illustrated in Figure 21 based on the extent to which the patterns of the studied pollutants at each catchment resemble one another. TSS and TP had the closest relationship of all the pollutants, and only TN behaved differently from the other pollutants. The similarities can mainly be explained by the impact of runoff on the pollutant concentrations. The concentrations of TSS, TP and COD increased during runoff events, while the smallest concentrations were observed during the baseflow between the events. In contrast, the TN concentrations sometimes became diluted during runoff events. Especially in the developing SR catchment, the highest TN concentrations were observed in low-flow conditions during the building construction period SR2. The different temporal behaviour of the TN concentrations indicated that the soluble fraction was larger in comparison to the other pollutants and that subsurface runoff was an important source of nitrogen. For the other pollutants, the particle-bound fraction was dominant and the main source was direct runoff during the storm events.

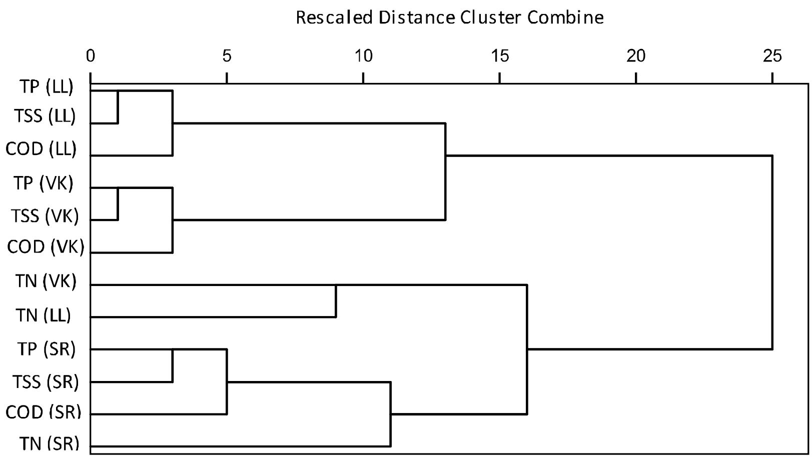


Figure 21. Dendogram of monthly pollutant concentrations using the Ward's linkage.

The HCA results were supported by Pearson correlations. The correlations between three closely grouped pollutants, TSS, TP and COD, were statistically significant ($p<0.001$) at all three catchments. Weaker correlations ($r = 0.6...0.75$) at SR reflected the higher degree of variability in the pollutant behaviour and transport than at VK and LL ($r \geq 0.8$). The TN did not correlate equally strongly with other pollutants at the control catchments, although the TN at SR had significant positive correlations with the TP ($r=0.43$, $p<0.01$) and TSS ($r=0.54$, $p<0.001$). These correlations are also illustrated by the dendogram in Figure 21, where the TN was attributed to the same cluster as the other pollutants at SR, whereas it formed its own cluster at the control catchments. The results indicated that compared with the control catchments, for SR the TN shared periods of similar behaviour with other pollutants, probably as a result of the erosion from disturbed soil surfaces or the periods with wastewater influence.

In Figure 22, the seasonal three-month concentrations at SR had mostly larger average values and higher interannual variations than at the control catchments. Only the average winter concentrations of TSS and TP at SR were below those at VK. The large confidence intervals at SR resulted from the wide variations in water quality caused by construction works, but also from the fact that only three seasons were available for the winter and spring.

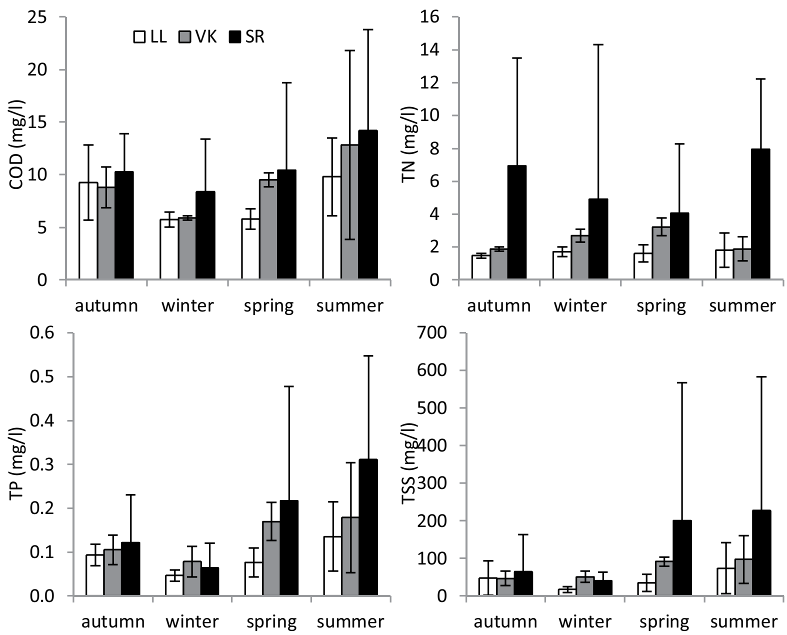


Figure 22. Average seasonal three-month concentrations with their 95% confidence intervals based on the Student's T distribution. The number of seasons (LL/VK/SR): summer (4/5/5), fall (5/5/5), winter (4/4/3), and spring (4/5/3).

The most pronounced differences between the LL and VK control catchments were observed in the spring concentrations of pollutants (Figure 22), which did not have overlapping confidence intervals for any pollutants at the two catchments. Although higher pollutant concentrations at VK were expected based on the annual pollutant concentrations (Section

3.1.5), the differences between the control catchments within the same year depended on the season. Usually, the differences in average seasonal pollutant concentrations between the control catchments were smallest in autumn, whereas equal TN concentrations for summer and COD concentrations for winter were observed (Figure 22).

In Figure 22, the average seasonal TSS, TP and COD concentrations followed a similar annual pattern for all of the catchments: the concentrations were high during the summer and thereafter decreased towards autumn and winter, and then they increased again during the spring. The seasonal pattern of TN concentrations differed between the catchments and also from the other studied pollutants: at VK, the cold period concentrations (winter and spring) were larger than the warm period concentrations (summer and autumn), whereas the situation was the reverse at SR. At LL, average seasonal TN concentrations only varied slightly from season to season

Discriminant analysis (DA) was conducted using the log-transformed monthly data to investigate whether the seasonal concentration patterns had any statistical significance. With DA, the values of the Box's M test statistic did not indicate violations of the assumption of homogeneity of variance-covariance matrices between the discriminating variables. Statistically significant discriminant functions were obtained ($p<0.001$ LL and VK, $p<0.01$ for SR) for all of the catchments. The most discriminating seasonal classification was achieved using three seasons (spring, winter and combined summer and autumn) for VK, two seasons (cold period and warm period) for LL and four seasons for SR (Table 13). The order of the magnitude of the concentrations, which is based on the seasonal classifications, is given in Table 13. By using these classifications, the discriminant functions, D_i, successfully classified 87% of the months at LL and VK. The high percentage (>80%) of successfully classified samples for cross-validation data using the leave-one-out procedure indicated that the discriminant functions may classify cases outside the sample. At SR, the classification results based on seasonality were less successful (40%), showing the strong impact of the ongoing construction works on water quality.

Table 14 shows the standardized values of D_i and their structure matrices, which are needed for interpreting the DA results in Table 13. The standardized discriminant function coefficients (i.e. z-scores) are shown because they are not affected by the units of the independent variables. In order to effectively separate the seasonal groups, the discriminant functions D_i used three water quality variables at VK (TN, TP, COD), two variables at LL (COD and TN) and one variable (TSS) at SR (Table 14). The structure matrix in Table 14 shows the correlations of each water quality variable with D_i. Based on similar correlations, the structure matrix supports the HCA results presented earlier, in which TSS, TP and COD behaved in the same manner at all catchments, whereas TN showed either weaker correlations or an opposite sign of correlation compared with the other pollutants.

Table 13. Seasonal differences in the mean monthly concentrations based on the discriminant analysis and the percentages of successfully classified observations.

Catchment	Function	Order of mean seasonal concentrations	Classification*
VK	D_1 D_2	cold period > warm period spring > summer/autumn > winter	87% / 82%
LL	D_1	warm period > cold period	87% / 87%
SR	D_1	spring > summer > autumn > winter	40% / 40%

* percentage of successfully classified months for all data / cross-validation data

Table 14. Outcome of the discriminant analysis with the log-transformed monthly concentrations.

Catchment	Standardized discriminant functions D_i	Structure matrix*
VK	D_1 = 0.964(TN)+0.173(TP)-0.764(COD) D_2 = 0.912(TP)+0.297(TN)	0.79 (TN), -0.26 (TP), -0.33 (TSS), -0.38 (COD) 0.96 (TP), 0.76 (TSS), 0.76 (COD), 0.43 (TN)
LL	D_1 = 1.162(COD)-0.773(TN)	0.75 (COD), 0.54 (TSS), 0.48 (TP), -0.16 (TN)
SR	D_1 = 1.0(TSS)	1.00 (TSS), 0.70 (TP), 0.55 (COD), 0.20 (TN)

* pooled within-group correlations between discriminating variables and standardized discriminant functions D_i

The DA results supported the seasonal concentration patterns anticipated based on Figure 22. At LL, the simpler concentration pattern (warm vs. cold) required that only one discriminant function, D_1, be adequately described, whereas two discriminant functions, D_1 and D_2, were needed at VK (Table 14). Hence, the variations in monthly concentrations can be illustrated at VK as a two-dimensional space of discriminant scores (Figure 23). In Figure 23, D_1 illustrates the behaviour of the TN concentrations, showing higher scores (i.e. high concentrations) during winter and spring and lower scores during summer and autumn. D_2 illustrates the seasonal behaviour of TP and the variables that correlate more strongly with TP (TSS and COD). For these variables, spring showed high scores and winter low scores, while summer and autumn exhibited large variations between the lower scores and the high scores. The order of magnitude of the seasonal concentrations in Table 13 was based on the group centroids, as illustrated in Figure 23.

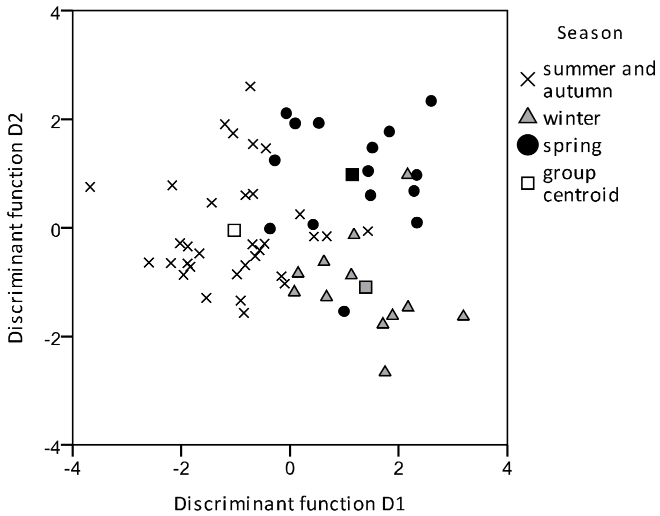


Figure 23. Plot of discriminant functions D_1 and D_2 of monthly pollutant concentrations at VK.

The seasonal concentration pattern (Table 13) at SR resembled the pattern at VK for all pollutants except TN; however, this leaves 60% of the observed variations in monthly concentrations unexplained. In fact, the seasonal patterns in TSS, TP and COD concentrations during the construction works were characterized by discrete time periods of very high concentration levels lasting less than a year, which are illustrated for the entire monitoring period in Appendix A. Appendix A demonstrates that three periods with distinctively high seasonal TSS and TP concentrations included the spring/summer of 2002, the summer/fall of 2004 and the spring of 2006. The high concentration levels during these periods were linked to the erosion of disturbed soil surfaces. The importance of disturbed soil surfaces as a key factor explaining water quality during construction works was also reflected by the selection of TSS as the only independent variable in discriminant function D_1 in Table 14. Seasonal concentrations at SR were eight times higher for TSS and four times higher for TP than at VK (summer 2002) and 18 times higher for TSS and five times higher for TP than at LL (spring 2002). The highest seasonal concentrations of TSS, TP and COD were observed already in spring and summer of 2002 when the TIA was only 1.5%. The seasonal COD concentrations were slightly elevated throughout the construction period and mainly followed the temporal pattern of TP and TSS (Appendix A).

The lack of distinct seasonal patterns for TN concentrations at SR is illustrated in Appendix A: the TN concentrations began to increase in summer 2002, peaking in the summer of 2004, and thereafter steadily declined. The likely sources affecting the TN concentrations during the construction works included the erosion of the soil surfaces, wastewater discharges, blasting and the pumping of drainage water from the building pits. Various documented wastewater incidents have been reported in Section 2.2 that specifically affected the TN concentrations starting from summer 2002. After January 2004, significant wastewater discharges were eliminated through on-site inspections by the local water company. During the period of the highest TN concentrations, the pumping of water from construction sites during wet weather conditions likely enhanced nitrogen export. For example, the impact of similar pumping was once observed at the LL control catchment during small-scale construction works at one of the properties: the highest TN concentrations (12 mg/l) were observed in July 2002, when drainage water from an excavation was temporarily pumped into the drainage network after a rainy weekend. The highest seasonal concentrations at SR reached 13 mg/l in the summer of 2004; however, individual concentrations in baseflow temporarily reached 25 mg/l. At their highest, the seasonal TN concentrations at SR were six to seven times higher than at VK and eight times higher than at LL (autumn 2003 and summer 2004).

3.1.7 Patterns and differences in seasonal pollutant export

The average monthly pollutant export from the individual catchments showed high variations in the overlapping confidence limits for the monthly values (Figure 24). The most striking difference was the frequently large values for the average monthly export and the high degree of variability between the monthly export at the developing SR catchment compared with the LL and VK control catchments. The occurrences of the highest seasonal export rates at SR are illustrated in Appendix A. Seasons with high pollutant export (three-month periods) produced a TSS load of 21000-38200 kg/km^2/season, a TP load of 18-65 kg/km^2/season and a TN load of 400-2900 kg/km^2/season, which for several seasons even exceeded the maximum annual export observed at VK. The COD export peaks at SR were relatively lower than the peaks of the other pollutants in comparison with the control catchments.

The monthly pollutant export was lower at LL than at the other two catchments. The variability and average level of monthly TSS, TP and COD export were highest in November, April and August (Figure 24). The high pollutant export in April was driven by a peak in average monthly runoff caused by the spring snowmelt and rain-on-snow. It is likely that pollutant export in November was also affected by pollutant sources related to winter, such as the gritting of streets. Nevertheless, both November and August were characterized by large variations in runoff generation, from low to moderate/high monthly runoff volumes. The TN export was concentrated in the period outside the summer season and the largest export occurred in April, following the monthly runoff pattern (Figure 12).

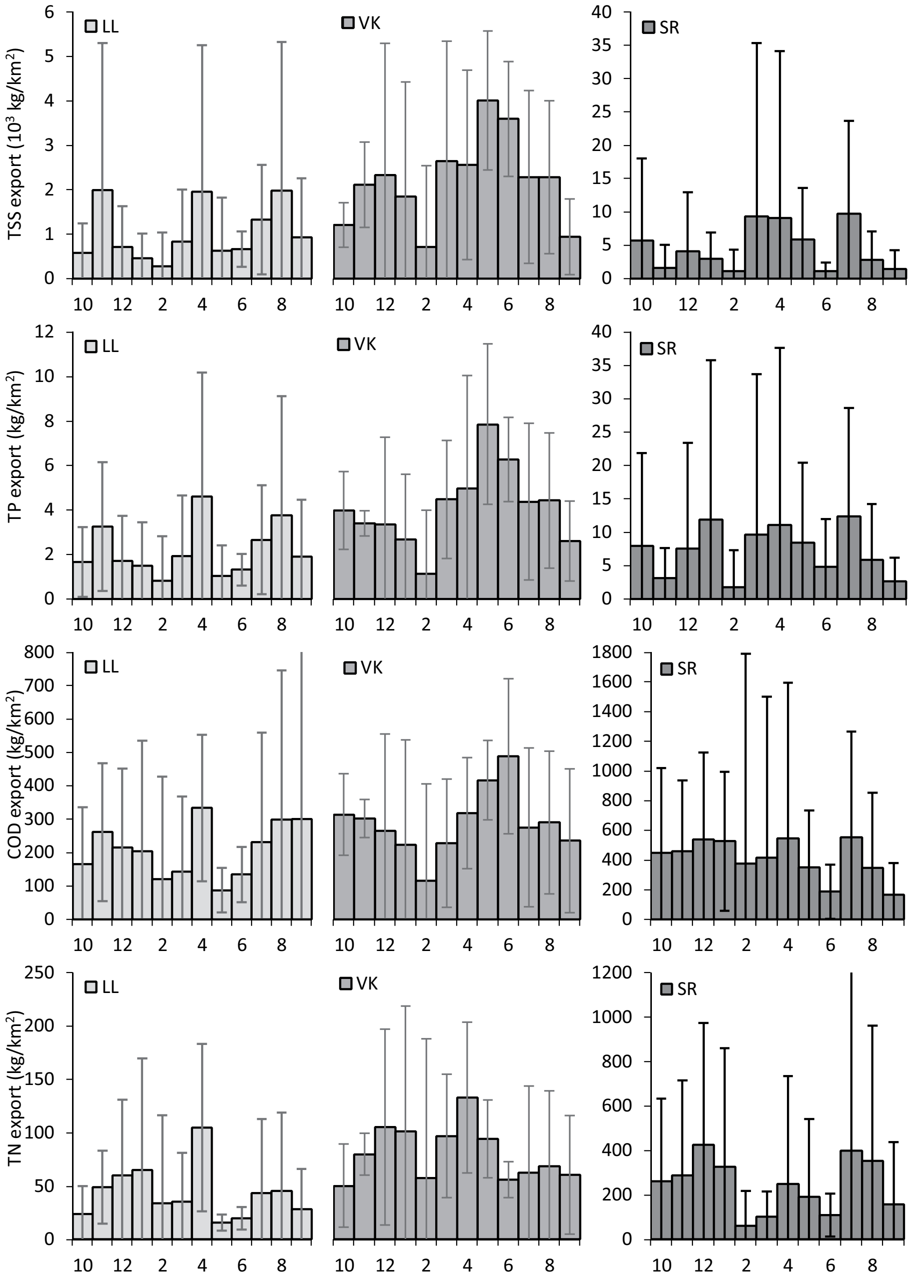


Figure 24. Average monthly pollutant export for TSS, TP, COD and TN with their 95% confidence intervals based on the Student's t distribution. Note the different scales of the pollutant export axes for the developing SR catchment.

At VK, the monthly variations in pollutant concentrations resulted in a pollutant export pattern that clearly differed from the even runoff distribution illustrated earlier in Figure 12. The average pollutant export peaked during late spring or early summer (Figure 24): in April for TN, in

May for TSS and TP, and in June for COD. The monthly pollutant export in May and June was clearly higher at VK than at LL. In comparison to LL, the pollutant export at VK was increased by higher pollutant concentrations during winter and spring and larger runoff during summer and autumn.

Based on the average seasonal proportions of pollutant loads in Table 15, no single season or few seasons dominated the pollutant export in the annual scale. Spring alone did not contribute, on average, more than 35% of the annual pollutant export. However, owing to large annual variations in the weather conditions, annual proportions of more than 40% were observed during individual years for any particular season depending on the pollutant. At LL and VK, the largest proportions of annual TSS and TP export took place in spring and summer, whereas approximately 60% of the annual TN export was produced during the cold period.

Table 15. Average seasonal percentage of annual pollutant load (range in parenthesis) at the developing catchment SR and the LL and VK control catchments. The number of seasons used in calculation (LL/VK/SR): winter (4/4/3), spring (4/5/3), summer (4/5/5), and fall (5/5/5).

		Winter	Spring	Summer	Autumn
TSS	LL	12 (4-23)	28 (10-45)	33 (8-51)	28 (7-50)
	VK	19 (10-27)	35 (24-49)	30 (20-41)	16 (14-19)
	SR	12 (7-18)	45 (4-72)	26 (4-40)	17 (0.4-61)
TP	LL	15 (6-28)	29 (13-45)	31 (10-49)	25 (8-41)
	VK	15 (8-21)	35 (23-54)	30 (19-42)	20 (14-29)
	SR	12 (9-17)	36 (6-64)	32 (7-50)	20 (2-56)
TN	LL	30 (12-48)	29 (16-49)	23 (6-40)	18 (5-31)
	VK	27 (15-41)	33 (17-51)	20 (9-41)	20 (12-27)
	SR	27 (13-36)	16 (6-46)	32 (6-41)	25 (11-41)
COD	LL	21 (8-41)	22 (11-38)	28 (8-50)	28 (7-51)
	VK	17 (7-27)	28 (16-45)	30 (20-45)	25 (18-28)
	SR	28 (15-41)	26 (7-52)	23 (7-37)	22 (3-41)

At the developing SR catchment, seasonal percentages larger than at the control catchments were occasionally observed as a result of the construction works (Table 15). For example, during the construction period SR1, 91% of the annual TSS export (Figure 25b) and 84% of the annual TP export (Figure 25c) occurred in spring and summer of 2002, whereas their proportion of the annual runoff was only 35% (Figure 25a). During the construction period SR3, 42% of the annual runoff occurred in spring, but the last earth-moving activities increased its proportion of the annual TSS to 72%. The results demonstrate that the developing catchment could produce large pollutant loadings during any season of the year depending on the weather, catchment conditions and construction activities.

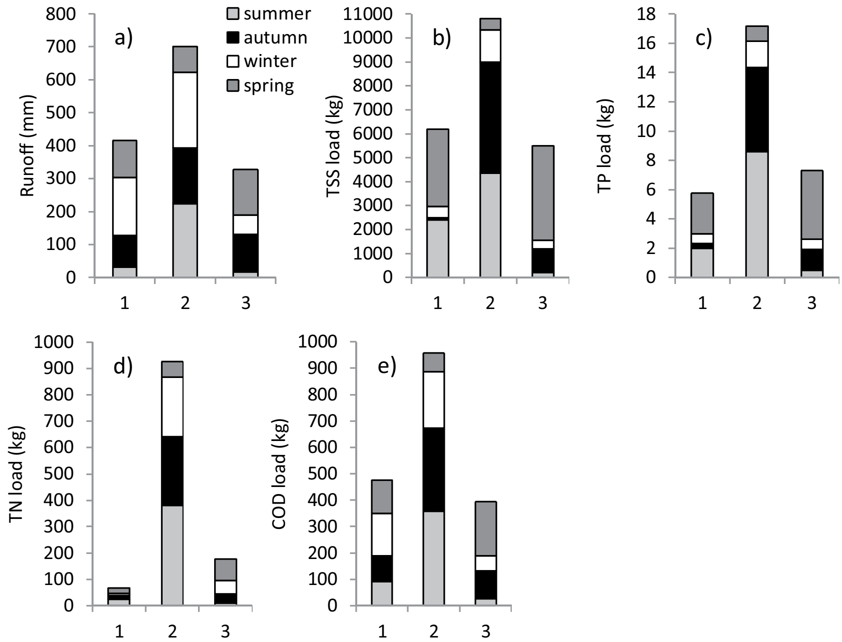


Figure 25. Seasonal distribution of a) runoff (mm) and the load (kg) of b) TSS, c) TP, d) TN, and e) COD at the SR catchment during the construction phases 1-3.

3.2 Discussion

3.2.1 Effects of urbanization on long-term runoff generation

In the following section, the main consequences of urbanization on annual runoff are first discussed and compared to the common principles of urban hydrology established previously in different climatic conditions. Next, the principles that are established in the present study and that underline deviations from the basic theory, especially in local cold climate conditions, are discussed.

Impacts of urbanization on runoff generation according to the common principles of urban hydrology

The widely documented hydrological impacts of urbanization, such as increased runoff volumes and higher peak flows, are commonly linked to catchment imperviousness (Leopold, 1968; Schueler, 1994; Arnold and Gibbons, 1996; Booth and Jackson, 1997; Shuster et al., 2005; Dougherty et al., 2006a; Hur et al., 2008; Schueler et al., 2009; Burns et al., 2012); for example, Dietz and Clausen (2008) reported a systematic, exponential increase in annual stormwater runoff and annual runoff ratios that corresponded to changes in the TIA during construction works at a 2 ha site in Connecticut, where annual precipitation during the study years (~950…1400 mm) greatly exceeded the precipitation range observed in Espoo. In accordance with the prevailing concepts, urbanization increased the total annual runoff in the study catchments based on comparisons between the medium-density VK catchment (TIA 50%) and the low-density LL catchment (TIA 20%), which was discussed in Section 3.1.1. Section 3.1.3 focused on the distinct increase in the monthly high-flows and modest increase in the mean flow rates at the developing SR catchment during the construction works, when the TIA increased from 1.5% to 37%. The six-fold change in the monthly peak flow rates supports findings from other studies conducted in the US, where researchers have observed increases in peak flows by a factor of between 2 and 30 as a result of urbanization (Ferguson and Suckling, 1990; Roesner, 1999; Line and White, 2007; Bedan and Clausen, 2009). The studies conducted in North Carolina (Line and White, 2007) and Connecticut (Bedan and Clausen, 2009) also revealed a larger increase in the peak flows than in the mean flow rates or runoff volumes.

While urbanization clearly increases high-flow rates, its impact on low-flow rates is equivocal. According to Schueler et al. (2009), the commonly assumed inverse relationship between TIA and baseflow has not been confirmed by recent research because irrigation and leakage from the existing water infrastructure tend to increase baseflow. The results from the developing SR catchment also do not support the theories about decreasing low-flows (Section 3.1.3, Figure 15); however, the changing weather conditions and the ongoing construction activities may mask those changes during the monitoring period.

Although urbanization changed the hydrology of the study catchments, the results did not always readily reflect the simple relationship between TIA and the hydrological consequences: for example, the increases in the TIA during the construction works at SR did not result in a straightforward increase in the annual runoff or annual runoff ratios (Section 3.1.1). Data from SR and the LL and VK control catchments also demonstrated that suburban development caused a dissimilar impact on runoff generation over a range of weather conditions: the differences in annual runoff between the study catchments increased with increasing annual precipitation and diminished during dry years. Previously, Ferguson and Suckling (1990) concluded, based on a study conducted in Atlanta, Georgia, that urbanization increased total runoff during wet years; however, they noticed a decrease in runoff during dry years. The weather dependency of the change caused by urbanization on runoff has rarely been reported in climatic conditions similar to those in Espoo. One reason for this is the relatively low annual precipitation in Finland (~660 mm): in many studies conducted abroad, the average annual precipitation corresponds to the highest observed precipitation in the Espoo catchments. In the local conditions for the current study (Sections 3.1.1-3.1.3), several factors in addition to imperviousness influenced long-term runoff generation, including the ongoing construction works, natural catchment characteristics, long-term weather conditions and seasonal variations, which are discussed in the following subsections.

Factors affecting runoff generation during construction works

The developing SR catchment had large annual runoff ratios already at the beginning of the construction works, during the initial tree felling and earth-moving works (the construction period SR1), despite having a low TIA (~1.5%) compared with the control catchments (Section 3.1.1). Burns et al. (2005) studied two suburban catchments with a TIA ranging from 6 to 11% (45 and 56 ha) in New York State and concluded that the expected effects of urbanization may be changed by the features of the remnant natural landscape and other anthropogenic water sources. In the study by Burns et al. (2005), these features included natural wetlands, a deep groundwater supply and septic systems. In Espoo, high runoff generation during the period SR1 was caused by smaller rainfall losses due to the low soil storage and rocky topography of the catchment.

Studies that investigate hydrological impacts during construction and particularly during the different construction phases are rare. Line et al. (2002) observed enhanced runoff generation during the building construction period at a small construction site (4 ha) in North Carolina. They found that 70% of the rainfall produced runoff at a construction site during the house construction phase. At that time, the annual runoff ratio at the construction site exceeded the ratios observed at the reference sites (a residential area, a golf course, a pasture and a wooded site), although it did not have the highest TIA. The annual runoff ratio during the house construction phase was also higher than during the preceding clearing, grubbing and grading phase (Line et al. 2002) and also higher than after the development was finished (Line and White, 2007). Similar runoff behaviour was observed at the developing SR catchment (Chapter 3.1.1) between the construction periods SR1-SR3, during which time the second building construction period SR2 produced the largest annual runoff and the highest annual runoff ratio of all the study catchments. Line et al. (2002) and Line and White (2007) explained the high runoff ratio during the building construction by the lack of established vegetation in pervious areas and the reduced infiltration rate due to compaction caused by heavy machinery. The same factors evidently also increased runoff volumes at SR. In fact, it can be concluded that the high runoff generation during the building construction period SR2 resulted from a combined influence of i) the natural catchment features, ii) the increase in TIA compared with the construction period SR1, iii) the lower evapotranspiration resulting from reduced vegetation, iv) the generation of surface runoff from the disturbed, compacted and saturated soil surfaces with access to new asphalt areas due to wet weather conditions, and v) the artificial pumping of drainage from the construction sites, which were kept as dry as possible during construction.

Seasonal patterns of urban runoff generation

The annual high-flow rate is always an important design factor in water resources management: as in many cold climate countries, the annual high-flow rate in Finland is often observed during spring or early summer as a result of the spring snowmelt (Hyvärinen, 1986). However, the design of urban pipe sewer systems has relied on principles established in warmer climates, with a typical design event being a rather short summer rainstorm (Bengtsson and Semádeni-Davies, 2000). In southern and coastal Finland, the natural runoff pattern can be generalized as having the largest monthly runoff caused by snowmelt during the spring and a secondary runoff peak in autumn, whereas the months with the smallest runoff occur during two seasons, typically in February and in July (Gottschalk et al., 1979). This applies to agricultural catchments, where the most runoff occurs during spring and autumn and the contribution of summer runoff is rather low (Puustinen et al., 2007); in fact, Vakkilainen et al. (2010) concluded that usually more than 90% of the annual runoff occurs outside the growing season for agricultural fields in Finland. Based on the results from the urban catchments in the present study, urbanization changed the natural runoff processes particularly during the warm period of the year: in the developing SR catchment, the warm period runoff ratios increased during the construction works (Section 3.1.2) and the largest high-flow rates already consistently occurred during the warm period at the low-density LL catchment (Section 3.1.3). The results agree with the findings of Dougherty et al. (2006b), who concluded, based on regression analysis for an urbanizing 127 km^2 Cub Run catchment in Washington D.C., that the impact of increased impervious coverage on runoff generation was the clearest during the growing season. The results from the Espoo catchments showed that the seasonal change in runoff generation is more pronounced in places with wintry conditions compared with milder climatic conditions.

In Table 16, the differences in seasonal runoff volumes between the urban study catchments in Espoo and two agricultural catchments in the south and south-western parts of Finland are compared for the period 2001-2005 (Järvinen, 2007). The agricultural catchments of Hovi (12 ha) and Löytäneenoja (562 ha) have 100% and 68% cultivated area, respectively, and the soils are fine-grained, consisting mainly of fine sand, silt and clay (Vuorenmaa et al., 2002). In accordance with the findings on the runoff increase in the warm period runoff, the largest differences between the urban and rural catchments occurred in summer and autumn, whereas the smallest differences were observed in spring (Table 16).

Table 16. Mean increase (%) in seasonal runoff at the urban study catchments compared with two agricultural catchments (data from the years 2001-2005 by Järvinen (2007)). The number of seasons used in the comparisons (winter/spring/summer/autumn): 4/4/4/5 (VK), 3/3/4/5 (LL), 3/2/4/4 (SR).

	Agricultural catchment 1				Agricultural catchment 2			
	summer	autumn	winter	spring	summer	autumn	winter	spring
VK	510	680	120	12	12000	1360	360	38
LL	170	210	100	-4	7200	400	82	25
SR	320	380	270	0	11300	540	240	56

Agricultural catchment 1 = Hovi catchment, 100% cultivated (12 ha)
Agricultural catchment 2 = Löytäneenoja catchment, 68% cultivated (564 ha)

At the agricultural catchments of Hovi and Löytäneenoja, the average proportion of annual spring runoff was 45-56% during the study period, whereas the average proportion of spring runoff did not exceed 30% at the urban study catchments (Section 3.1.2). The decrease in the seasonal proportion of annual spring runoff, however, did not result from a distinct decrease in cold period runoff after urbanization caused by, for example, the transport of snow, but from the increased importance of the warm period runoff. The results of the current study showed that at the medium-density VK catchment, urbanization caused a shift towards an evenly distributed runoff pattern throughout the year, while at the low-density LL catchment the largest monthly runoff still occurred in April as a result of spring snowmelt, and, on average, the cold period still produced more runoff than the warm period for the year (Section 3.1.2).

Despite the different cold climate types, the average monthly runoff pattern at LL (TIA 20%) corresponded to that observed in Trondheim, Norway at a 20 ha residential catchment (TIA 29%) during a five-year monitoring period (Thorolfsson and Brandt, 1996). In Trondheim, runoff during the winter months from November to April was double in comparison to runoff during the summer period, but the largest high-flow rates occurred during the summer season.

Results from larger catchment areas, such as a monitoring study of urban streams (catchment areas 2...23 km^2) in Helsinki, Finland (Ruth, 2004) and a city-scale modelling study of Luleå, Sweden (Semádeni-Davies and Bengtsson, 1999), reflected rather natural seasonal runoff patterns, with the largest monthly discharge occurring in April and decreased runoff during the summer months. The catchments studied by Ruth (2004) had rather large TIAs ranging from 30 to 35%. It is likely that at larger catchments, the area of pervious surfaces and the contributions from subsurface runoff increases, whereas the changed runoff mechanisms at small urbanized sub-catchments are masked by runoff inputs from other land uses. However, taken together with the results obtained by Thorolfsson and Brandt (1996) and Ruth (2004), the results from Espoo (Section 3.1.2) indicate that at a low level of TIA (<30…35%), the monthly runoff still shares the features of natural runoff pattern; however, at a TIA of 20% the occurrence of high-flow rates at small urban catchments shifts towards the dominance of the warm period of the year. It seems that a moderate level of TIA (>40%) is needed to increase runoff during the warm seasons to such an extent that the shift towards an evenly distributed runoff pattern similar to the one at the medium-density VK catchment (TIA 50%) occurs. It should be noted that large variations in weather conditions were observed during the study years (Section 3.1.2): thus, short monitoring periods may lead to some bias in the information about the long-term seasonal runoff patterns in urban areas and about the role of snowmelt or rainfall-runoff in urban water management.

Both rural and urban catchments produce large runoff volumes during the cold period owing to decreased evapotranspiration, and at urban catchments, large runoff volumes are also affected by the snowmelt runoff generated from pervious surfaces, easily reaching paved surfaces and the urban drainage network (Taylor 1977, 1982; Westerström, 1984; Buttle and Xu, 1988; Bengtsson and Westerström, 1992; Thorolfsson and Brandt, 1996). Taylor (1982) observed that at construction sites, saturated conditions in disturbed soil surfaces during spring snowmelt generated runoff that reached a drainage system normally disconnected from the area. The results of this thesis support Taylor's (1977) conclusion that the simple relationship between impervious surfaces and runoff response does not apply in cold climate conditions, as the high total runoff ratios at LL and VK during the cold period were not governed by the extent of TIA as much they were during the warm seasons (Section 3.1.2). Owing to high total runoff generation from the developing SR catchment during the cold period throughout the different construction phases (Section 3.1.2), it seems that disturbed soil surfaces also provided an increase in the runoff-contributing area similar to what Taylor (1982) found during the cold period.

As discussed in Section 1.2.4, conflicting results can be found about the extent to which urbanization affects runoff generation during the cold period of the year (Taylor, 1977, 1982; Buttle and Xu, 1988; Buttle, 1990; Matheussen, 2004). Taylor (1977) compared spring runoff generation at rural and urbanizing sub-catchments in Ontario, Canada, concluding that urban development increases runoff generation during spring snowmelt more than during summer and autumn conditions. Additionally, Taylor (1982) concluded that the seasonal differences in runoff generation are more pronounced at urban catchments than at rural sites. Buttle and Xu (1988) and Buttle (1990) applied Taylor's (1977, 1982) results to a longer period of time for the same study area in Ontario. Buttle and Xu (1988) compared two spring seasons at the suburban sub-catchment and, similar to the results presented in Section 3.1.2, observed a fairly constant runoff generation during the spring snowmelt based on ratios of quickflow to precipitation. Buttle (1990) characterized the results for the impacts of urbanization on cold period runoff generation as equivocal and suggested that more subtle changes occurred under wintry conditions compared with warm period rainfall events. The present study supports Buttle's (1990) conclusions by showing that although the study catchments in Espoo confirmed a TIA-dependent increase in warm period runoff generation, the differences in total runoff ratios between the low- and medium-density study catchments diminished during the cold period. In contrast to Taylor's (1977, 1982) conclusions, the suburban development did not increase long-term runoff depths during the cold period and the seasonal differences in runoff depths became smaller as the TIA increased from low development densities to 50% (Section 3.1.2). It is likely that the different conclusions proposed by Taylor (1977, 1982) regarding seasonal urbanization impacts resulted from the fact that Taylor (1977) conducted his analyses without urbanized reference catchments and that he only reported the results for direct runoff and not the total runoff, as studied in the Espoo catchments.

3.2.2 Impacts of urbanization on annual pollutant concentrations and export rates

Annual concentrations and export rates compared with previous studies

Though a number of researchers have previously studied the increases in pollutant loads with an increasing TIA (Sonzogni et al., 1980; Hatt et al., 2004; Wollheim et al., 2005; Dougherty et al., 2006a; Dietz and Clausen, 2008; Bedan and Clausen, 2009), few have conducted studies in cold climate conditions. The local conditions in Wisconsin (Sonzogni et al., 1980) resemble most closely the conditions in Finland in terms of average annual temperature and precipitation. Yet, Sonzogni et al. (1980) concluded, contrary to the common assumption, that concentrations in urban runoff do not vary much with flow; their conclusion is not supported by the wide concentration variations observed in the present study (Section 3.1.4).

Based on seven urban catchments in Finland, Melanen (1981) also found a strong link between TIA and annual pollutant export. For the Helsinki area weather stations near the residential study catchments (TIA 29 to 40%), Melanen (1981) reported annual precipitation ranging from 475 to 798 mm for the study years, which fits the wider range observed in Espoo (Section 3.1.1). Although Melanen's (1981) study represented one of the most sophisticated monitoring studies of urban areas at the time, certain assumptions were made when calculating the annual runoff and pollutant export, which complicated the generalization of the results and their comparisons in the current study. Melanen (1981) calculated the estimates of mean annual pollutant export using the sum of the average precipitation for the growing season from select weather stations in Finland and the average maximum SWE derived from Mustonen (1973); average concentrations were determined as a flow-weighted mean of the collected composite samples during rainfall-runoff and select snowmelt events, and the proportion of directly connected impervious surfaces as an average runoff coefficient for all seasons. Hence, Melanen (1981) did not use monitored on-site runoff volumes and continuous pollutant concentration data for the annual pollutant export estimates.

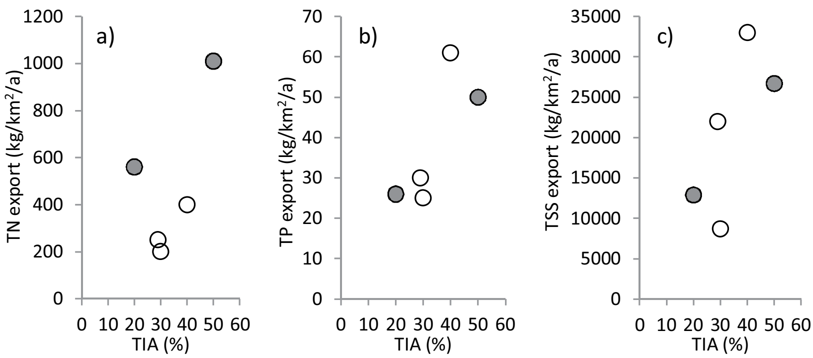


Figure 26. Comparison of average annual pollutant export rates for the LL and VK control catchments (grey circles) to those reported by Melanen (1981) for urban residential catchments in Finland (white circles) for a) TN, b) TP, and c) TSS.

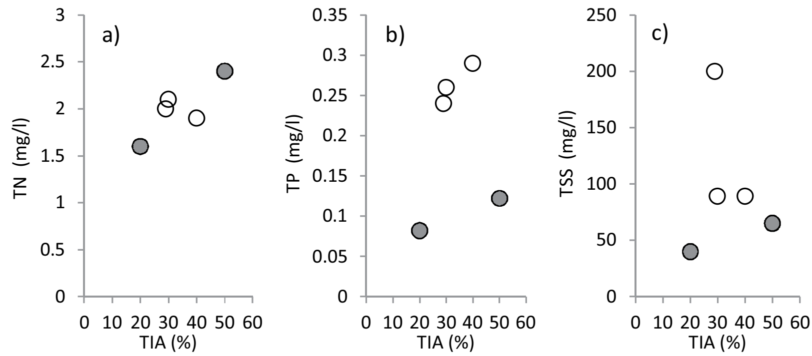


Figure 27. Comparison of average annual concentrations for the LL and VK control catchments (grey circles) to those reported by Melanen (1981) for urban residential catchments in Finland (white circles) for a) TN, b) TP, and c) TSS. For TSS, the average concentration of the warm period events has been used for Melanen (1981).

In accordance with the previous studies, the medium-density VK catchment (TIA 50%) in Espoo produced larger pollutant export rates than the low-density LL catchment (TIA 20%) (Section 3.1.5). In Figure 26a, the average annual TN export rates in Espoo are higher than in the study by Melanen (1981), even though equal TN concentrations (Figure 27a) were observed in both studies. Owing to the higher TP and TSS concentrations (Figure 27b-c), the average annual TP and TSS export rates presented by Melanen equalled or exceeded the average export rates in Espoo (Figure 26b-c). The annual export rates determined by Melanen (1981) still fit the total range of observed annual values at LL and VK (Figure 19 in Section 3.1.5): the equal export rates for certain sites or pollutants reported in both studies are rather coincidental; the findings do not support each other because of the different methods for estimating annual loads. In conclusion, the results of both Melanen (1981) and the present study reveal the TIA impact on pollutant export, but the previous absolute annual levels of pollutant concentrations and loads are biased. The annual export rates of the present study were based on continuous runoff and water quality monitoring for several years and, thus, provide an essential update to the previous results from Finland. The differences in pollutant concentrations between the present and the past studies are further discussed in Section 5.2.6 based on the results for event-scale water quality.

In addition to quantifying the annual pollutant concentrations and export rates, the hierarchical cluster analysis (HCA) in Section 3.1.6 provided results about the long-term temporal behaviour of pollutants and illustrated different temporal behaviour between TN and the other studied pollutants. In Espoo, the concentrations of TSS, TP and COD increased during runoff events and the wash-off of particulate pollutants was mainly associated with direct runoff. TN concentrations did not show as a strong correlation with other pollutants and the concentrations easily became diluted during peak flows, indicating a larger soluble fraction in comparison to other pollutants and baseflow as one source of nitrogen pollution. These results are supported by recent studies conducted in the US and Australia, which report similar differences in temporal behaviour between TSS, TP and TN as observed in Espoo (Goonetilleke et al., 2005; Mallin et al., 2009; Beck and Birch, 2012) and that nitrogen concentrations and export rates are not as strongly associated with wet-weather flow events as the more particle-bound pollutants (Groffman et al., 2004; Taylor et al., 2005; Kaushal et al., 2008; Beck and Birch, 2012).

Annual pollutant export during construction works in comparison to international studies

Concerns about construction sites as a major pollution source in urban areas have been expressed by many authors, especially owing to the erosion of exposed soil surfaces (Wolman and Schick, 1967; Sonzogni et al., 1980; Harbor, 1999; Burton and Pitt, 2002; Hur et al., 2008; Maniquiz et al., 2009). The results of this thesis also strengthen the evidence for the high pollution capacity of developing urban land, since the largest annual pollutant concentrations and export rates during the monitoring study were observed in the developing SR catchment (Section 3.1.5). For this reason, it is surprising that studies investigating the hydrological and water quality changes during construction works are rather scarce outside the US and, to the best of the author's knowledge, no studies have been conducted in Scandinavia, where the geographic and climatic conditions are similar to those in Finland. The need for local data in Finland and in other cold climate countries is evident, since the applicability of monitoring results from abroad is limited to the local conditions, as will be shown in the following paragraphs.

Previously reported annual export rates from construction sites and developing areas in different parts of the US and Canada range from 2,100 to 550,000 kg/ha/a for suspended solids (Wolman and Schick, 1967; Daniel et al., 1979; Sonzogni et al., 1980; Waller and Hart, 1986; Line and White, 2007), compared to which the annual export rates of 420…830 kg/ha/a at SR seem rather low (Section 3.1.5). Similarly, the annual TP export rates in Espoo (0.55…1.3 kg/ha/a) hardly reach the annual values of 1.3…23 kg/ha/a reported for construction sites in the US (Daniel et al., 1979; Sonzogni et al., 1980; Line and White, 2007). At SR, only TN export rates ranging from 6.4 to 70.8 fit the range reported in the previous studies, which were from 10.4 to 63 kg/ha (Daniel et al., 1979; Sonzogni et al., 1980; Line and White, 2007). Fewer studies are available for nutrients than for sediment export and no reference studies from construction sites were found for COD. The COD showed the smallest differences between the study catchments, and hence, it is not as important a study variable as the other pollutants: but the results show that construction works also increase COD transport, as both the COD concentrations and export rates were elevated throughout the monitoring period in comparison to the control catchments.

The possible reasons for the large differences in pollutant export between the different studies include the various local rainfall and catchment characteristics at construction sites (see Section 1.3.2), in addition to the divergent methods of monitoring and data analysis. Previously, sediment concentrations were shown to increase with increasing event precipitation and the kinetic energy or maximum intensity of rainfall (Walling, 1974; Daniel et al., 1979; Nelson 1996, as cited in Burton and Pitt, 2002; Schueler, 2000). The reported annual precipitation for these construction site studies varied from 750 to 1,500 mm per year, whereas in Finland both the average annual precipitation (660 mm) and rainfall energy are rather low. Also, the finer soil types in many studies (e.g. silt loam in the case of Daniel et al., 1979) compared with the sandy till in Espoo explain the lower TSS and TP export at SR. For instance, the suspended solids concentrations for moderate rainfall events (15000…20000 mg/l) observed by Daniel et al. (1979) at three construction sites in Wisconsin highly exceeds the TSS concentrations observed during this study (Table 12). Wolman and Schick (1967) also found a dilution effect based mainly on catchments located in Maryland, leading them to conclude that sediment yields from construction sites declined with increasing catchment areas because construction often occupies only a small percentage of the total area. The highest reported annual sediment yields, such as 550,000 kg/ha/a by Wolman and Schick (1967), only considered an area of 0.65 ha that was completely under construction; thus, a high unit load is expected, even though it seems unrealistic in comparison to the current study. At SR, the area under construction never reached 40% of the catchment area.

Based on the literature review in Section 1.3.2 and the results from the developing SR catchment in Espoo, pollutant export rates from developing areas are affected by so many factors that the results of the monitoring studies are always unique and site-specific. Walling (1974), who studied the event loads and concentrations of suspended sediments at construction sites in Exeter, England, concluded that the increase in sediment export during the construction works was modest compared to the export rates reported in the US despite large increases in event concentrations and loads in comparison to the predevelopment conditions. In fact, the sixfold increase in annual TSS export during the initial earth-moving activities and the eightfold increase in annual TN export during the building construction period at SR in comparison to the low-density LL catchment (Section 3.1.5) are in line with the 8.5-fold increase in sediment loads during separate rainfall events observed by Walling (1974).

Impact of construction phase on pollutant export

Dietz and Clausen (2008) observed an exponential increase in pollutant export according to the changes in TIA during construction works at a 2 ha residential site in Connecticut, but this site had erosion and sediment controls 'typical of other construction sites state wide', which likely reduced the temporary impact of construction works on pollution loads. Thus, this does not correspond to the situation at uncontrolled construction sites. Based on the results from the developing SR catchment (Section 3.1.5), high pollutant concentrations and export rates can be expected during any phase of construction regardless of the TIA, but differences in the timing of pollutant export between the studied pollutants were observed: TSS and TP export rates were already high in the beginning stages of the development, yet TN export and concentrations increased later during the building construction period.

The results from Espoo agree with the findings that TSS transport is related to the times of greatest soil disturbance (e.g. Wolman, 1975). Researchers have disagreed about the role of construction sites as a source of nutrients, especially phosphorus (e.g. Cowen and Lee, 1976; Sonzogni et al., 1980; Waller and Hart, 1986; Line et al., 2002; Ellis and Mitchell, 2006). Based on the results from this study, construction activities have a significant impact on nutrient export and pollutant concentrations: nutrient levels were affected both by additional pollution sources (e.g. wastewater contamination) and by the processes involved with disturbing soil surfaces (erosion from the surface, subsurface leaching). Construction sites have been documented as the source of many construction-related and urban pollutants (e.g. U.S. EPA, 2000): a leaking wastewater sewer, cross-connections between wastewater and stormwater pipes, sanitary wastes and construction debris, the careless storage of construction soils and sand, detergents, oil, paints and the erosion of landscaping mulch and topsoil were observed at SR during the monitoring period, but their impact on total loadings is difficult to quantify. Also, blasting of the bedrock has likely affected pollution loads at the study catchment, a source that has not been emphasized in previous studies.

Although Ellis and Mitchell (2006) mention construction sites as a documented source of nitrogen in the United Kingdom, there are not many detailed studies available about the nitrogen export from construction sites. One example can be found in the previously mentioned studies by Line et al. (2002) and Line and White (2007) of a 4 ha construction site in North Carolina. They divided their monitoring results into phases: the first phase included the earth-moving works and the second phase the building construction and the installation of roads. In their study, TN export and average event mean concentrations (EMCs) increased during the building construction phase, while TSS and TP export rates and concentrations were highest during the initial earth-moving works and decreased during the subsequent building construction phase. The results from the developing SR catchment showed similar temporal patterns in the pollutant behaviour during different construction periods SR1-SR3 (Section 3.1.5), but the main mechanisms affecting TN export and concentrations at SR were only partly the same as those discussed by Line et al. (2002) and Line and White (2007). Line and White (2007) pointed out that fertilizer applications and the organic mulch in plantings were the main source of nitrogen during the building construction period, and other possible sources included enriched topsoil, pet wastes and immature vegetation (Line et al., 2002); yet, they also noted that the concomitant low phosphorus export during the building construction phase was not expected figuring that commercial fertilizers were the main source of the high nitrogen export. Line et al. (2002) did not consider subsurface transport as an important mechanism in nitrogen transport; they presumed that the high runoff during the construction period resulted from low infiltration and washoff of nitrogen instead of transport to the root zone and below. However, based on the results from Espoo, subsurface mechanisms were at least one of the important factors affecting nitrogen transport during the building construction period SR2. Nevertheless, the results of the present study and the studies by Line et al. (2002) and Line and White (2007) support the same conclusion about the lag in TN export during construction works in comparison to the particle-bound pollutants related to the erosion of disturbed soil surfaces.

Based on the findings presented in this study, nitrogen transport from SR shared features with both agricultural and silvicultural land uses, but the nitrogen export was further fortified by the activities and pollutant sources related to the ongoing construction works. According to Wakida and Lerner (2005), pollution caused by nitrate leaching is generally associated with agricultural land use and fertilizers, but the groundwater quality beneath urban areas is also affected by non-agricultural nitrogen sources. Although the main causes of urban nitrogen transport are related to wastewater and solid waste disposal, the nitrate leaching resulting from building construction is potentially similar to that due to the ploughing of pastureland (Wakida and Lerner, 2005). In addition to this similarity to agricultural operations, the first stages of the construction process at SR included clear-cutting of the existing forest. At forested catchments, the increased N leaching after clear-cutting results from changes in the N processes and hydrological fluxes (Laurén et al., 2005). These changes are affected by the on-site amount of decomposable organic matter, the disruption in the uptake of N by trees and the interception of N by the forest canopy, as well as to biological changes in the ground vegetation and microbial populations. At a forested catchment in Finland, clear-cutting increased the N export to a nearby buffer zone 31-fold (Laurén et al., 2005). In Sweden, Jacks and Norrström (2004) observed an increasing TN export after clear-cutting, and estimated an annual export of 41 kg/ha/a during the third year after the operation. At SR, the highest annual TN export rates during the building construction period varied from 60 to 70 kg/ha/a, which is equal to the average annual nitrogen export (65 kg/ha/a) observed by Wakida and Lerner (2002) at three construction sites in Nottingham, England based on soil sampling. Thus, the same mechanisms and patterns of nitrogen export in managed forest areas are likely to also be found during a construction period. Previous construction site studies have not demonstrated that a clear relationship exists between forest operations and urban development in forested areas. It should be noted that temporarily high TN concentrations were also observed at the low-density LL catchment during dry weather as a result of pumping from a small-scale construction works, as described in Section 3.1.6: thus, high nitrogen concentrations were associated with subsurface runoff from a construction site even without the considerable removal of vegetation.

Because construction works immediately increase sediment loads and associated pollutants, they are also the most apparent, the most reported and the most monitored consequences of construction works. The research done in forested catchments has shown that clear-cutting resulted in increased nitrogen export rates only after a considerable lag (e.g. Jacks and Norrström, 2004). This might partly explain why nitrogen pollution during construction works has not been reported if the monitoring periods are short, from several months up to a year. For instance, the large increase in TN export at SR was not observed by Kotola and Nurminen (2003), who concluded that construction works mainly increased the export of phosphorus and suspended solids based on monitoring data from the first monitoring year. Also, monitoring programmes focusing only on runoff event samples may miss the elevated nitrogen levels in runoff during baseflow.

3.2.3 Seasonal patterns of pollutant concentrations and export rates

Data on snowmelt concentrations are scarcer than data for rainfall-runoff events (Oberts, 1990). Semádeni-Davies and Titus (2003) particularly emphasized the lack of catchment scale studies on seasonal water quality in cold climates. Also, the majority of studies have focused on event-scale quality (e.g. Melanen, 1980; Brezonik and Stadelmann, 2002; Semádeni-Davis and Titus, 2003; Westerlund et al., 2003; Hallberg et al., 2007), which raises concerns about the transferability of the monitoring results to longer time scales. Based on a review of several studies in Minnesota, Brezonik and Stadelmann (2002) found seasonal differences in event mean concentrations (EMCs) for commonly studied pollutants, e.g. the median TP and TN EMCs were higher in snowmelt runoff than in rainfall-runoff at most sites. In Minnesota, Oberts (1990) reported elevated COD concentrations in snowmelt for most sites and similar TP concentrations for two event types (snowmelt and rainfall), but lower TSS concentrations in snowmelt. Semádeni-Davis and Titus (2003) compared event TSS concentrations from a 320 ha catchment of industrial and residential land uses in Växjö, Sweden and found only marginally higher TSS concentrations for snowmelt events. Additionally, in a 1986 study Pitt and McLean (as cited in Pitt et al., 1996) found no substantial differences in median TSS, TP and COD concentrations between snowmelt and warm period runoff events in a residential area in Toronto, Canada. At the study catchments in Espoo, summer and spring represented the seasons with the worst water quality (Section 3.1.6); yet, the most pronounced differences in pollutant concentrations between the low-density LL catchment and the medium-density VK catchment were related to spring, and thus, to spring snowmelt and wintertime pollution sources.

Based on the previous literature discussed above, the seasonality of pollutant concentrations in urban runoff is a rather site-specific phenomenon; however, the discriminant analysis discussed in Section 3.1.6 revealed systematic, statistically significant seasonal concentration patterns, which can be explained by the level of urbanization, i.e. the TIA of the study catchments. Similar patterns have not been discussed in the previous literature from abroad. Based on the first year of monitoring data from the study catchments in Espoo, Kotola and Nurminen (2003) suggested that at catchments with a TIA ≥40%, the quality of snowmelt runoff (TSS, COD and TP) is often worse than the summer runoff quality, whereas it is the reverse at urban catchments with a TIA <40%. The results of this thesis from a longer monitoring period demonstrate that the observed seasonal concentration patterns are also statistically significant. Especially at residential areas, the increasing TIA can be associated with higher traffic loads, higher building and population densities, and increased pollution from wintertime road maintenance. The differences in the amount of pollutants stored in snow between the low-density LL catchment and the medium-density VK catchment are further analysed in Chapter 4. Already Melanen (1980) concluded that in city centres and other densely built areas in Finland, the quality of snowmelt runoff was clearly poorer than summer runoff, a phenomenon that was not observed in suburban catchments. Higher event concentrations of TSS and particulates during snowmelt compared with rainfall events were reported in studies conducted in road and highway areas in Sweden (Westerlund et al., 2003; Westerlund and Viklander, 2006; Hallberg et al., 2007). With those sites, a large part of the contributing area consists of traffic-related areas, which are the main source of winter pollutants, and likely only a small amount of ‘clean’ snow exists in comparison to dirty roadside snow. At the study catchments in Espoo, the dilution effect of ‘clean’ snow on concentrations is much stronger than at traffic sites or in city centres.

According to Melanen (1980), only TN had clearly higher concentrations in snowmelt than in rainfall-runoff in all of the studied catchment categories (suburban residential, city centre/commercial, traffic areas, industrial). Also in the current study, the established seasonal concentration patterns discussed in Section 3.1.6 changed according to the pollutants, and, in particular, TN had a different seasonal pattern compared with more particle-bound pollutants. However, the cold period concentrations exceeded the TN concentrations during the warm period only at the medium-density VK catchment. At the low-density LL catchment, a distinct seasonal pattern in TN concentrations was not observed, and the highest seasonal TN concentrations at the developing SR catchment were observed in summer.

Examples comparable to the seasonal pollutant export patterns shown in Section 3.1.7 are rarely reported in cold climate urban runoff studies. Oberts (1994) and Pitt and McLean (1986; as cited in Burton and Pitt, 2002) reported proportions higher than 60% of annual export during spring snowmelt for solids, COD and nutrients in the US and Canada. Bannerman et al. (1983; as cited in Oberts, 1994) observed that spring snowmelt contributed approximately 20 to 33% of the annual loads of sediments and trace metals at sites in Wisconsin. The average annual springtime proportions (22-35%) at LL and VK in Table 15 (Section 3.1.7) mostly resembled the levels in Wisconsin. Moreover, in Espoo, no particular season dominated the majority of pollutant export in the long term, yet during individual years any three-month period can produce more than 40% of the annual pollutant export depending on the pollutant. Higher seasonal percentages were temporarily observed during construction works, especially for TSS.

When the seasonal pollutant export patterns in Section 3.1.7 are set against results from rural areas in Finland, urbanization is clearly found to change the seasonal pollutant export by increasing the importance of the growing season in the annual pollutant export. The annual runoff pattern for agricultural fields in Finland has a substantial impact on the seasonal TSS and nutrient export (Vakkilainen et al., 2010). Usually the greatest loads occur together with the runoff peaks in spring and autumn: for example, at two Finnish agricultural catchments (12 and 1,540 ha, with 100% and 39%, respectively, of the total area being cultivated) studied by Puustinen et al. (2007), only 1-11% of the annual erosion and phosphorus loading occurred during summer, depending on weather conditions and tillage practices. However, the increased importance of the growing season for the annual pollutant export observed in Espoo may not be visible at larger catchments, including less urbanized and more rural areas. For example, at urban stream catchments (2-24 km^2) studied by Ruth (2004) in southern Finland, 31-49% of the annual TSS and nutrient export occurred during spring snowmelt, and the majority of the annual pollutant export occurred outside the summer months.

In Espoo, seasonal concentrations were strongly affected by the ongoing construction activities, and only 40% of the variation in monthly concentrations at the developing SR catchment was explained by a seasonal pattern similar to that at the medium-density VK catchment (Section 3.1.6). At SR, shorter periods with elevated TSS, TP and COD concentrations occurred during each season during the construction works if disturbed soil surfaces or earth-moving works were present at the catchment, regardless of the amount of impervious surfaces. Unlike the control catchments, the construction works caused a pronounced increase in TN concentrations and export in the summer, especially during the building construction.

3.2.4 Pollution potential of urbanizing areas as a diffuse pollution source

Needs for urban runoff treatment derived from water quality criteria

Examples of concentration quality criteria for urban runoff are not easy to find. The possible reasons for this are the high degree of variability in pollutant concentrations and the various catchment and receiving water conditions, which have to be taken into consideration before the impacts of urban runoff can be assessed. Also, the acute impacts associated with high concentrations are rare in comparison with chronic water quality impacts (Harremoës, 1988); thus, the usefulness of concentration criteria for urban runoff is rather limited. In this thesis, the stormwater quality criteria used in Stockholm, Sweden (Stockholm Vatten, 2001) were selected as a reference for the study catchments. Comparisons to the quality criteria are conducted based on annual and seasonal average concentrations in Sections 3.2.2-3.2.3; thus, an exceedance of a limit indicates a more profound increase in the pollutant concentration level than comparisons based only on event mean concentrations or individual quality observations. It should be noted that only four water quality constituents were observed in the current study. As described in Section 1.3.1, a variety of pollutants are commonly observed in urban runoff, which should be taken into account while evaluating treatment need.

For the Stockholm criteria, stormwater concentrations are divided into three categories: low, moderate and high concentrations. According to Stockholm Vatten (2001), stormwater with only low pollutant concentrations does not generally require treatment, whereas moderate or high pollutant concentrations usually require a certain level of treatment. The criteria do not include guidelines for COD concentrations. Stockholm Vatten (2001) emphasizes that, in addition to concentration criteria, annual loadings from the different subareas within the catchment have to always be taken into consideration. 'Treatment' includes all measures aimed at reducing pollutant loadings ranging from source control to structural treatment.

The average annual pollutant concentrations exceeded the threshold for moderate concentrations for all pollutants at the medium-density VK catchment and the developing SR catchment and for TN at the low-density LL catchment (Figure 28). In fact, the average TN concentrations reached the moderate concentration class for all seasons, indicating a year-round treatment need at all catchments. In the case of more particulate pollutants, TSS and TP, treatment is needed especially during summertime at all catchment types, but also during springtime at VK and SR.

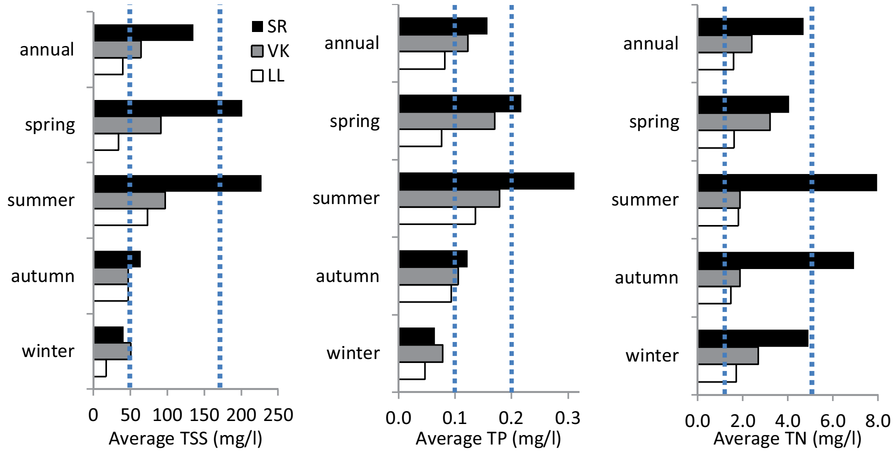


Figure 28. Comparisons of average annual and seasonal concentrations at the developing SR catchment, the medium-density VK catchment and the low-density LL catchment to water quality guidelines set by Stockholm Vatten (2001). In each figure, the first and second vertical lines represent the concentration thresholds between the classes of low/moderate concentrations and moderate/high concentrations, respectively.

Regardless of the type of ongoing construction activities (earth-moving works, building construction, landscaping), the average annual concentrations for all pollutants (Figure 20) indicate a need for treatment during all construction phases. Figure 28 shows that the average seasonal concentrations at SR even reached the threshold for high concentrations, which, according to Stockholm Vatten (2001), is always a sign of the need for treatment. Also, small-scale construction works can raise catchment concentrations to a high level, e.g. at the low-density LL catchment, the seasonal TP concentration exceeded the threshold for high concentrations in summer 2002.

Obviously, the treatment needs depend on the criteria and the chosen quality indicator. Hallberg (2007) based his conclusions about treatment needs for road runoff in Stockholm, Sweden on the TSS discharge requirement of the EU Directive (1991/271/EEC) for urban wastewater treatment. The required threshold of 60 mg/l is only slightly higher than the threshold for the moderate TSS concentration category (50 mg/l) in the classification by Stockholm Vatten (2001) and would not change the previous conclusions about treatment needs based on Figure 28. However, in the strictest sense, the NOEL concentration (*no observable effects limit*) of TSS, 25 mg/l, has also been used as a quality criterion for urban surface runoff as an indicator for potential problems in receiving water ecology (Ellis and Mitchell, 2006); TSS concentrations exceeding the NOEL concentration can, for instance, increase fish mortality (Waller and Hart, 1986). Even low TSS concentrations may have negative impact on fish habitats, e.g. due to the siltation of spawning grounds. If the NOEL concentration for TSS would be taken as the quality criteria, it would be exceeded by the average annual TSS concentrations at all study catchments.

Comparisons of pollutant export from small urban and rural catchments

Another approach to evaluating the importance of urban land use as a diffuse pollution source is to compare unit loads with rural land uses. Figure 29 illustrates a range of annual export rates and their land-use-specific average values based on this study and other monitoring studies conducted in forest, agricultural and urban areas in Finland. No reference values were found for COD; thus, the comparisons only include TSS, TN and TP export rates. The residential areas and city centres were divided into two land use groups because of the statistically significant difference in water quality between the catchment groups observed by Melanen (1981). The residential land use group includes the two residential catchments from this study (TIA 20% and 50%) and three residential catchments (TIA 29-40%) from the study by Melanen (1981). The city centres include two catchments with TIAs ranging from 64 to 67% (Melanen, 1981). The average annual TN and TP loads for forest and agricultural catchments are from Vuorenmaa et al. (2002), and the average value for TSS export is calculated from the data presented by Mattsson et al. (2006) for three forest catchments and from the data presented by Puustinen et al. (2007) for two agricultural catchments. In Table 17, the average values for each land use group are compared with the average values for the forest catchments. The range of export rates for the forest and agricultural catchments in Figure 29 has been obtained from Vuorenmaa et al. (2002), Mattsson et al. (2003, 2006), Granlund et al. (2005), Kortelainen et al. (2006) and Puustinen et al. (2007), and from Vakkilainen et al. (2010) for the TP and TN loads from the agricultural sites in Siuntio and Nummela.

Basically, the agricultural catchments, city centres and developing catchment represent the highest loadings in Figure 29. The annual pollutant export from the residential areas exceeds the pollutant loads from the forested areas. It should be emphasized that Figure 29 only shows the general tendencies between the different land use groups. First, the group of residential catchments included a wide range of different TIAs. Second, the values used for the different land use groups are not directly comparable, for example owing to the different monitoring and calculation methods, the dates and duration of the monitoring periods, and the catchment characteristics in the different studies. The average TN export for residential areas in Figure 29 likely underestimates the TN loading due to the lower values reported by Melanen (1981) for reasons discussed in Section 3.2.2. For instance, the average TN export rate at the medium-density VK catchment was higher than the average for the city centres in the study by Melanen (1981).

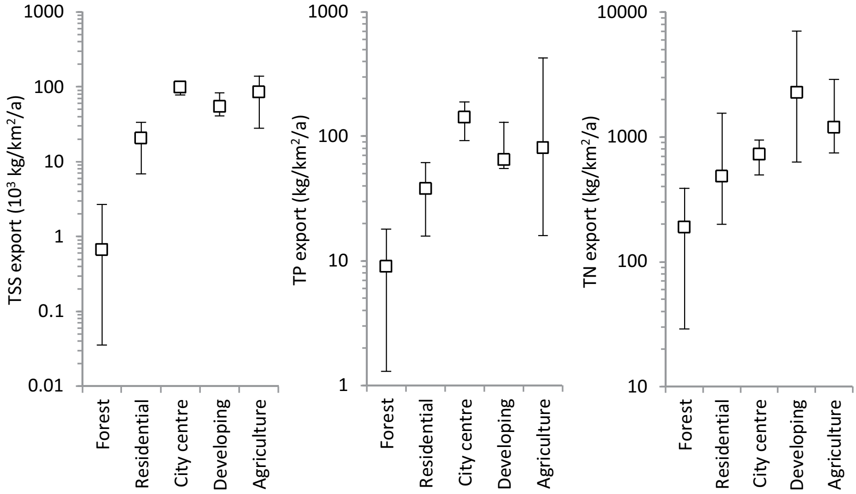


Figure 29. Range of the reported annual export rates in Finland based on land use. Average values are shown as boxes. Reference values from Melanen (1981), Vuorenmaa et al. (2002), Mattsson et al. (2003, 2006), Granlund et al. (2005), Kortelainen et al. (2006), Puustinen et al. (2007), and Vakkilainen et al. (2010).

The average TSS export rates for urban and agricultural land use areas were 30 to 150 times greater than for forest areas and two to 16 times greater than the TN and TP export rates (Table 17). Although the impacts from construction are rather short term in nature due to the rapid decrease in sediment export upon completion of the development (Wolman, 1975; Burton and Pitt, 2002), a single year of construction equals several decades' worth of annual pollutant loads from a forest area, irrespective of the final land use type. The differences in annual pollutant export rates between the land use types are much higher than those observed in runoff: average annual runoff ranging from 150 to 338 mm for small forested catchments located in southern Finland has been reported (Vuorenmaa et al., 2002; Mattsson et al., 2003; Kortelainen et al., 2006), and 240 to 378 mm for agricultural catchments (Vuorenmaa et al., 2002; Puustinen et al., 2007). The average annual runoff based on the monitoring years in Espoo (Figure

10) was 343 mm at LL, 395 mm at VK, and 442 mm at the developing SR catchment.

If the modern sustainable approaches to urban runoff management (see Section 1.1) are used in Finland in the near future, all of the studied urban land use groups in Table 17 would benefit from a reduction in runoff volumes, flow rates and pollutant concentrations as a means of reducing pollutant transport in comparison to forest areas. Based on the unit loads, the need for treatment in urban catchments increases during construction works and as the catchment TIA increases, but this does not take into consideration the different receiving water conditions and mix of different land use types always present in larger areas.

Table 17. Ratios of the average annual export rates for urban and agricultural catchments to forest catchments.

		Residential area	City centre	Developing catchment	Agricultural catchment
Forest areas	TSS	31	148	82	127
	TP	4.2	16	7.2	9
	TN	2.6	3.8	12	6.3

When urban, urbanizing and rural land use types are examined (Figure 29 and Table 17), probably the greatest changes presented by urbanization to rural pollutant export relate to the increases in pollutant loadings during the growing season in addition to the changes in pollutant concentrations owing to urban sources. Previously, the role of spring snowmelt has been emphasized in discussions about urban runoff management. Semádeni-Davies and Bengtsson (1999) conjectured that receiving waters are the most susceptible to pollution during spring owing to high pollutant loads in urban snow and the occurrence of pumping station bypasses. Brezonik and Stadelmann (2002) speculated that years with large amounts of winter snowfall (thus, large amounts of snowmelt runoff), can lead to elevated nutrient loads washed into lakes and streams in early spring, which are then available for uptake during the subsequent growing season and which may cause eutrophication problems. Soranno et al. (1996) discussed the year-round changes in urban runoff, concluding that an increase in urban land use within a catchment may both increase phosphorus loading and change the pollutant export that is less variable over time, resulting in a higher probability of blue-green algal blooms.

3.2.5 Sources of error

It is well known that urban stormwater flow rates and pollutant concentrations are highly variable in both time and space. Hence, a higher temporal and spatial resolution is required for hydrological monitoring in urban catchments than in rural areas. Maksimović (1996) lists the data requirements for some common purposes as ranging from one to five minutes for time series analysis, modelling, real time control and flood mitigation. Daily and seasonal values are adequate for general planning purposes. In terms of the urban hydrological calculations for pollutant transport, Krejci and Schilling (1989) found that a temporal resolution of between 10 and 20 minutes is required for rainfall (as cited in Niemczynowicz, 1996). In addition to these general guidelines, the catchment characteristics affect the required measurement resolution. In the case of the study catchments used for this thesis, the greatest uncertainties are related to the measurement resolution at the medium-density VK catchment, where the 10-minute measurement interval is roughly equal to the time of concentration. The measurement interval was changed to 2 minutes during the summer of 2005. This change also took into account the changes occurring at the developing SR catchment, where the time of concentration was about 10 minutes after the paving works in the summer of 2004. For the purpose of identifying general long-term trends and differences in long-term hydrological and water quality variables, the most detailed resolution is not required, and thus, the monitoring resolution is considered adequate for the results presented in this chapter.

The measurement arrangements at each catchment were different, and thus, they cause uncertainty in the data analysis. The flow measurements were conducted both in sewer pipes and in open weirs. It is expected that the measurements conducted in open weirs allow for more inputs from baseflow, although some baseflow was always present in the sewer pipes as well. Still, regardless of the differences in the measurement techniques, the data series represent runoff from small residential catchments with typical drainage systems for those area types.

At the developing SR catchment, large runoff ratios were observed during the cold periods. There are several possible reasons for larger runoff depths at SR than at the control catchments, e.g. the rocky topography of the catchment and the pumping and other additional spills from the construction sites. Still, owing to the large cold period runoff ratios (>90%), it is likely that the precipitation data from the Helsinki-Kaisaniemi weather station used for the winter months underestimate the amount of precipitation. SR is located furthest away from the weather station and is located along the coastline, whereas the other study catchments are located more inland. There is also a possibility that the catchment area was underestimated: the area used in this study was defined by Kotola and Nurminen (2003), and since then, small changes in the catchment water divide may have happened. However, inaccuracies in the catchment border large enough to cause major errors to the calculated runoff are unlikely.

The measurement installations in open weirs are vulnerable to extreme conditions caused by freezing and thawing. In an urban setting, proper locations for monitoring stations are difficult to find due to a lack of space, and the suitability of a chosen site for construction is often overlooked. The measurement equipment in open weirs is more exposed to harsh weather than those in sewer pipes. For this reason, freezing and thawing caused the most problems to the flow and water quality monitoring at SR and the low-density LL catchment. Often these problems appeared as leaking weirs and led to the rejection of parts of the data from the cold periods. For other parts of the data, the water level data were corrected based on the estimated rates for the leaks. Also, the pressure transducers tend to overestimate flow rates if there is an ice cover in the measurement weir: this effect was corrected in the data with the help of manual water depth measurements.

General rules for water quality sampling are difficult to find and the data requirements depend on the study objectives and available resources. The most important factors affecting the uncertainty of water quality data are the number and representativeness of the collected samples (Marsalek, 1973). In this study, a large number of samples were analyzed (Section 3.1.4) representing all seasons and both wet-weather and dry-weather flows. There are several different methods available for calculating pollutant loads: in the present study, the linear interpolation method was chosen to ensure consistency with the methods used by Kotola and Nurminen (2003).

Monitoring at the developing SR catchment was especially challenging because the accuracy of the measurements was affected by factors related to the construction works. For instance, the monitoring equipment was exposed to damage caused by construction workers operating nearby or by machinery. Coarse sand and gravel from the construction sites broke the sampling tubes several times. The wastewater discharges in January 2004 caused a long data break owing to the solid wastes, which blocked the sampler. Because of these problems, fewer samples were obtained from SR than from the control catchments. Also, during the first monitoring years the runoff volumes and flow rates during rainfall events were often so small that the sampler was not activated. In 2003, fewer samples were obtained from all of the catchments because the monitoring was not conducted as intensively 'between projects'. All of these changes in the sampling frequencies had an impact on the representativeness/accuracy of the measurements, which was impossible to quantify. For SR, accurate information regarding all pollutant sources cannot be given based on the measurements. The chosen sampling method and analyses were not able to quantify the coarser solid material originating from the construction sites, and many discharges associated with the construction works occurred irregularly. Thus, these factors cause great uncertainties in the total loads estimated for the developing catchment.

4. Impacts of urbanization on snow properties

4.1 Results

4.1.1 General description of the snow study period in 2006

January 2006 was relatively warm and the temperature rose above 0 °C several times (Figure 30). In the middle of January, temperatures started to drop and mainly stayed below the freezing point. In the middle of March, snowmelt started with small amounts of daily runoff initiated by solar radiation and large diurnal temperature variations, with above 0 °C peaks. The final melt period commenced in late March and was accompanied by a two-week period of 60 mm of precipitation (about 45% of the total precipitation for the period). Figures 31-32 illustrate the snow conditions at the onset of the spring snowmelt (a) and two weeks later (b), when the snow covered area had shrunk to scattered patches. Although most of the snow had melted by the 18th of April, piles of snow, often completely covered by sand, still remained in shaded areas at the end of the month.

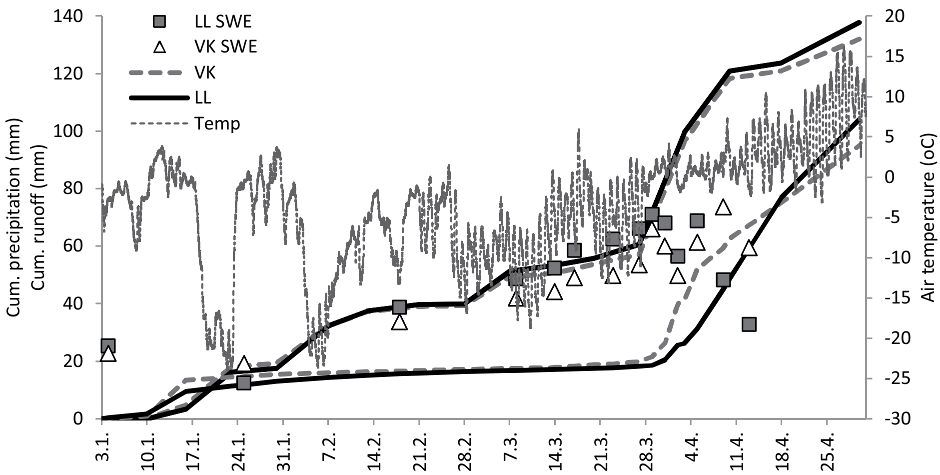


Figure 30. Cumulative precipitation, total runoff and air temperature during the snow surveys in 2006. Also the average SWEs of untouched snow at the study catchments are shown. VK = the medium-density catchment, LL = the low-density catchment.

Both study catchments generated similar runoff volumes during the snow study period (Figure 30). Still, differences in runoff volumes and rates were observed between the catchments, particularly on two occasions: during a mid-winter rain-on-snow event in the middle of January and during the final spring melt. The mid-winter event produced 60% more runoff at VK than at LL. Runoff during this event was 12.6 mm and 7.8 mm at VK and LL, respectively, and clearly exceeded the event precipitation (~3-4 mm). The spring melt started with higher runoff intensity at VK, and after the first two weeks, runoff volumes at LL exceeded those at VK (Figure 30). At LL, the recession phase of the spring melt continued through the first weeks of May, whereas at VK it finished during the month of April.

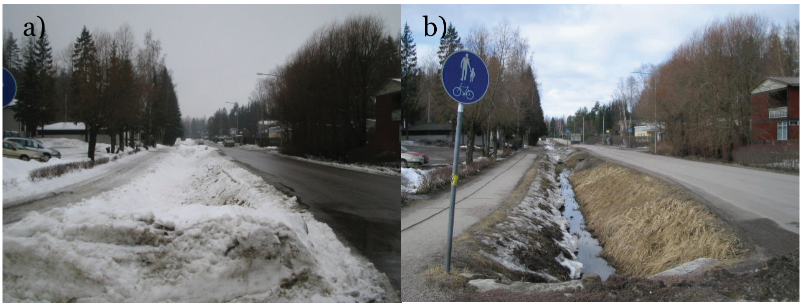


Figure 31. Snow conditions at the main street in the low-density LL catchment a) on the 29th of March and b) on the 12th of April.

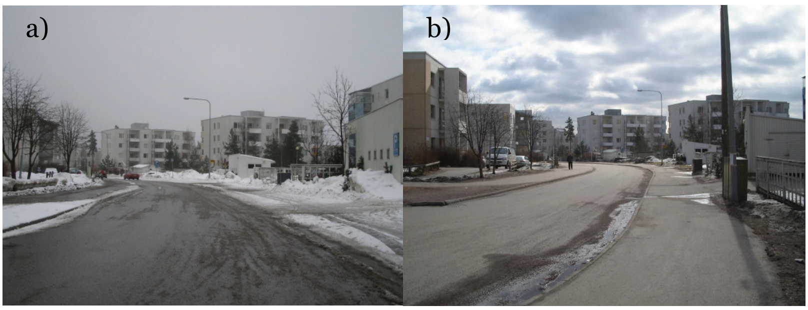


Figure 32. Snow conditions on a residential street in the medium-density VK catchment a) on the 29th of March and b) on the 12th of April.

4.1.2 Snow depth, density and SWE

The surface areas for urban snow types were determined by Samposalo (2007) based on maps and visual inspections of the study catchments. Untouched snow covered the largest area, and the second largest surface group comprised the surfaces with reduced snow cover, such as streets and parking lots (Table 18). Ploughed snow comprised only 1.4% and 0.9% of the total catchment area at the medium-density VK catchment and at the low-density LL catchment, respectively. In Table 18, the combined areal percentage of roofs, streets and parking lots (30%) in LL is larger than its TIA (20%): this is because the unpaved streets in LL are also cleared of snow (Samposalo, 2007).

A summary of the snow depth, density and SWE observations is provided in Table 19. In the following paragraphs, the temporal evolution of the measured snow variables for different snow types are presented using their survey-specific averages (Figures 33-35). The 95% confidence intervals for each snow survey are illustrated in Appendix B. It should be noted that the survey averages presented in the figures for the last surveys are not spatially representative of the total catchment because the last observations were obtained from the existing snowpacks in the shaded areas, when a large part of snow had already melted. This is especially obvious in the final, large SWE values obtained for disturbed snow at VK (Figure 34).

Table 18. Snow types and their surface areas in the medium-density VK catchment and the low-density LL catchment (modified from Samposalo (2007)).

Snow type	Description	VK		LL	
		Area (ha)	Area (%)	Area (ha)	Area (%)
untouched snow	snow in forest, yard, park	6.3	48.2	21.4	69.1
untouched snow	snow on roofs	2.5	19.2	4.6	14.7
snow-free	street, parking lot	4.1	31.2	4.8	15.3
disturbed snow with little contamination	ploughed snow along a walkway	0.1	0.8	0.2	0.5
disturbed snow, significant contamination	ploughed snow along a street with vehicular traffic	0.1	0.6	0.1	0.4
	In total	*13.0*	*100.0*	*31.0*	*100.0*

Table 19. Summary of snow depth, density and SWE observations in the low-density LL catchment and the medium-density VK catchment. COV is the coefficient of variation, i.e. standard deviation divided by the average.

	Snow type	n	mean	min	max	COV
Snow depth (cm)						
LL	untouched	63	25	7.5	39	0.4
	disturbed	61	30	7.5	69	0.4
VK	untouched	110	22	9.0	44	0.3
	disturbed	85	43	12	94	0.4
Density (kg/m^3)						
LL	untouched	62	218	115	372	0.3
	disturbed	57	252	115	437	0.2
VK	untouched	107	223	123	483	0.3
	disturbed	75	300	181	503	0.2
SWE (mm)						
LL	untouched	62	59	9.8	112	0.4
	disturbed	57	91	9.8	276	0.5
VK	untouched	107	45	12.9	133	0.5
	disturbed	75	112	23.1	385	0.5

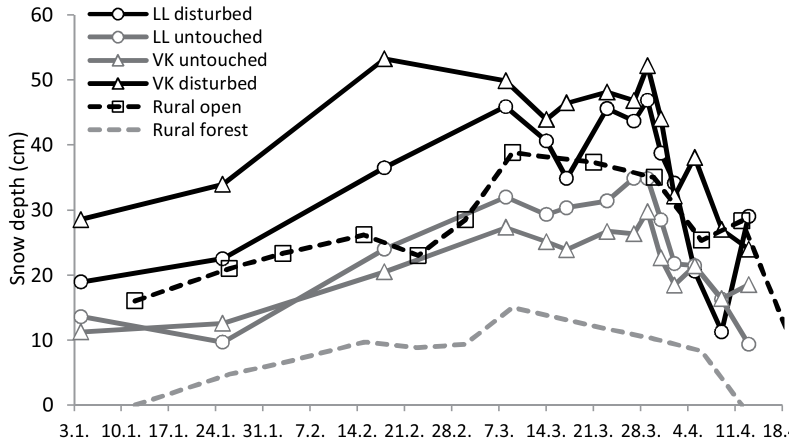


Figure 33. Temporal changes in average snow depths for urban snow types (untouched and disturbed snow) and rural snow (an open clearing and a forest) for each snow survey.

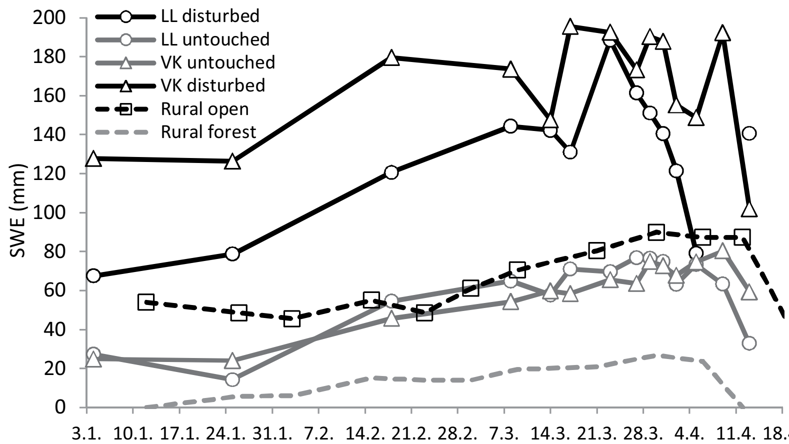


Figure 34. Temporal changes in average SWEs for urban snow types (untouched and disturbed snow) and rural snow (an open clearing and a forest) for each snow survey.

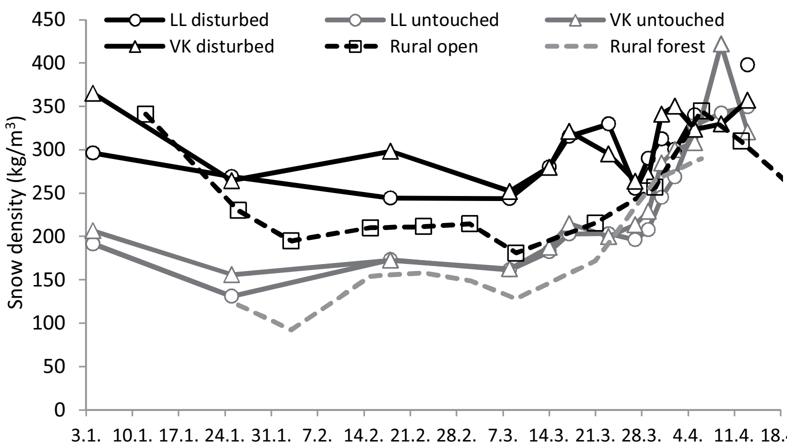


Figure 35. Temporal changes in average snow densities for urban snow types (untouched and disturbed snow) and rural snow (an open clearing and a forest) for each snow survey.

Untouched urban snow did not display distinct differences in its snow depth (Figure 33) or SWEs (Figure 34) between the study catchments based on their overlapping confidence intervals (Appendix B), although the average snow depths were usually higher at LL during the snow accumulation period (Figures 33-34). This probably results from the selection of the measurement points and does not reflect major differences between the catchments. Disturbed urban snow had similar snow depths and SWEs between the urban study catchments starting from March. In comparison to rural snow, the depth and SWE of urban snow types exceeded those of forest snow, but snow depths in the open clearing fell between the different depths of the urban snow types.

The density of the snow exhibited different temporal patterns than the snow depths and SWEs (Figure 35). The density of the disturbed urban snow was high throughout the monitoring period. Untouched urban snow and rural snow did not show distinct differences in their temporal behaviour: the densities of these snow types remained low (130- 215 kg/m^3) until the onset of the spring melt, when the density started to increase. Based on Figure 35 and Appendix B, disturbed urban snow had higher densities in comparison to untouched urban snow up until the final spring snowmelt. During the spring snowmelt period, all studied snow types had high densities above 250 kg/m^3. Based on the overlapping confidence intervals (Appendix B), there were no distinct differences in the snow densities between the urban study catchments.

In terms of snow properties and runoff generation potential, often the situation before the final spring snowmelt is of the most interest; for this reason, the season maximums and their 95% confidence intervals are illustrated in Figure 36. The maximum values were usually observed in the latter half of March; however, the differences in the timing of the season maximums can be seen in Figures 33-35. The values for the density of snow represent the situation during the last survey in March, at the onset of the spring melt, after which the point densities increased throughout the melt period. In Figure 36, disturbed snow exhibited larger variability than untouched snow. Only the SWE had distinctively different maximums for the different urban snow types at both urban study catchments (Figure 36c). The density of snow at the onset of the spring melt showed no pronounced differences between the urban snow types due to the overlapping confidence intervals, although disturbed snow yielded the highest average values (Figure 36b).

The maximum SWEs in Figure 36c were also used to determine the areal SWEs at the onset of the spring melt. The calculation was based on the assumption about snow-free streets derived from SCA observations;

however, sand/gravel roads in particular had some snow and ice, which could not be measured. The surface areas for the calculation of areal SWEs were taken from Table 18 as untouched snow, disturbed snow and snow-free areas. If only the snow-covered area was considered, both study catchments had equal areal SWEs (~77-78 mm). Nevertheless, if the total catchment areas are considered, the areal SWEs shown in Figure 36d were affected by the extent of snow-free areas, resulting in a lower areal SWE at VK (53 mm) than at LL (66 mm). Especially at VK, ploughed snow was transported away from the catchment during the latter half of March. Accurate information about the quantity of the removed snow was not available while conducting the study. However, the city employees have estimated that approximately 100-200 truckloads of snow can be transported away from VK in wintertime; this accounts for approximately 3-7 mm of available water for snowmelt. Less snow is transported outside the catchment area at LL.

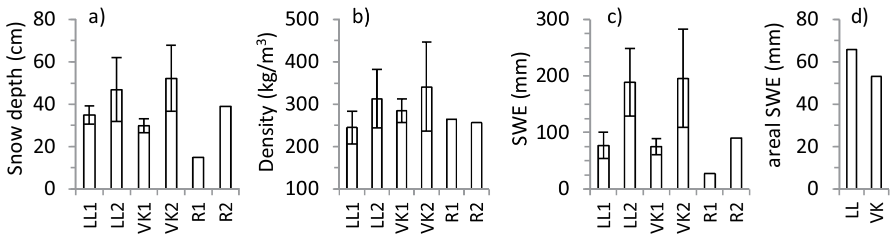


Figure 36. The maximum snow depths (a), densities (b), and SWEs (c) as survey averages from point measurements (3-8 measurements per snow type) and their 95% confidence limits from the Student's t distribution (modified from Sillanpää and Koivusalo, 2013). Density values represent the situation at the end of March. Areal SWEs (d) calculated from the season maximums are shown for the urban study catchments. LL1/LL2 = untouched/disturbed snow in LL, VK1/VK2 = untouched/disturbed snow in VK, R1 = rural forest snow, R2 = rural clearing.

4.1.3 Pollutant concentrations and unit mass loads in snow

After a visual inspection of snow concentrations and their time series, the measurement points were classified into three snow groups: ploughed snow with a direct connection to vehicular traffic (group 1), ploughed snow along walkways without a close connection to vehicular traffic (group 2) and untouched snow (group 3). This classification led to a slightly different composition of ploughed snow types between the study catchments. At the medium-density VK catchment, group 1 included measurements from roadsides and ploughed snow on pedestrian walkways alongside vehicular streets. Group 2 consisted of ploughed snow from two pedestrian walkways in a park and forest area without any vehicular traffic except for maintenance vehicles. At the low-density LL catchment, group 1 mainly consisted of measurements of roadside snow along vehicular streets, whereas group 2 consisted of pedestrian streets separated from vehicular streets by snow banks.

Table 20. Range (min-max) of concentrations for different snow types including all snow surveys at the low-density LL catchment and the medium-density VK catchment.

		n	Group 1 *street with traffic*	Group 2 *street without traffic*	Group 3 *untouched snow*
LL					
TSS	(mg/l)	10/8/18[1]	280-2627	49-500	9.6-44
TP	(mg/l)	10/8/18	0.421-2.905	0.078-1.396	0.018-0.083
TN	(mg/l)	10/8/18	0.7-2.0	0.4-2.4	0.4-2.4
COD	(mg/l)	10/8/18	6.3-32.9	2.2-9.8	1.1-6.2
pH	(-)	7/6/14	6.2-9.0	4.9-6.3	4.3-5.3
EC[2]	(mS/m)	7/6/14	2.1-190	0.6-10.4	0.02-24.7
VK					
TSS	(mg/l)	31/19/53	157-2843	56-506	2.8-168
TP	(mg/l)	31/19/53	0.239-5.709	0.059-5.826	0.022-0.253
TN	(mg/l)	31/19/53	1.1-26.5	1.3-31.0	0.4-3.3
COD	(mg/l)	31/19/53	3.3-76.5	2.7-32.3	0.5-10.4
pH	(-)	28/18/47	6.1-9.0	5.0-7.3	4.3-6.5
EC	(mS/m)	28/18/47	2.3-209	1.0-14.2	0.4-3.9

[1] number of observations: street with traffic/street without traffic/untouched snow
[2] electrical conductivity

Table 21. Range (min-max) of unit mass loads for different snow types including all snow surveys at the low-density LL catchment and the medium-density VK catchment. Note the different unit for TSS.

		n	Group 1 *street with traffic*	Group 2 *street without traffic*	Group 3 *untouched snow*
LL					
TSS	(g/m^2)	10/6/18	31-283	16-41	0.6-3.1
TP	(mg/m^2)	10/6/18	53-326	58-109	1.1-9.2
TN	(mg/m^2)	10/6/18	33-278	121-263	21-190
COD	(mg/m^2)	10/6/18	798-5243	264-757	46-210
VK					
TSS	(g/m^2)	31/18/51	23-1041	1.8-75	0.06-13
TP	(mg/m^2)	31/18/51	34-1458	1.9-1120	0.5-24
TN	(mg/m^2)	31/18/51	140-3736	49-3536	13-347
COD	(mg/m^2)	31/18/51	475-20264	91-6205	17-1064

[1] number of observations: street with traffic/street without traffic/untouched snow

The point snow measurements covered a large range of pollutant concentrations (Table 20) and unit mass loads (Table 21). The pollutant concentrations and unit mass loads did not exhibit clear temporal trends during the monitoring period owing to the high variability between the measurement points and snow surveys, and the highest concentrations could occur any time during the winter and spring. In the absence of distinct trends, differences between the snow types were investigated using the arithmetic average of survey-specific means for each snow type and their confidence intervals (Figure 37).

In Figure 37, the 95% confidence intervals illustrate the higher variability observed in the quality of ploughed snow in comparison to untouched snow. At the medium-density VK catchment, all of the studied pollutants except for TN had the highest mean concentrations and unit mass loads for group 1, the second highest for group 2 and the lowest for group 3. In contrast to other pollutants, group 2 had the highest TN concentrations and mass loads at VK (Figures 37b and 37h). The sampling points at VK were located along pedestrian walkways in park and forest areas, where pet excrement was a major contributor to the observed high nitrogen levels. At the low-density LL catchment, TN concentrations and mass loads were nearly the same for groups 1 and 2. At VK, high TP concentrations were also observed for group 2 snow, which is illustrated as larger confidence intervals in Figure 37c.

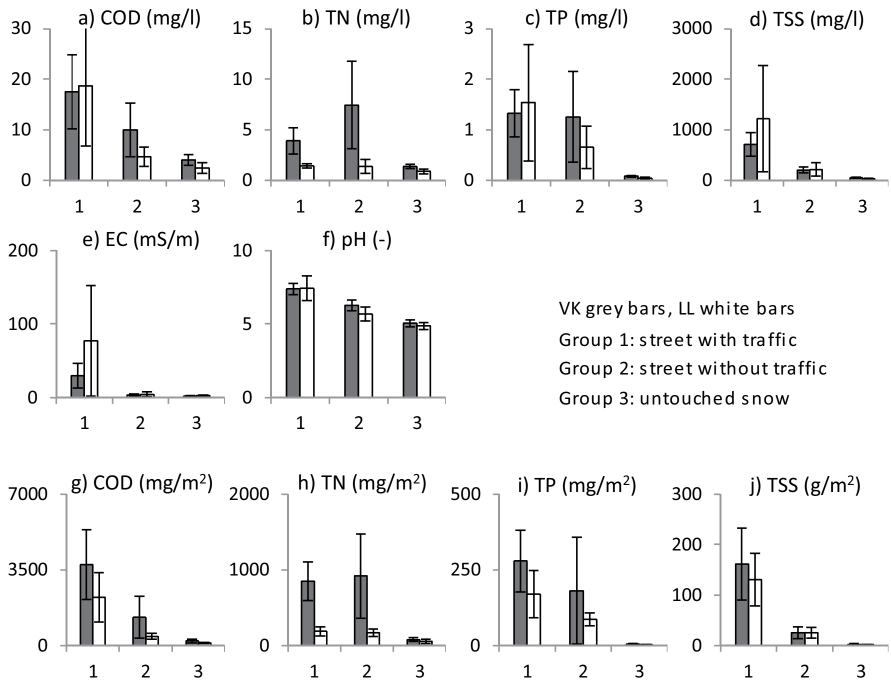


Figure 37. The arithmetic means of pollutant concentrations (a)-(d), conductivity (e), pH (f), and unit mass loads (g)-(j) for the three groups of urban snow based on the survey means (Sillanpää and Koivusalo, 2013, reprinted with permission from IWA Publishing). The 95% confidence intervals are shown as error bars. The number of survey means for different snow types: 11-13 in VK and 5-7 in LL.

The use of road salt for de-icing vehicular streets appeared as distinctively higher conductivity for group 1 snow than for the other snow types (Figure 37e). At LL, the mean conductivity of roadside snow was more than double the conductivity of roadside snow at VK. This can likely be explained by the location of the sampling points rather than by different routines in the usage of de-icing salt — at LL, more measurement points were located in the actual snow pile along vehicular streets, whereas at VK they were located along elevated walkways attached to the main roads. Road salt is mainly used for the safety of vehicular traffic, thus conductivity in group 2 did not differ from untouched snow as much as it did for group 1 snow. The location of the measurement points in group 1 also explained the higher TSS concentrations at LL compared with VK, while equal TSS concentrations for group 2 indicated similar snowpack conditions and usage of sand as an abrasive at both catchments (Figure 37d). For COD (Figure 37a) and TP (Figure 37c), large differences in average concentrations for group 1 snow were not observed between the catchments (Figures 37a and 37c). The pH level was the only quality parameter exhibiting equal values for all snow types at both catchments (Figure 37f).

Although the differences between the study catchments were not always consistent in terms of their pollutant concentrations, average unit mass loads for each snow type were usually higher at VK than at LL (Figure 37g-j); however, overlapping confidence intervals between the catchments were observed for all pollutants except the TN mass loads in snow groups 1 and 2 (Figure 37h). Unit mass loads at VK were increased by the larger amount, i.e. higher SWE, of disturbed roadside snow exposed to vehicle activity, especially during the first part of the winter, and also by the pet wastes mentioned earlier. Also, the impact of atmospheric deposition was likely higher at VK owing to slightly higher mass loads of untouched snow.

During nine and six snow surveys at VK and LL, respectively, samples were also analysed for dissolved P, N and COD concentrations (usually 1-2 samples per sampled snow course). During the spring melt, descending temporal trends were observed in the dissolved proportions of the total concentrations. The example in Figure 38 shows the proportions of dissolved concentrations from the snow courses VK1 and LL1, which included untouched and disturbed snow near the main streets (see the locations in Figure 3).

In the middle of March, nearly all TN was in a dissolved form in all snow types at both catchments (Figure 38). The high percentages (>100%) of dissolved TN at LL for untouched snow (Figure 38d) indicate inaccuracies in the chemical analysis for the first two field surveys. By the end of the monitoring period, the percentage of dissolved N decreased to 25-66% for both catchments and snow types. The TP and COD had lower dissolved fractions compared with TN. For COD, the dissolved percentage varied from 22 to 84% in the middle of March to less than 10% at the end of the monitoring period. The higher dissolved fraction was observed in untouched snow (Figure 38c-d). Compared with TP and TN, the dissolved fraction of COD in untouched snow declined faster during the spring. For the dissolved TP in untouched snow, a descending trend was observed. Instead, for TP in ploughed snow, the dissolved fraction was low (<15%) at both catchments without there being a distinct trend (Figure 38a-b). A reason for the absence of a trend in the dissolved TP in ploughed snow was the strong particle-bound nature of phosphorus and the abundance of solid material due to the gritting of streets throughout the snow monitoring period.

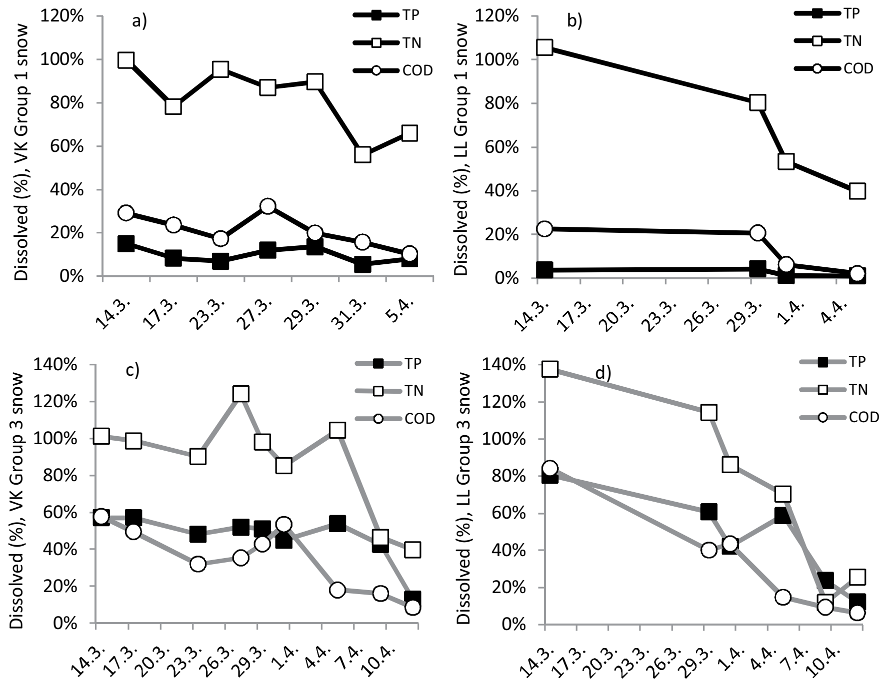


Figure 38. Proportions of dissolved substances in relation to the total concentrations (%) in the low-density LL catchment and the medium-density VK catchment: a) VK group 1, b) LL group 1, c) VK group 3, and d) LL group 3. Group 1 and group 3 mean ploughed snow on vehicular streets and untouched snow, respectively. Concentrations are based on one sample per the snow course for each survey. Proportions over 100% indicate inaccuracies in the laboratory analysis.

4.1.4 Areal pollutant mass loads

The survey-specific mean unit mass loads and their surface areas were used to estimate areal *snow mass loads* (SML) for both catchments. SMLs were estimated for both the total catchment area and the snow-covered area. Based on Table 18, the surface areas in the medium-density VK catchment for each snow type were 0.1 ha for the ploughed snow along streets with traffic (group 1), 0.1 ha for the ploughed snow along walkways (group 2) and 8.8 ha for the untouched snow (group 3). The corresponding surface areas in the low-density LL catchment were 0.1 ha, 0.2 ha and 26.0 ha.

The representative unit mass loads for each snow type were chosen in two different ways. First, the highest survey-specific mean unit mass loads for each snow type and pollutant were chosen to represent the maximum mass storage capacity of a pollutant before the initiation of spring snowmelt (Table 22). Hence, the unit mass loads presented different dates because different pollutants and snow types exhibited their maximum loads during different surveys. Second, SMLs were calculated for all snow surveys using the survey-specific average unit mass loads for each snow type, and the largest SML before the spring melt was chosen: thus, for each pollutant, unit mass loads from the same survey were used. The differences between the two estimates were not large, as can be seen in Table 23. At the medium-density VK catchment, SMLs were about four-fold (COD), two-fold (TN) and three-fold (TP and TSS) compared with the low-density LL catchment.

Table 22. The survey-specific maximum unit mass loads used in the calculation of areal mass loads. The date of the snow survey for each unit load is given in the parenthesis.

		Unit mass load (date of occurrence)			
	Snow type	**COD (mg/m^2)**	**TN (mg/m^2)**	**TP (mg/m^2)**	**TSS (g/m^2)**
LL	street with traffic	4227 (18.2.)	233.5 (14.3.)	257.0 (18.2.)	191.5 (18.2.)
	street without traffic	615.0 (18.2.)	227.9 (31.3.)	108.5 (18.2.)	40.1 (18.2.)
	untouched snow	129.1 (29.3.)	85.4 (18.2.)	4.9 (31.3.)	2.4 (31.3.)
VK	street with traffic	6976 (23.3.)	1690 (8.3)	587.7 (23.3.)	390.0 (23.3.)
	street without traffic	2602 (18.2.)	3124 (27.3.)	235.0 (27.3.)	39.3 (31.3.)
	untouched snow	540.7 (23.3.)	169.7 (23.3.)	11.3 (23.3.)	5.4 (23.3.)

Table 23. Areal pollutant mass loads of snow based on the snow covered area and the total catchment area (modified from Sillanpää and Koivusalo, 2013).

	Computational area	**COD (kg/km^2)**	**TN (kg/km^2)**	**TP (kg/km^2)**	**TSS (kg/km^2)**
LL	snow covered area	136…149	86.8…86.9	6.4…6.6	3176…3406
	total catchment area	115…126	73.4…73.5	5.4…5.6	2688…2883
VK	snow covered area	615…631	186…213	19.2…19.7	9834…10018
	total catchment area	423…434	128…147	13.2…13.6	6762…6889

At both catchments, untouched snow had very high aereal coverage, and only 2% (VK) and 1% (LL) of the SCA was covered by ploughed snow (Figure 39). Therefore, the largest proportion of the pollutant mass was stored in untouched snow at both catchments. Still, nearly half of the pollutant mass load of TSS and TP was stored in ploughed snow piles along roads and walkways in VK. The contribution of ploughed snow to the TN and COD mass loads was smaller, but still high in comparison with their proportion of SCA. At LL, the contribution of ploughed snow to the pollutant loads was smaller, although TSS and TP still accounted for approximately 1/3 of the total pollutant mass. The proportion of the TN mass load for ploughed snow was smaller compared with other pollutants due to smaller TN concentrations at LL than at VK. At both catchments, group 1 snow (ploughed snow along streets with traffic) comprised a higher percentage of the areal mass loads of TSS, TP and COD than ploughed snow at a greater distance from vehicular traffic. In contrast, the TN had a higher mass percentage for group 2 snow (ploughed snow along streets without vehicular traffic). At VK, this was caused by high TN concentrations along pedestrian walkways. At LL, the obvious reason was the larger surface area of snow in group 2 compared with group 1.

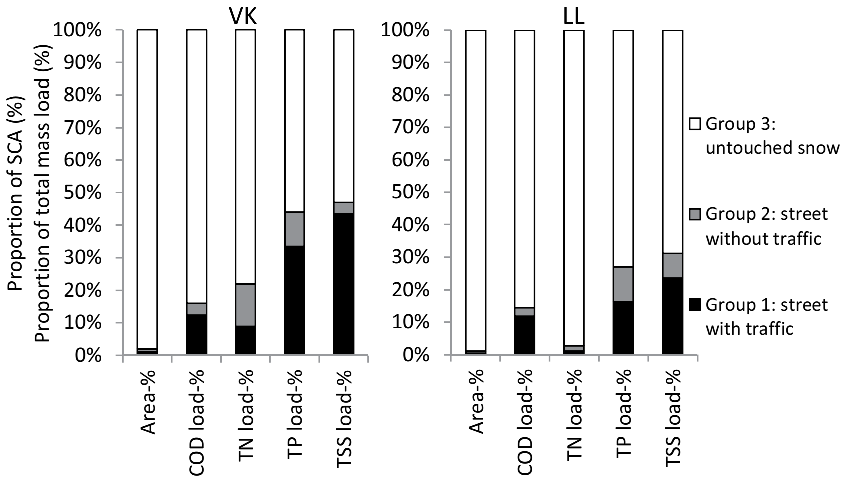


Figure 39. Contribution of different snow types to the areal pollutant mass loads of snow at the medium-density VK catchment and the low-density LL catchment (Sillanpää and Koivusalo, 2013, reprinted with permission from IWA Publishing).

4.2 Discussion

4.2.1 Effects of urbanization on snow depth, density and SWE

Effects of urbanization on point snow observations

The urban snow conditions discussed in different studies need to be compared with a certain amount of caution, because the snow depth and SWE are bound to a particular location owing to the different weather and climate conditions, development densities/land use (the extent of impervious surfaces, buildings, etc.) and winter maintenance practices (ploughing, the transport of snow). Many studies are conducted in climates where intermittent snowmelt events are typical for the whole duration of a snow period, such as in Trodheim, Norway (Matheussen, 2004) and in Canada (Buttle, 1990; Ho and Valeo, 2005). In Luleå, Sweden, snow accumulates over a period of several months, ending with a final melt event during spring (Semádeni-Davies, 1999a). In Finland, the snow accumulation period typically lasts for several months; however, the study period in 2006 was warmer and less snowy than an average year: the snow accumulation period lasted only a few months and the maximum SWEs were approximately 20% below the 100 mm average for the area (Solantie 1981, as cited in Kuusisto, 1986b).

Despite regional and climatic differences, previous studies have all emphasized the distinct features of urban snow, especially the higher snow depths, densities and SWEs of ploughed snow, as well as its lower albedo in comparison to untouched urban snow. Semádeni-Davies (1999b) compared the properties of urban snow at three sites representing different land use types (residential, commercial, industrial) in Luleå, Sweden. Ho and Valeo (2005) conducted a field study in a low-density residential area in the city of Calgary, Canada. Both studies concluded that piled snow had higher snow depths, densities and SWEs than other, less-disturbed snow types. Also, ploughed snow at the study catchments in Espoo (Section 4.1.2) had higher snow depths, densities and SWEs in comparison to untouched urban snow. Additionally, the high degree of variability observed by other scholars, particularly in the properties of ploughed snow (e.g. Buttle and Xu, 1988; Semádeni-Davies, 1999b; Matheussen, 2004; Ho and Valeo, 2005), was observed in the current study as well. Particularly at the medium-density VK catchment, the differences between untouched and disturbed snow were likely statistically significant based on the non-overlapping 95% confidence intervals. The underlying sample distributions have not usually been considered while comparing snow properties between different locations; yet Matheussen (2004) also investigated the confidence intervals of SWE observations for different snow types.

Semádeni-Davies (1999b) concluded that the properties of undisturbed urban snow were similar to those of rural snow. Her study mainly considered the albedo and density of snow. In a study by Buttle and Xu (1988) done in Ontario, Canada, the front yards in a suburban catchment had higher maximum SWEs than the open fields and forest in a rural catchment due to shovelled snow. Based on the results presented in Section 4.1.2, urban untouched snow had similar properties as rural snow, especially when compared with an open rural area. However, rural snow accumulation cannot be compared to urban environment at points where the spatial distribution of snow is also governed by a unique topography, e.g. by buildings and the snowdrift from rooftops (Semádeni-Davies, 1999a; Matheussen, 2004). In Section 4.1.2, the density of snow in a rural forest was equal to that of urban untouched snow, but the snow depths and SWEs were notably lower due to interception losses (Koivusalo and Kokkonen, 2002). Semádeni-Davies (1999a) and Semádeni-Davies et al. (2001) also pointed out that exposed open sites, despite undisturbed snow accumulation, may have non-existent snow depths in urban areas, especially on south-facing roofs and slopes. These spatial differences in the snow accumulation and melt are caused by the differences in the exposure to solar radiation and wind, and by the changes in the snowpack energy balance with respect to buildings.

Previous studies on urban snow have investigated snow properties at the onset of melt events (Semádeni-Davies, 1999b; Buttle and Xu, 1988) or throughout the winter period (Matheussen, 2004; Ho and Valeo, 2005). Given the fact that the need for urban snow measurements has been recognized by several researchers, the amount of published information on temporal changes in urban snow properties during winter is rather limited. Matheussen (2004) investigated the SWEs of urban snow types (snow deposits, park snow, snow on roofs and roads) throughout the winter period from several different snow surveys in a low-density residential area in Trondheim, Norway and pointed out that the differences between the snow types increased during the snow accumulation period without any overlapping confidence intervals. The results of this study strengthen Matheussen's (2004) results, whose discussion focused on SWE. In Espoo, the differences between the snow types and locations were best illustrated by the SWEs (Section 4.1.2). Additionally, the results showed how the density of snow behaved differently than the snow depth and SWE. The density of untouched and rural snow remained relatively low until the final stages of the snow accumulation period. The density of the disturbed snow was high in comparison to untouched snow for the majority of the snow accumulation period, but at the end of March all snow types had similar densities based on overlapping confidence intervals. Thus, the differences in the density of the snow depend on the timing of the observations, and they may not yield such pronounced differences between the snow types at the onset of the spring melt as the SWEs. Although comparisons of snow depths and SWEs between studies are somewhat arbitrary, different studies (Semádeni-Davies, 1999b; Ho and Valeo, 2005) report similar densities for urban snow types as those observed in Espoo. This indicates that although snow properties are affected by several different factors, and thus, difficult to generalize, the density of snow varies less between sites and studies.

Effects of urbanization on areal SWEs

In urban snow studies, snow properties are often discussed based on point observations, but Semádeni-Davies (1999b) considered a larger areal scale and concluded that the SCA and the area of undisturbed snow decrease as the land use intensity increases. Buttle (1990), who investigated snow properties at an urbanizing catchment over a period of 14 years in Ontario, Canada, reported that the redistribution of snow by urban activities became more pronounced as the catchment developed. Matheussen (2004) compared the areal SWEs of urban and rural parts of his study catchment and concluded that the areal SWEs of the urbanized parts of the catchment were lower than the areal SWEs in the park areas. Based on these results, the most pronounced catchment-scale impact of urbanization on the studied snow properties is a lower areal SWE owing to larger snow-free areas. In Espoo (Section 4.1.2), the low-density catchment had a higher areal SWE than the medium-density catchment owing to a larger SCA and a smaller TIA. The larger snow-free areas are the result of winter maintenance, such as ploughing and de-icing, the snowdrift from rooftops, and the rapid snowmelt from heat-absorbing impervious surfaces and snow deposits with lower albedos due to dirty snow (Oberts, 1994; Bengtsson and Semádeni-Davies, 2000; Matheussen, 2004). In point scale, urbanization increased snow depths, densities and SWEs for ploughed snow, but the changes are related to the winter maintenance practices and not directly to land use intensity. Under more snowy conditions, and in areas with less free space for snow storage, disturbed snow could have a stronger impact on the areal SWEs. Semádeni-Davies (1999b) concluded that the density of snow increases with increasing land use intensity; this cannot be confirmed in light of the point snow observations for this study because the physical properties of the urban snow types were similar at both urban study catchments.

4.2.2 Snow quality based on point observations: concentrations and unit mass loads

Effects of urbanization on point snow quality

Section 1.3.3 introduced studies that revealed the main factors influencing urban snow quality. These factors include differences in vehicular traffic, road maintenance practices and weather patterns (e.g. Oberts, 1994; Hautala et al., 1995; Viklander, 1997; Marsalek et al., 2000; Sansalone and Glenn, 2002; Reinosdotter and Viklander, 2005; Engelhard et al., 2007; Reinosdotter, 2007). In the existing literature, the urban snow quality is usually presented as pollutant concentrations instead of unit mass loads. Unit mass loads were previously reported by Viklander (1997, 1999) and Reinosdotter and Viklander (2005) for urban sites in Luleå and in milder winter conditions in Sundsvall, Sweden (Reinosdotter, 2007). In these studies, unit loads showed larger differences in snow quality between the study sites than concentrations. Also in Section 4.1.3, the differences in point snow quality between the study catchments were more distinct in terms of the unit mass loads, which on average were higher at the medium-density catchment than at the low-density catchment.

In light of the results presented in Section 4.1.3, urbanization affected the most the properties of ploughed snow along vehicular streets, where the highest concentrations and unit mass loads were typically observed. The study sites of Reinosdotter and Viklander (2005) in Luleå and Sundsvall had comparable traffic loads (13,000-13,200 vehicles/day) to the medium-density catchment (10,200 vehicles/day) in Espoo, but the Swedish sites showed much higher average TSS concentrations in ploughed snow than those observed in Espoo. However, the conductivities measured in this study were notably higher than those observed in Luleå by Viklander (1999). The differences in snow quality between Espoo and the Swedish sites are primarily explained by the different practices in slipperiness control: only sand was used in Luleå, and a mixture of sand and salt in Espoo and Sundsvall. Additional influencing factors include the differences in the snow accumulation period and the location of the snow piles. In Espoo, the location of the ploughed snow on the roadside affected both the conductivity and TSS concentrations, which were higher at LL than at VK, despite the higher traffic load at VK. This indicates that a greater amount of the salt and sand remains on the street surfaces if the snowpack is not located right on the street (LL), but ploughed onto elevated pavement along the side of the street (VK). Also, the mixing of roadside snow with walkway snow at VK may dilute the observed concentrations to some extent. Viklander (1999) also observed that the location of the snowpack influenced the quality of the snow: higher TSS concentrations in ploughed snow were observed in a residential area compared with a central area. In the centre, snow was ploughed onto a downward-sloping bank away from the street, but in the residential area snow stayed on the side of the street until it melted or was transported away.

The current study revealed other location-dependent pollutant source differences in snow quality by dividing the observations of ploughed snow into two different snow groups: ploughed snow along vehicular streets and along pedestrian walkways without a close connection to traffic. The latter snow type usually yielded lower unit mass loads than ploughed snow along vehicular streets, but higher mass loads than untouched snow (Section 4.1.3). Like in vehicular streets, sand was the main source of pollution along pedestrian walkways, but other traffic-related sources, such as the deterioration of car parts and the road surface, de-icing salts and exhaust emissions (Hautala et al., 1995), have a smaller impact on pollutant concentrations. Another distinct feature observed for this snow type at VK was the high TN concentrations and mass loads along the pedestrian streets originating from pet faeces. Due to the high TN concentrations, the average TN mass load in ploughed snow along pedestrian streets was even higher than the average mass load along vehicular streets. Pet faeces also increased TP mass loads because both nutrients varied greatly among the different field surveys, which was not observed for other pollutants (TSS and COD).

Reference values for similar snow type along pedestrian streets without vehicular traffic were not found in the literature. Nevertheless, Malmqvist (1983) developed mass balances for two urban catchments in Göteborg, Sweden, and concluded that animal faeces were a major nutrient source in urban catchments, comprising 30-40% of the total nitrogen and phosphorus inflows, while the rest of the pollutants originated from atmospheric deposition (nitrogen and phosphorus) and traffic sources (phosphorus). The focus of previous urban snow studies on traffic areas and pollutants other than nitrogen might explain why these aspects of urban snow pollution have not been emphasized in previous studies. It should be noted that pet faeces likely pose a rather local impact on snow quality.

Despite the different study locations, the concentrations of untouched snow had a similar pH, electrical conductivity and TSS and TP concentrations as the untouched snow in the residential areas in Sundsvall and Luleå (Viklander, 1999; Reinosdotter and Viklander, 2005; Reinosdotter and Viklander, 2006). Reinosdotter and Viklander (2005) concluded that the higher pollutant concentrations in untouched snow in city centres were influenced by the higher content of airborne pollutants. Also, the differences between the concentrations of untouched snow in the studied catchment in Espoo can be explained by the level of airborne pollution, which is likely higher at the medium-density VK catchment because of the higher traffic loads. The impact of atmospheric loading from longer distances has not been evaluated.

Despite the different road maintenance practices, an equal pH level was observed in roadside snow at the medium-density catchment in the current study and in the central area in Luleå with a similar traffic load (Reinosdotter and Viklander, 2006). Viklander (1999) argued that the higher TSS concentration explained the higher pH of roadside snow in comparison to untouched snow. The comparisons between the three urban snow types in Section 4.1.3 strengthen this conclusion, because the pH varied according to the TSS concentrations between the different snow types: ploughed snow along streets without vehicular traffic had lower TSS concentrations and pH than the ploughed snow near vehicular traffic, but higher TSS concentrations and pH than untouched snow. It should be noted that pH of snow can also be affected by pH of the gritting material, often imported from other locations.

Temporal behavior of pollutants in snow

The absence of distinct temporal trends in the total concentrations and unit mass loads of urban snow has been previously observed by Engelhard et al. (2007), Reinosdotter and Viklander (2005) and Reinosdotter (2007) for suspended solids and select metals. Engelhard et al. (2007) studied the pollutant concentrations in roadside snow in Innsbruck, Austria. Reinosdotter and Viklander (2005) and Reinosdotter (2007) concluded that the pollutant accumulation pattern in urban snow was clearer in Luleå, where winter air temperatures were lower compared with Sundsvall and only sand was used in road maintenance instead of de-icing salts. The conditions in Espoo during the study year more closely resemble those in Sundsvall rather than Luleå in terms of the length of the snow accumulation period and the methods of road maintenance (sand and salt). Overall, the causes for the nonexistent or unclear trends in pollutant accumulation include road maintenance, such as ploughing, gritting, de-icing, the time since snowfall and the inputs of new, cleaner snow throughout the winter period (Sansalone and Glenn, 2002; Viklander, 1997; Engelhard et al., 2007). In Section 4.1.3, it was also concluded that the large spatial variability in pollutant concentrations for the same snow type masked general temporal trends. In any case, the lack of clear temporal trends in the total pollutant concentrations and unit mass loads in urban snow in Espoo is supported by other studies, and the present study reveals the same phenomenon also for nutrients and COD.

The results for the descending trends in the dissolved concentrations presented in Section 4.1.3 support the theories that the soluble pollutants tend to leave the snowpack earlier during the snowmelt than the more particle-bound pollutants (Oberts, 1990; Viklander, 1997, 1999; Marsalek et al., 2000). A decreasing trend of dissolved metals, especially at the end of the winter season, was found by Reinosdotter and Viklander (2005) at all sampling sites with different traffic loads, road maintenance activities and weather conditions. In Espoo (Section 4.1.3), decreasing trends were observed in the dissolved pollutant concentrations especially for untouched snow and for TN and COD in ploughed snow. In particular, soluble COD seemed to leave the snowpack earlier than the other pollutants, especially in untouched snow. According to Viklander (1997, 1999), spatial variations in the dissolved pollutant fractions can mainly be explained by the presence of suspended solids, which decrease the soluble content of particle-bound pollutants, such as phosphorus and metals. In Section 4.1.3, this was observed as smaller soluble fractions in ploughed snow with a higher TSS content in comparison to untouched snow. Furthermore, COD and TP also had smaller soluble fractions than TN in untouched snow. Larger fractions of dissolved phosphorus were observed in untouched snow in Espoo (up to ~60-80%) compared with a residential area in Luleå (~30-40%) (Viklander, 1999), whereas the dissolved fractions of ploughed snow seemed similar in both studies (mainly less than 15%).

A limited number of studies have addressed the behaviour of TN and COD concentrations. Viklander and Malmqvist (1993) studied two artificially constructed snow deposits and found that TN and COD left the deposits earlier during the snowmelt, while the more particle-bound phosphorus load followed the runoff pattern. In a laboratory-scale snowmelt experiment (Viklander and Malmqvist, 1994), nitrogen again tended to leave the snowpack earlier than the particle-bound substances, while somewhat divergent results were obtained for COD. The results from Espoo strengthen the findings presented in the previous studies by demonstrating that in actual snow banks in Espoo, both COD and TN had higher dissolved fractions than TP and the soluble fraction of COD decreased more rapidly than TP. However, the particle-bound fraction of COD was more similar to TP than to TN, indicating that COD is also influenced by the presence of suspended solids. Based on the results for the quality of motorway snow, Sansalone and Glenn (2002) concluded that COD is strongly linked to TSS. The differences in the temporal behaviour of dissolved snow concentrations, in fact, reinforce the same behaviour that was previously observed based on monthly runoff concentrations in Section 3.1.6, which demonstrates that TSS has the strongest relationship with TP and the second strongest with COD, whereas its linkage with TN is weak.

4.2.3 Catchment-scale analysis of urban snow pollution

Ideally, snow provides temporary detention/retention storage for urban runoff and pollutants, which is a unique management opportunity available only in cold climate conditions. For this reason, it is important to investigate urban snow from a catchment-scale perspective with respect to pollutant export via runoff to evaluate the pollution capacity of urban snow storage. However, previous studies on urban snow quality have not used a catchment perspective. In this section, SMLs are compared with pollutant export rates during the spring snowmelt, and point snow concentrations are compared with runoff water quality during the study period. Furthermore, snow concentrations are compared with the stormwater quality criteria provided by Stockholm Vatten (2001) and the preliminary snow classification suggested by Reinosdotter and Viklander (2006).

With a catchment-scale perspective, the contributions of each snow type to areal snow mass loads (SML) depended on the areal extent of each snow type and the associated unit mass loads, i.e. the pollutant concentrations and SWE (Figure 39 in Section 4.1.4). In comparison to the low-density LL catchment, multifold SMLs were observed at the medium-density VK catchment despite the differences in the SCA. This is also reflected by the larger pollutant export (Table 24) and pollutant concentrations (Table 25) observed for VK based on runoff monitoring, even though nearly equal runoff volumes were generated at both catchments during the study period. It should be noted that increased runoff volumes during snowmelt in April resulted in high loads of especially particulate pollutants at LL (Table 24). Due to earlier snowmelt, 15-23% of the pollutant export at VK washed off already in March, whereas nearly all (94-96%) of the pollutant load was exported in April at LL (Table 24).

Table 24. Pollutant export from the study catchments during March-April 2006 and in April 2006 (based on 54 and 56 runoff samples at the low-density LL catchment and the medium-density VK catchment, respectively). Percentages show the proportion of pollutant export occurring in April (modified from Sillanpää and Koivusalo, 2013).

	Pollutant export (kg/km^2)			
	COD	**TN**	**TP**	**TSS**
March-April 2006				
LL	489	149	9.9	5180
VK	639	271	14	6790
April 2006				
LL	465	140	9.4	4970
VK	544	225	11.8	5240
LL	*95%*	*94%*	*95%*	*96%*
VK	*85%*	*83%*	*84%*	*77%*

Table 25. Seasonal concentrations of the studied pollutants in runoff at the catchment outlets during the spring 2006 (modified from Sillanpää and Koivusalo, 2013).

	Seasonal concentration (mg/l), Spring 2006			
	COD	**TN**	**TP**	**TSS**
LL	5.4	1.6	0.100	52
VK	9.9	3.3	0.230	97

The SMLs presented in Section 4.1.4 are smaller than the pollutant export reported for runoff in Table 24 at both catchments; only the TSS and TP SMLs at the medium-density VK catchment approximate the observed pollutant export rates. This finding is somewhat surprising because it has previously been reported that snowmelt transports only a part of the pollutants from the snowpack (Oberts, 1994; Viklander, 1996, 1997, 1999; Saxton et al., 2006; Reinosdotter, 2007), and thus, it was expected that the SMLs would exceed the pollutant export from the study catchments. Consequently, it is not possible to evaluate the extent to which pollutants stored in snow are transported away from the catchments based on the study results. In light of the results, other sources in addition to snowpack contribute to the runoff pollutant loads. During winter, the bulk of solids and other pollutants are deposited on impervious surfaces outside the snow storage area. Rain-on-snow and rain-after-snow transport pollutants from both pervious and impervious surfaces, which could not be separately estimated based on this study. In April, for instance, it rained approximately 34 mm. Previously, Westerlund (2007) noted that high TSS loads in snowmelt runoff from a road area in Luleå, Sweden were affected by the amount of available material for washoff, both in the snowpack and on the road surface, in addition to the overland flow intensity. Compared with the annual pollutant export rates presented in Section 3.1.5 (the reference periods LL3 and VK3), the SMLs were approximately 20-30% of the annual TP and TSS export, about 20% of the annual TN export and less than 10-20% of the annual COD export at both catchments, with lower percentages observed for LL. Hence, the treatment of urban snow does not capture the major part of the pollutants originating outside the snow storage area.

The pollutant concentrations in runoff (Table 25) are usually notably lower than those for ploughed snow but clearly higher than the concentrations for untouched snow (Section 4.1.3), indicating that ploughed snow, despite its small areal extent, increases runoff concentrations. The lower runoff concentrations at the low-density LL catchment (Table 25) can be explained by the dilution effect, which is caused by the larger proportion of untouched snow at LL compared with VK, in addition to differences, for example, in the traffic loads and the extent of impervious areas. In any case, the pollutant concentrations or mass loads of snow did not directly reflect the quality of runoff observed at the catchment outlet in the current study. However, snow observations provided information about the type of pollutants expected in the runoff.

If the average snow concentrations are compared with the stormwater quality criteria for TSS, TP and TN provided by Stockholm Vatten (2001), the threshold of high concentrations is exceeded by the TSS and TP concentrations in ploughed snow at both catchments. Also, the average TN concentration in ploughed snow along pedestrian streets in VK exceeds the threshold of high concentrations, whereas the other snow types had either moderate or low concentrations. The classification provided of Stockholm Vatten (2001) was previously discussed in Section 3.2.4, and, according to the classification, low pollutant concentrations do not require treatment whereas the exceedances of moderate and high concentration thresholds usually imply a need for treatment. Given that the average runoff concentrations for TSS, TP and TN in Table 25 also fall into the moderate or even high concentration classes, appropriate management of urban snow can be a useful tool for improving water quality during the spring melt. Obviously, it should be kept in mind that the stormwater criteria are developed for runoff concentrations and not for snow.

Already in the 1990s, the Swedish Environmental Protection Board recommended separating snow into heavily or less polluted snow to mitigate the adverse effects from winter maintenance and snowmelt (Viklander, 1997), but it has been difficult to implement the strategy because of difficulties in identifying appropriate snow quality criteria

(Reinosdotter, 2007). Reinosdotter and Viklander (2006) proposed management strategies for urban snow based on the expected level of pollution according to traffic loads. According to their treatment recommendations, the ploughed roadside snow at the low-density LL catchment would not require treatment and snow should be stored on land at the medium-density VK catchment. On the grounds of the catchment-scale analysis presented in Section 4.1.4, the treatment of ploughed snow could have a significant impact especially on TP and TSS loads, which covered 1/3 to 1/2 of the total pollutant mass stored in snow and which are stored better in the snowpack than the more soluble pollutants. This approach could be especially effective at VK, where the treatment of snow from a relatively small surface area could result in a large reduction in accumulated pollutants. In this way, the results support Reinosdotter and Viklander's (2006) recommendations. However, a catchment-scale assessment provides more insight into snow pollution than evaluations based only on roadside ploughed snow, e.g. about the pollutant sources and the spatial distribution of the pollutant mass within the catchment.

4.2.4 Sources of error

The traditional approach to studying snow courses with equally spaced measurement points is difficult to apply to an urban area because of the presence of solid urban structures (roads, buildings) and the high spatial and temporal variability in snowpack conditions owing to ploughing, transport and other sources of 'disturbance', such as parked cars and pets. Some snow types are not monitored owing to practical reasons, e.g. roofs and street surfaces. The problems with constant measurement points or snow courses has been previously reported by Semádeni-Davies (1999a, 1999b), Matheussen (2004), and Ho and Valeo (2005). The lack of established methods for urban snow monitoring causes uncertainties in the interpretation of the monitoring data. Matheussen (2004) previously raised concerns about the spatial representativeness of urban snow data. In this study, sampling was conducted for different snow types, including samples taken from several different locations and snow types, but the possible inaccuracies in the areal representativeness of the observations should be acknowledged. It should also be noted that the conclusions about the temporal behaviour of the dissolved pollutants are based on only a few samples.

The comparisons of the different snow types were based on point values, and the areal values were determined only for the conditions at the onset of the spring snowmelt. The SCA was estimated based on visual observations, photographs and maps provided by Samposalo (2007) for the catchments, but it only gives a rough approximation of the snow cover. A similar approach has been used by for example, Semádeni-Davies (1999b). The assumption that the streets would be free of snow at the beginning of the spring snowmelt has been verified in many climate conditions, such as in Luleå, Sweden (Bengtsson and Westerström, 1992) and Ontario, Canada (Buttle, 1990). However, the snow from roofs melts quickly, but is often ignored in snow monitoring owing to practical and safety problems. This inevitably affects the accuracy of the areal estimates; in this study, the values for untouched snow were used for the roofs. Using the chosen approach, the estimates of the maximum areal SWEs and SMLs can be made with reasonable accuracy, but the temporal development of the SCA cannot be documented in detail. Thus, there is a need for better methods for estimating the SCA than just doing a visual inspection. Matheussen (2004), for instance, used digital images taken with a camera at a high rooftop to estimate the SCA throughout the winter season. Another problem is that the exact dimensions of the individual snowpacks were not available, which can cause large uncertainties in the estimation of areal values. In the study by Semádeni-Davies (1999a), conducted in two residential suburbs, approximately 10% of the SCA consisted of ploughed snow. These areas, however, represented colder conditions than those in Espoo during the winter in question. There are also uncertainties in the estimation of transported snow, although the snow monitoring period was less snowy than an average year.

Problems with runoff measurements were encountered during the snow monitoring period, although the conditions were not as severe as during very cold winters. In the middle of March, a leak was observed in the measurement weir at LL; a continuous effort was made to minimize the leak throughout the spring snowmelt period. The impact of the leak on water levels was compensated for by correcting the flow data upwards based on the estimated rate of leaking water. The water depth measurements, however, were subject to larger measurement errors and inaccuracies during this period. There were also infrequent problems with automatic samplers, especially during the early stages of the spring snowmelt at both catchments.

5. Event-scale urban runoff generation and water quality

5.1 Results

5.1.1 Summaries of the event characteristics

Main characteristics of runoff events

Summaries of the runoff event variables are shown for all study catchments in Appendices C and D. In the summaries, the event data for the developing SR catchment is divided into two groups representing the years before and after major paving works (2001-2003 and 2004-2006). Rainfall depths (P_{TOT}) during individual rainfall events ranged from 0.2 mm to 124 mm, but only those events producing direct runoff are included in Appendix C: 65% and 73% of rainfall events produced direct runoff at the low-density LL catchment and the medium-density VK catchment, respectively. At SR, the percentage of runoff-producing events doubled from 29% to 59% between the two periods.

On average, the median dry period (DAYS) between the runoff-producing rainfall events was 1-2.5 days at the study catchments (Appendix C). The mean values (2.5-4 days) were higher due to some occasional extended periods of dry weather: the longest periods without events of at least 1 mm of rain lasted from 23 to 29 days. The median dry periods between the cold period events were longer than those for the warm period events; they ranged from about four days at LL to nine days at SR (Appendix D), although direct comparisons between seasons are not valid owing to different methods of determination (see Table 7).

The median rainfall depths during runoff events were rather small: 2.7 mm within three to four hours at VK and SR, and 4.4 mm within 5.5 hours at LL (Appendix C). The higher median rainfall depth at LL can be explained by the fact that it has a smaller amount of impervious surfaces and a longer catchment lag compared with the other catchments. Thus, separate events at VK often appeared as a single event at LL because the previous runoff event had not ended when a new rain event started. For the same reasons, the median rainfall depth at SR during the years 2001-2003 was 7.0 mm within eight hours in comparison with 2.7 mm within three hours during the years 2005-2006.

Based on the warm period event characteristics describing the runoff volumes (R_{TOT}, R_{EFF} and C_{VOL} in Appendix C), the study catchments consistently followed the same order: VK (the largest median values), SR during the years 2005-2006, LL, and SR during the years 2001-2003 (the smallest median values). A similar order was seen in the catchment imperviousness, which increased from SR (2001-2003) and LL to SR (2005-2006) and VK. In contrast, total runoff depths (R_{TOT}) during the cold period events followed a reverse order of magnitude, with SR having the largest median runoff volume during the early years and VK having the smallest median runoff volume (Appendix D).

A common feature for both warm and cold period runoff events was the high degree of variability (COV ≥ 0.8) in the event characteristics (Appendices C and D). Only the C_{VOL}s for VK and SR during the years 2005-2006 had lower COV values (0.5 in VK and 0.3 in SR). In addition to the high COV values, the large differences between the medians and arithmetic averages implied skewed distributions for most of the event characteristics at all catchments.

Selection of events for water quality analysis

For the event-scale water quality analysis, runoff events were assessed based on their event mean concentrations (EMCs) and pollutant mass loads (EMLs). The basic statistics on the EMCs and EMLs are represented in Table 26 (EMCs) and Table 27 (EMLs). The number of events in the water quality analysis was less than in the analysis of the event runoff characteristics because i) not all events were sampled due to their small runoff volume or ii) the samples were not representative of the total runoff volume for the event, e.g. in the case of an event with a long duration and high runoff volume. In the existing literature, runoff events have typically been selected for water quality analysis based on the number of discrete samples during an event. For example, Westerlund et al. (2003) chose runoff events with at least three water quality samples for their study. Charbeneau and Barrett (1998) reported that the EMC estimates include a great deal of uncertainty when only three to four water quality samples are available for an event. A small sample count causes uncertainty in the estimation of EMCs especially for large runoff events. Additionally, the choice of events based on a minimum sample requirement can easily cause a shift towards larger events, i.e. the analysed water quality events no longer represent the original distribution of runoff events.

In this study, the events for the water quality analysis were first chosen based on an appropriate minimum amount of samples following the suggestions given in the existing literature. As a minimum criterion for the calculation of EMC and EML, four water quality samples per event were chosen as the minimum amount for VK and LL and for events from the years 2004-2006 for SR. For the years 2001-2003, a minimum of three samples per event was adopted. At VK, for example, the exclusion of the warm period runoff events based on the minimum criterion led to a median volume of 620 m^3 for the selected runoff events, whereas the median volume of all runoff-producing events was only 125 m^3, indicating a shift of distribution towards the larger events.

In order to maintain the original runoff event distribution for the chosen water quality events, the selection of water quality events was repeated by introducing a new approach, which was based on the assumption that the water quality is adequately represented if there is a sufficient number of water quality observations in relation to the volume and duration of the runoff event. The same selection criteria were followed at all sites. First, all events with only one water quality observation were excluded. Second, all events with two water quality observations that produced runoff volumes exceeding 200 m^3 were excluded. After this, all events with high volumes of runoff compared with their sample counts were separately examined if the samples were representative throughout the total duration of the event. Finally, events with an average time between samples of more than 24 hours were excluded (defined as a ratio of the event duration to the event sample count). For example, for VK this approach meant that 151 warm period events with a median runoff volume of 353 m^3 were included. This improved the representativeness of the different event sizes for the original event distribution. A total of 100 out of 151 events had at least four water quality samples when using this approach. It should be noted that even though the new event selection approach increased the number of water quality events used for further analysis, it also meant some events with higher (>4) sample counts were excluded. For example, events with four to five samples were excluded for VK due to the fact that the volume was too high or the duration of the runoff event was too long compared with the sample count.

Table 26 shows three different measures for representing the average EMC: the site mean concentration (SMC) as a volume-weighted average EMC, the median EMC and the mean as an arithmetic average. Usually, the SMC was closer to the median than the mean EMC; however, the greatest differences between the median EMC and SMC were observed during the cold period TSS EMCs for LL, during the warm period TSS EMCs for VK and during the warm period TSS, TP and TN EMCs for SR, for which the SMCs exceeded the medians by at least 50%.

Table 26. Summary of the event mean concentrations (EMC) for the warm and cold period events. SMC is the site mean concentration defined as the volume-weighted average of EMCs.

Event Mean Concentrations, EMC (mg/l)								
	event group	**SMC**	**median**	**mean**	**COV**	**min**	**max**	**n**
TSS, total suspended solids								
LL	warm period	53.7	43.8	67.1	1.0	4.9	329.1	83
	cold period	32.4	20.4	27.3	0.9	2.8	102.2	28
	all events	*42.6*	*38.1*	*57.0*	*1.1*			*111*
VK	warm period	73.4	50.3	113.4	1.5	4.6	975.0	151
	cold period	71.5	76.2	100.1	1.2	2.8	621.5	31
	all events	*72.8*	*51.7*	*111.1*	*1.4*			*182*
SR	warm period	138.9	53.0	128.4	1.4	6.9	879.4	57
	cold period	121.8	117.5	224.9	1.1	4.8	841.3	21
	all events	*127.1*	*62.6*	*154.3*	*1.3*			*78*
TP, total phosphorus								
LL	warm period	0.107	0.100	0.126	0.7	0.040	0.569	81
	cold period	0.070	0.049	0.058	0.5	0.016	0.131	28
	all events	*0.088*	*0.087*	*0.109*	*0.8*			*109*
VK	warm period	0.148	0.138	0.219	1.1	0.028	1.637	153
	cold period	0.117	0.091	0.137	1.0	0.026	0.789	32
	all events	*0.137*	*0.129*	*0.205*	*1.1*			*185*
SR	warm period	0.242	0.141	0.304	1.4	0.029	2.504	66
	cold period	0.148	0.167	0.266	1.0	0.017	1.067	21
	all events	*0.180*	*0.142*	*0.295*	*1.3*			*87*
TN, total nitrogen								
LL	warm period	1.6	1.2	1.3	0.3	0.6	3.0	81
	cold period	1.7	1.5	1.6	0.3	0.8	2.5	28
	all events	*1.7*	*1.3*	*1.4*	*0.3*			*109*
VK	warm period	1.8	1.8	2.0	0.5	0.4	5.7	153
	cold period	2.8	2.4	2.7	0.4	1.1	4.9	32
	all events	*2.2*	*2.0*	*2.2*	*0.5*			*185*
SR	warm period	8.3	3.4	5.4	0.8	1.0	15.8	66
	cold period	4.1	4.4	4.2	0.5	0.3	7.9	21
	all events	*5.5*	*3.6*	*5.1*	*0.8*			*87*
COD_{Mn}, chemical oxygen demand								
LL	warm period	11.5	8.7	10.3	0.7	3.1	67.5	81
	cold period	6.4	5.9	5.8	0.3	3.2	10.8	28
	all events	*8.8*	*8.0*	*9.2*	*0.7*			*109*
VK	warm period	10.2	9.9	14.6	1.0	3.9	128.0	153
	cold period	7.1	7.1	8.4	0.9	4.0	48.6	32
	all events	*9.1*	*8.9*	*13.5*	*1.0*			*185*
SR	warm period	12.7	11.0	13.3	0.6	5.0	42.1	65
	cold period	9.8	9.8	12.4	0.6	5.3	33.3	21
	all events	*10.8*	*10.7*	*13.1*	*0.6*			*86*

Table 27. Summary of the event unit mass loads (EML) for the cold and warm period events.

Event Mass Loads, EML (kg/ha)							
	event group	**median**	**mean**	**COV**	**min**	**max**	**n**
TSS, total suspended solids							
LL	warm period	0.84	2.74	2.2	0.002	44.1	83
	cold period	1.84	5.38	1.8	0.017	47.1	28
	all events	*1.03*	*3.41*	*2.1*			*111*
VK	warm period	1.52	3.78	1.5	0.049	32.4	151
	cold period	7.00	9.16	1.1	0.153	37.8	31
	all events	*1.86*	*4.69*	*1.5*			*182*
SR	warm period	1.23	6.04	3.7	0.007	165.0	57
	cold period	21.80	32.90	1.1	0.298	132.1	21
	all events	*1.65*	*13.28*	*2.2*			*78*
TP, total phosphorus							
LL	warm period	0.002	0.006	2.0	0.00003	0.076	81
	cold period	0.003	0.012	1.6	0.00003	0.091	28
	all events	*0.002*	*0.007*	*1.9*			*109*
VK	warm period	0.004	0.008	1.2	0.00032	0.056	153
	cold period	0.009	0.015	1.3	0.00026	0.096	32
	all events	*0.004*	*0.009*	*1.3*			*185*
SR	warm period	0.003	0.010	2.3	0.00020	0.135	66
	cold period	0.025	0.039	1.0	0.00054	0.122	21
	all events	*0.005*	*0.017*	*1.8*			*87*
TN, total nitrogen							
LL	warm period	0.02	0.08	2.3	0.0003	1.00	81
	cold period	0.12	0.29	1.3	0.0006	1.39	28
	all events	*0.03*	*0.14*	*1.9*			*109*
VK	warm period	0.05	0.09	2.2	0.0075	1.77	153
	cold period	0.16	0.35	1.4	0.0102	1.87	32
	all events	*0.05*	*0.14*	*2.1*			*185*
SR	warm period	0.06	0.33	2.7	0.0041	5.64	66
	cold period	0.34	1.00	1.3	0.0176	4.63	21
	all events	*0.11*	*0.49*	*2.1*			*87*
COD_{Mn}, chemical oxygen demand							
LL	warm period	0.13	0.60	2.4	0.002	9.8	81
	cold period	0.42	1.06	1.2	0.003	4.5	28
	all events	*0.19*	*0.72*	*2.0*			*109*
VK	warm period	0.29	0.52	1.5	0.041	5.6	153
	cold period	0.52	0.88	1.1	0.014	3.8	32
	all events	*0.30*	*0.58*	*1.4*			*185*
SR	warm period	0.20	0.53	2.0	0.004	6.3	65
	cold period	2.10	2.72	1.0	0.060	9.7	21
	all events	*0.31*	*1.07*	*1.8*			*86*

Based on the COV values in Table 26, a large variation in the EMCs was observed at all catchments, and only the TN EMCs had a low COV of less than 0.5. Larger COVs were typically obtained for EMLs (Table 27), indicating an even higher event-to-event variability in event loads than in concentrations. The normality of the event variables was separately tested for the warm and cold period events using the Kolmogorov-Smirnov and the Shapiro-Wilk tests. The distributions of EMC and EML often had a strong positive skew and the normality of both variables was rejected at the 95% confidence level. Only the cold period COD EMCs for LL and the cold period TN EMCs for all of the study catchments followed a normal distribution without transformations. In almost all cases, the log-transformation clearly improved the symmetry of the EMC distributions to normal or near-normal levels based on histograms and Q-Q plots. Only for SR did the log-transformation of the cold period TN EMCs change the symmetry of the distribution in the direction of a left-handed skew. The EMLs after the log-transformation were accepted as normal, with the exception of the cold period TSS EMLs for VK and the warm period TN EMLs for LL, which also showed a near-normal distribution after transformations based on the Q-Q plots. Significant differences in event water quality between the warm and cold periods are further examined in Section 5.1.9.

5.1.2 Changes in the rainfall-runoff characteristics during the construction works

Division of study years into similar periods according to runoff characteristics

The changes occurring in runoff event characteristics at the developing SR catchment were first analysed by identifying similar periods based on annual box-and-whisker plots (Figure 40) followed by the Kruskal-Wallis test for events with at least 1 mm of rainfall. Before conducting the comparison tests, the normality of the annual data groups was examined. The normality of the log-transformed data was not rejected for the years 2005 and 2006. For the earlier years, the log-transformation improved the symmetry of the distributions so that they better resembled a normal distribution, but the data were not always normal based on the normality tests. Highly skewed distributions were especially typical for the early years at SR due to the large number of events that only produced small runoff volumes.

Statistically significant differences ($p<0.001$, the Kruskal-Wallis test) existed between the monitoring years in volumetric runoff coefficients (C_{VOL}), total event runoff depths (R_{TOT}), event direct runoff depths (R_{EFF}), peak flows (Q_{MAX}) and mean runoff intensities (R_{MEAN}), all of which showed larger values starting in the year 2004 (Figure 40a-e). After inspecting the annual groupings, the data were grouped according to similar phases based on C_{VOL} (Figure 40a), Q_{MAX} (Figure 40b) and R_{MEAN} (Figure 40d), which experienced the most distinct changes based on the box plots. These phases are later labelled as Phase 1, which refers to the pre-construction period without impervious surfaces (the years 2001-2003), Phase 2, which refers to the transition period with major changes occurring in the amount of impervious surfaces (the year 2004), and Phase 3, which refers to the post-construction period with an increased impervious area (the years 2005-2006) (see Section 2.2 for the description of the changing catchment characteristics). Phases 1-3 are not entirely identical to the construction periods SR1-SR3 used in Section 3.1.1 for the long-term runoff analysis; for this reason, different terms are used.

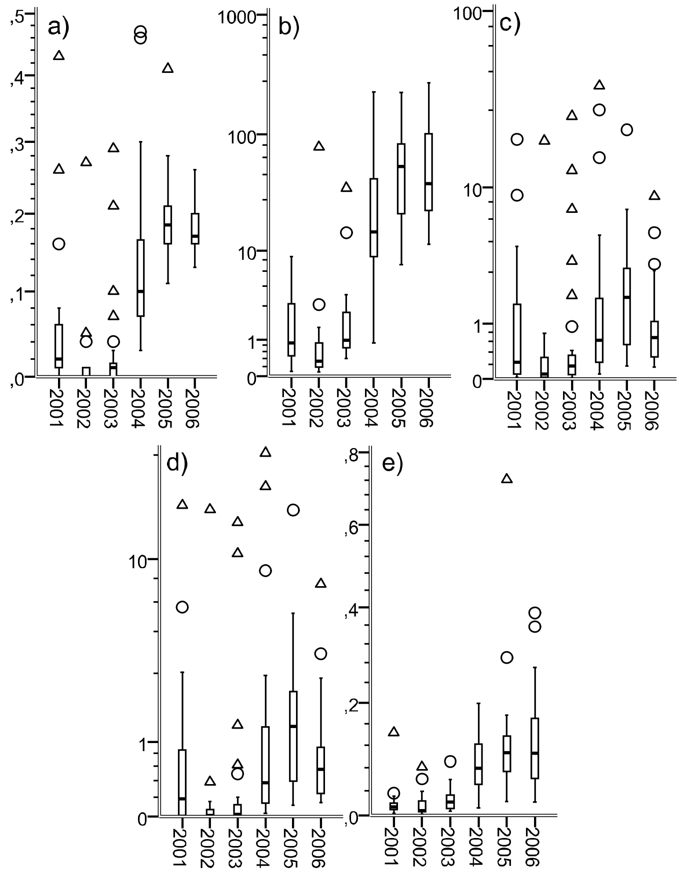


Figure 40. The box plots of annual groupings of a) volumetric runoff coefficient C_{VOL} (-), b) peak flow Q_{MAX} (l/s), c) total event runoff R_{TOT} (mm), d) direct runoff R_{EFF} (mm), and e) mean runoff intensity R_{MEAN} (mm/h). Circles and triangles illustrate mild and severe outliers, respectively, as defined in Chapter 2.4.3.

Identifying the changes in event variables during construction

To further examine and quantify the hydrological changes in the runoff variables during the construction process, the Kruskal-Wallis test was repeated using the three construction phases. Significant differences in the rainfall event variables P_{TOT}, P_{MAX}, P_{DUR} and P_{MEAN} were not observed (Figure 41a-d), which ensured that the changes observed at SR were due to the changes in the physical conditions of the catchment and construction activities rather than to changes in the meteorological conditions. Also, R_{DUR} did not show significant differences during the three phases (Figure 41e).

Significant changes ($p<0.001$, the Kruskal-Wallis test) were observed in C_{VOL}, Q_{MAX}, R_{TOT}, R_{EFF} and R_{MEAN} (Figure 42a-e); differences between the construction phases were further identified by paired comparisons using the Mann-Whitney test. The differences between Phase 1 and the later phases were always significant ($p<0.001$, the Mann-Whiteny U test). Phases 2 and 3 also showed differences in C_{VOL} and Q_{MAX} ($p<0.001$), R_{EFF} ($p<0.05$), but not in R_{TOT} ($p=0.128$).

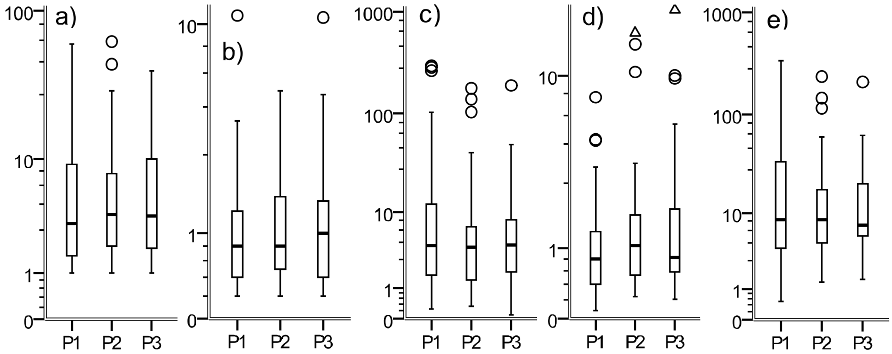


Figure 41. Similarity of a) event rainfall depth P_{TOT} (mm), b) maximum rainfall intensity P_{MAX} (mm/10 min), c) rainfall event duration P_{DUR} (h), d) mean rainfall intensity P_{MEAN} (mm/h), and e) runoff event duration R_{DUR} during the construction works (P1-P3 = Phases 1-3).

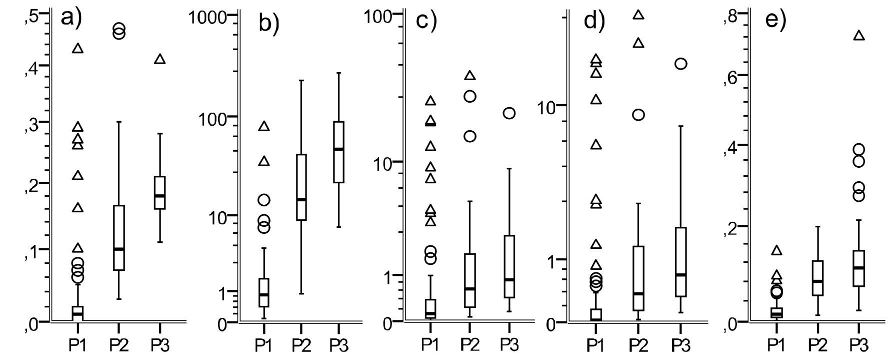


Figure 42. The runoff variables having statistically significant differences between the three development phases: a) C_{VOL}, b) Q_{MAX}, c) R_{TOT}, d) R_{EFF}, and e) R_{MEAN}.

A significant difference was observed in R_{MEAN} between Phases 2 and 3 ($p<0.05$, Figure 42e), although it was determined as the ratio of R_{TOT} to R_{DUR}, for which differences were not observed during the last two phases. The increase in R_{MEAN} was a combined result of a slight increase in R_{TOT} and a small reduction in R_{DUR}. A reduction in R_{DUR} was to be expected during the development period due to a shorter time of concentration upon completion of an efficient drainage system, but it seemed that R_{DUR} was more related to P_{DUR} and did not strongly reflect changes in the catchment conditions. Also, the observed changes in R_{TOT} were influenced by the rainy weather conditions, which increased the total runoff volumes for the catchment already during Phase 2 (Figure 42c). The weather conditions did not have an equally strong impact on R_{EFF} because it was not as sensitive as R_{TOT} to the elevated baseflow levels resulting from prolonged rainfall periods.

Identifying the hydrological changes and comparing them to the control catchments

To verify the observed changes in the hydrological variables for SR, the comparisons between the three phases were repeated with event data from the control catchments. For the medium-density VK catchment, significant differences ($p>0.05$, the Kruskal-Wallis test) between the phases were observed in P_{MEAN}, R_{MEAN} and R_{DUR} (Figure 43a-c). Thus, the differences observed at VK were either observed using different variables or not as distinct as those observed at SR, as shown in Figure 42.

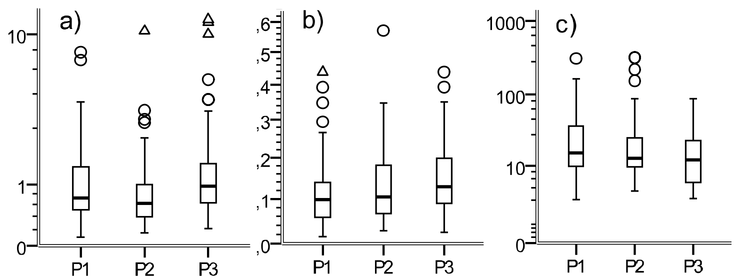


Figure 43. The event variables having statistically significant differences in VK between the three development phases: a) P_{MEAN}, b) R_{MEAN}, c) R_{DUR}.

For the low-density LL catchment, significant differences ($p<0.05$, the Kruskal-Wallis test) between the phases were observed in C_{VOL}, R_{TOT}, Q_{MAX}, R_{EFF}, R_{MEAN} and P_{MEAN} (Figure 44a-f). In comparison to SR, the events at LL showed changes in the runoff variables similar to the largest changes between the different construction phases. However, significant differences in the main runoff variables for LL (C_{VOL}, R_{TOT}, Q_{MAX}, R_{EFF}) were observed between Phase 1 and the other two phases ($p<0.05$, the Mann-Whitney U test), but not between Phases 2 and 3 owing to two wet summers, 2004 in Phase 2 and 2005 in Phase 3. For SR, C_{VOL}, Q_{MAX} and R_{EFF} in particular differed noticeably between Phases 2 and 3 (Figure 42). When considering both control catchments, Phase 2 had a lower P_{MEAN} than the other phases mainly because of the long event durations. In contrast, R_{MEAN} had smaller variations between the different phases in the control catchments than in SR, where a distinct change was observed, especially after Phase 1 (Figure 42e).

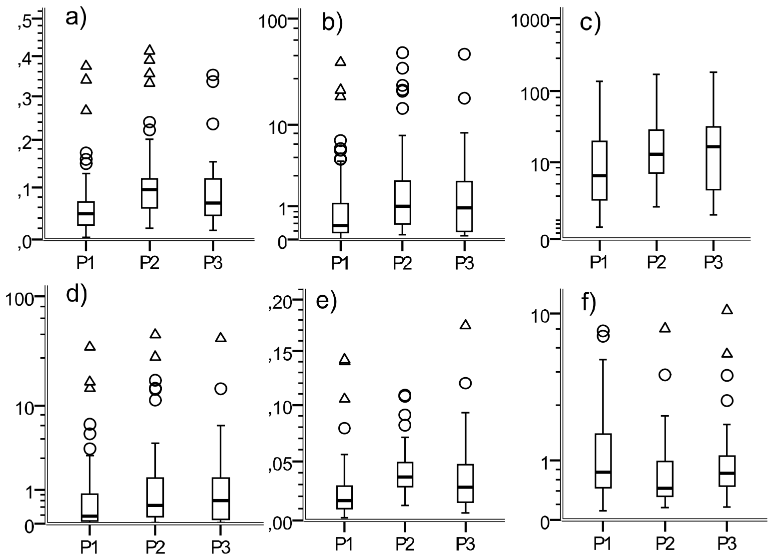


Figure 44. The event variables having statistically significant differences in LL between the three development phases: a) C_{VOL}, b) R_{TOT}, c) Q_{MAX}, d) R_{EFF}, e) R_{MEAN}, f) P_{MEAN}.

Based on the results presented above, the impact of the construction activities was apparent when i) significant differences were found at SR but not at the control catchments or when ii) the observed changes at the control catchments were smaller or opposite to those at SR. C_{VOL}, Q_{MAX} and R_{MEAN} had the most pronounced changes during all three development phases when comparing SR with LL (Figure 45). Although the median values were higher during Phase 3 than during Phase 1 for LL, the observed increase was much higher for SR (Table 28).

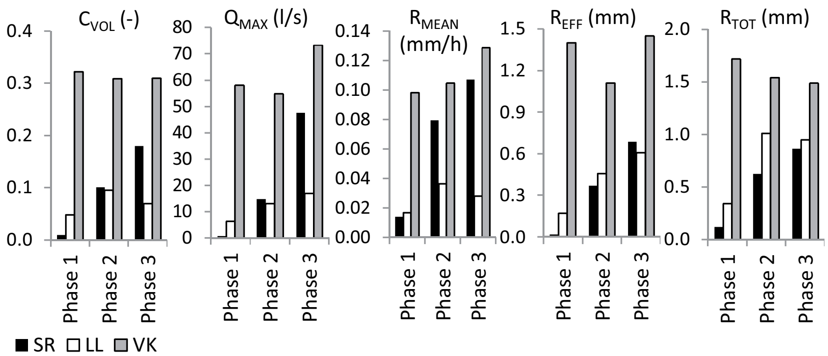


Figure 45. Medians of C_{VOL}, Q_{MAX}, R_{MEAN}, R_{EFF}, and R_{TOT} during the three construction phases: SR (black bars), LL (white bars), VK (grey bars).

Table 28. Increase (%) in the key hydrological variables between Phase 1 and Phase 3.

		C_{VOL}	Q_{MAX}	R_{MEAN}	R_{EFF}	R_{TOT}
SR	mean	447%	2332%	482%	45%	21%
	median	1700%	5492%	672%	3325%	622%
LL	mean	42%	53%	55%	41%	37%
	median	44%	169%	67%	252%	179%

Changes in hydrological variables during minor and major rainfall events

For SR, the maximum values of at least two variables characterizing runoff (R_{TOT}, R_{EFF}) were of a similar magnitude for both the early monitoring years 2001-2003 and the later years (see Figure 40). Also, Table 28 shows a similar increase by percentage in the mean R_{EFF} and R_{TOT} for both SR and LL between Phases 1 and 3. Nevertheless, the increase in the medians of all of the hydrological variables between Phases 1 and 3 for SR was much larger than the increase in their average values, or in the medians for LL (Table 28). This implies that the largest runoff events at SR were not as much affected by the construction works as by the minor rainfall events. This assumption was tested using paired comparisons (the Mann-Whitney U test), with the event data divided into two groups according to the event size. Obviously, there was a limited number of large rainfall events available in the data; by combining the data from Phases 2 and 3 and using P_{TOT} = 16 mm as a lower limit for major rainfall events, nine rainfall events were obtained to represent major rainfall events in Phase 1 and nine events for the combined Phase 2 and 3. Later, in Section 5.1.6, changes in the runoff response to rainfall at SR is assessed, when event precipitation is in the range of approximately 16 to 20 mm.

For the group of minor rainfall events, statistically significant differences between the periods were found for the same variables as when using the whole data set ($p<0.001$, the Mann-Whitney U test). For major events, however, the Mann-Whitney test detected significant differences only for Q_{MAX} ($p<0.001$) and R_{MEAN} ($p=0.001$). Significant differences were not found for C_{VOL}, R_{TOT} and R_{EFF}, indicating that the construction process did not cause as large a change in the runoff volumes during the major events as during the minor events. Differences in rainfall event characteristics (P_{TOT}, P_{MAX}, P_{DUR}, P_{MEAN}) between the periods were not observed for the group of major rainfall events.

5.1.3 Changes in direct runoff hydrographs

Instantaneous unit hydrographs (IUH) based on a two-parameter gamma distribution were used to quantify changes that occurred in the shape of the runoff hydrograph and the catchment time of concentration during urbanization. Events for the IUH analysis were selected based on the following criteria: 1) if there was an undisturbed recession phase in the observed runoff without precipitation during the runoff event, 2) if the algorithm used for the optimization of IUHs converged and 3) if the events were chosen from all phases of the construction works for the developing SR catchment. When the IUH was fitted against the measured runoff by allowing the effective rainfall to vary within a very large range (between zero and the measured rainfall), the method even reproduced multi-peaked runoff events quite well. The errors were smaller when simulating the peak flow rates than the direct runoff volumes and in the catchments representing higher levels of imperviousness, such as the medium-density VK catchment and during the later years of construction at SR (Table 29). A common feature of all the catchments was the fact that the gamma unit hydrograph had a steeper recession limb than the measured limb for events that had a prolonged recession phase, which also resulted in the largest errors in the modelled direct runoff (shown in Table 29).

Table 29. Summary characteristics of the events used in the IUH analyses and differences (%) between modelled and observed peak flows (Q_{MAX}) and direct runoff volumes (R_{EFF}).

Site	Data	Year	n	Range of event properties			Percent error (%)	
				P_{TOT}	P_{MAX}	C_{VOL}	Q_{MAX}	R_{EFF}
SR	10 min	2001	5	2.0-11.6	0.6-3.8	0.01-0.03	-10.1±7.6	-7.2 ± 10.0
SR	10 min	2002	4	4.2-11.6	2-4	0.002-0.01	-6.6 ± 8.6	-0.6 ± 2.0
SR	10 min	2003	6	2.0-9.2	0.6-1.4	0.01-0.06	-3.7 ± 4.3	-13.6 ± 13.7
SR	10 min	2004	8	2.0-13.8	0.4-2.8	0.09-0.33	-2.1 ± 5.8	-9.8 ± 8.3
SR	10 min	2005	11	2.6-25.2	0.4-10.6	0.19-0.36	-0.3 ± 0.4	-8.2 ± 5.7
SR	2 min	2005-2006	8	2.4-8.8	0.4-3.4	0.17-0.32	-5.9 ± 5.7	-10.0 ± 6.0
VK	2 min	2005-2006	8	1.8-9.6	0.6-5.6	0.24-0.58	-1.9 ± 1.7	-4.8 ± 4.5
LL	2 min	2005-2006	4	3.2-17.2	0.6-11.6	0.02-0.08	-6.5 ± 1.1	-4.9 ± 9.1

In order to detect how the construction activities changed the shape of the unit hydrographs, the comparisons of the study catchments and the monitoring years were conducted based on average IUHs. Before calculating the average gamma IUHs, the normality of the distribution of the gamma parameters, α and β, were tested and accepted (the Kolmogorov-Smirnov test, $p<0.05$). Urban development increased the flow peaks and reduced the recession phase of the runoff hydrographs for SR (Figure 46), but these changes were not solely related to the changes in TIA. For the years 2004 and 2005, the average IUHs for SR were almost identical, while for the first three years the average IUHs varied, especially between the years 2001 and the years 2002-2003 (Figure 46a). This difference can at least partly be explained by the fact that the year 2001 consisted primarily of autumn rainfall events. However, it is important to note that the sewer system was finished in 2002 together with new streets, which had not been paved yet (Section 2.2). Hence, while this development step did not increase the TIA, it certainly affected the shape of the runoff hydrograph. Figure 47a shows that, despite the lower TIA, SR had a sharper IUH than VK during the last monitoring year owing to the steeper topography of the catchment. The low-density LL catchment exhibited a gentle IUH, as expected, owing to the large percentage of pervious areas and the slow conveyance system, which mainly consisted of open ditches.

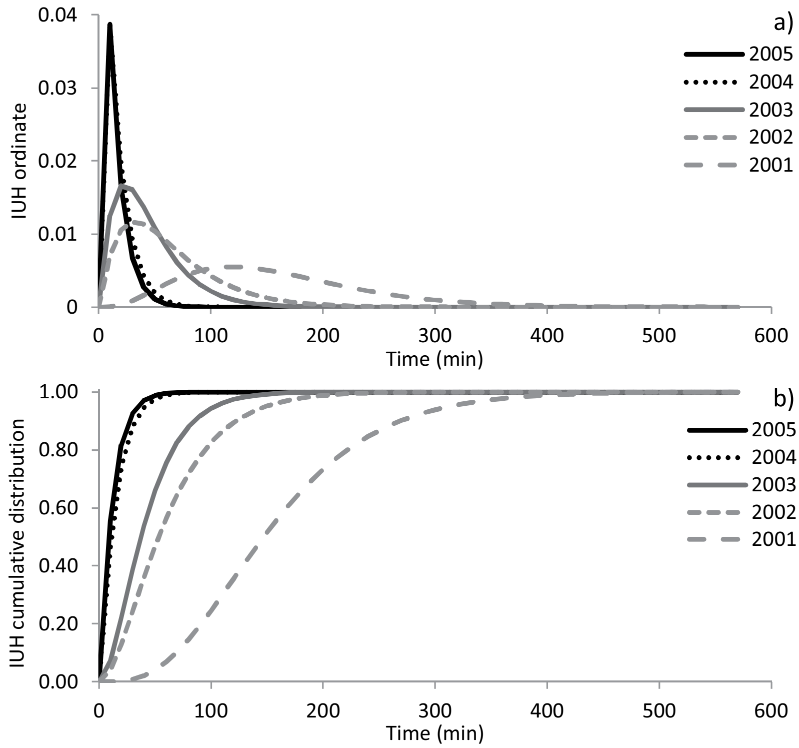


Figure 46. Average IUHs (a) and their cumulative distributions (b) for each monitoring year using 10-minute data at the developing SR catchment. IUH ordinate corresponds to the area of IUH between two consecutive time intervals. The number of events for each year: 5 (2001), 4 (2002), 6 (2003), 8 (2004), and 11 (2005).

Urbanization at SR led to a decrease in the average IUH parameters (Figure 48a-b) and in the catchment lag, which was measured as the mean transit time (MTT) (Figure 48c). Yet, the observed change was statistically significant only in the scale parameter, β, and MTT (the Kruskal-Wallis test, $p<0.001$), but not in the shape parameter, α ($p=0.478$). For shape parameter α, 53% of the 15 events before the year 2004 and 68% of the 19 events during the years 2004-2005 had a value of 1, demonstrating that α also had small values before development, whereas values above 2.4 were not identified after development (Figure 48a). However, the change in β (Figure 48b) and MTT (Figure 48c) was more pronounced, as rather high values were observed during the early years and small values (<20) occurred starting mainly in 2004. Urban development reduced the event-to-event variability of the IUHs and MTTs based on the 95% confidence intervals (shown in Figure 48).

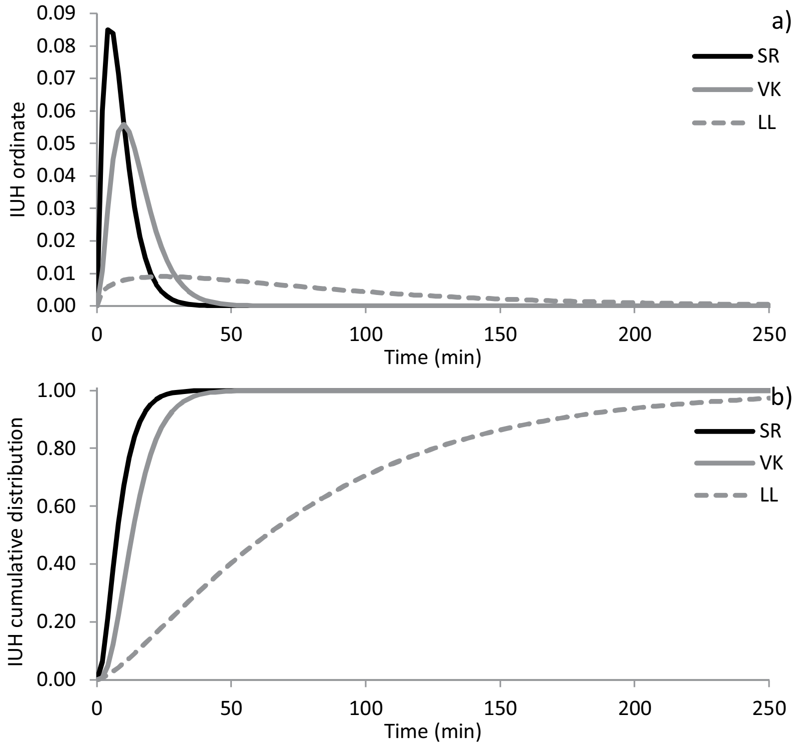


Figure 47. Average IUHs (a) and their cumulative distributions (b) for the developing SR catchment, and the LL and VK control catchments using 2-minute data from the years 2005-2006. The number of events (SR/VK/LL): 8/8/4.

Based on 2-minute IUHs, the average MTT was 9 min, 12 min and 76 min for SR, VK and LL, respectively, while in 2001 the average MTT for SR (Figure 48c) exceeded 100 minutes. These changes did not result from the selection of events for each year because no similar changes in the average P_{TOT} and P_{MAX} or in their confidence intervals were observed (Figure 48d-e). The shorter MTT for LL in comparison to the average MTT for SR in 2001 also reflected the impact of urbanization as an increased efficiency in the conveyance system at the low-density urban catchment.

Because individual events had unique IUHs for all of the catchments, the relationship between the gamma parameters, the MTT and the main rainfall event characteristics were examined for different years and catchments based on their bivariate correlations (Table 30). In 2002, two events out of four had rather similar characteristics, which likely appeared as deviant correlations in Table 30, such as strong correlations ($r > 0.80$) without statistical significance. The correlation between α and MTT weakened as the construction work progressed, whereas a positive, strong correlation between β and MTT was established during the later years of the development. In fact, during the first two years the MTT had a negative correlation with β. Based on the results, it seemed that the relationship between the gamma parameters and MTT changed as the catchment was developed. Statistically significant, negative correlation between MTT and P_{MAX} was also observed for the later part of the construction works at SR - this change, however, was not as clear as between MTT and β. Rainfall event characteristics mostly had no significant correlations with the gamma parameters. A common feature of all the catchments was the negative correlation between α and β; however, this relationship was not apparent at SR during the later years. The lack of correlation was partly a result of a decreasing variation in the IUHs and MTTs (Figure 48) as the construction work progressed.

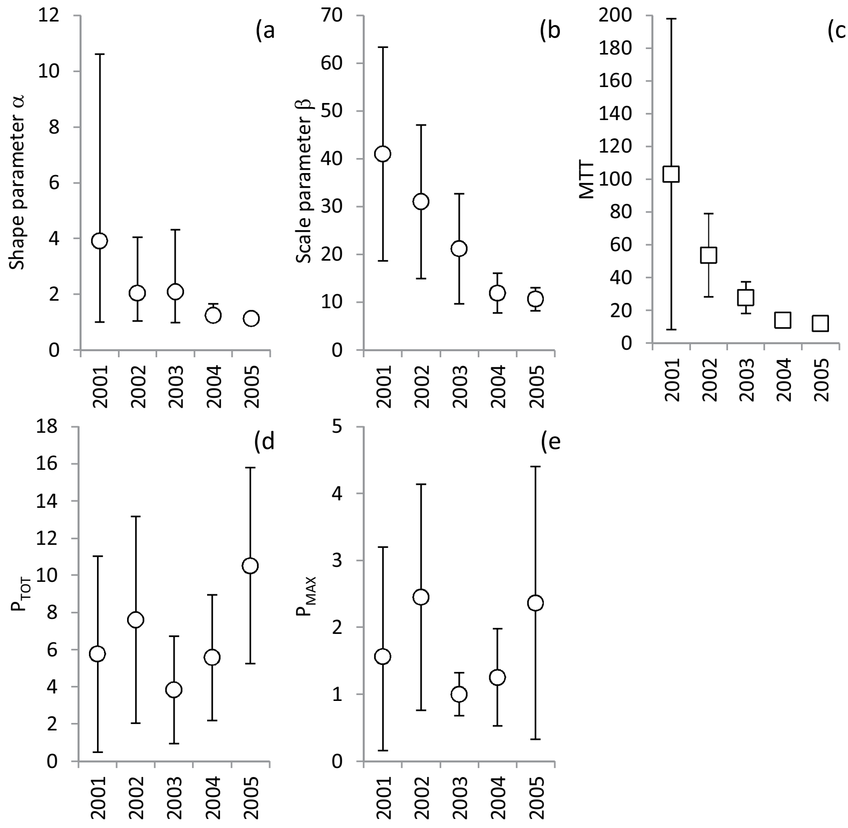


Figure 48. Annual averages of a) the shape parameter α, b) the scale parameter β, c) the mean transit time MTT (min), d) the event rainfall P_{TOT} (mm) and e) maximum rainfall intensity P_{MAX} (mm/10 min) with their 95% confidence intervals based on the Students t distribution in the developing SR catchment. Number of events (2001/2002/2003/2004/2005): 5/4/6/8/11.

Table 30. Pearson correlations between the gamma parameters, MTT and the main rainfall event characteristics P_{TOT} and P_{MAX}). Correlations given separately for each year for SR with 10-min data (2001-2005) and for all study catchments (LL, VK, and SR) using 2-min data from the years 2005-2006. Bolded correlations are statistically significant at $p<0.05$, strong correlations ($r>0.70$) are given with a grey background.

	P_{TOT}		P_{MAX}		MTT		MTT		α
Year/data	α	β	α	β	α	β	P_{TOT}	P_{MAX}	β
2001	-0.58	0.06	-0.23	-0.42	**0.94**	-0.53	-0.81	-0.52	-0.73
2002	0.81	-0.84	0.29	-0.33	0.95	**-0.96**	0.95	0.57	**-0.99**
2003	-0.15	-0.06	0.25	-0.60	-0.33	0.53	0.63	**-0.82**	**-0.86**
2004	-0.22	-0.23	-0.42	-0.64	0.35	**0.75**	-0.39	**-0.94**	-0.34
2005	-0.11	-0.41	-0.16	-0.46	0.45	**0.81**	-0.46	-0.51	-0.14
2-min (SR)	-0.21	0.40	-0.49	**-0.75**	0.53	**0.89**	0.16	**-0.83**	0.11
2-min (VK)	**-0.83**	0.54	0.46	-0.24	0.31	0.15	-0.67	0.67	**-0.88**
2-min (LL)	-0.61	0.18	-0.48	0.07	0.22	0.37	-0.58	-0.55	-0.82

5.1.4 Changes observed in the runoff characteristics during the cold period

The impacts of urbanization on the runoff characteristics during the cold period events were investigated using box plots and comparison tests. Three cold periods were chosen for the analysis: 2001-2002, 2004-2005 and 2005-2006. During each period, a complete set of events was available for the whole duration of the cold period starting from the time when the average monthly air temperature dropped below 0 °C and the first snowfall event occurred and lasting until the end of the last direct runoff event during spring snowmelt. In general, all of the variables had skewed distributions and most of them did not fulfil the normality assumptions.

It is difficult to compare winters owing to the varying weather conditions. Of the three periods, the cold periods 2001-2002 (Figure 49a) and 2004-2005 (Figure 49b) were more similar, with notably larger event runoff volumes, than the cold period 2005-2006 (Figure 49c). As already mentioned in Section 3.1.2, the developing SR catchment in general produced much more runoff than the LL and VK control catchments. The data for SR for the 2005-2006 period did not include the first event owing to the discarded data from November, which is illustrated in Figure 49c as smaller cumulative runoff in comparison to the control catchments. Also, the pumping of water from the construction sites likely increased flow depths during the building construction period (Figure 49b-c).

The cumulative runoff curves for the medium-density VK catchment and the low-density LL catchment overlapped (Figure 49). During the winter of 2005-2006, the early winter rainfall events at VK produced more runoff than at LL (Figure 49c), but after the seasonal snow cover was established in the beginning of January, the differences between the catchments diminished. The clearest differences between LL and VK are displayed in Table 31: the last direct runoff event at VK during the spring snowmelt ended about 11-15 days earlier than at LL. Also, the number of events for VK was notably larger than for LL and SR (Table 31). The influence of urbanization on the event count was also observed for SR, where the number of events increased during the development.

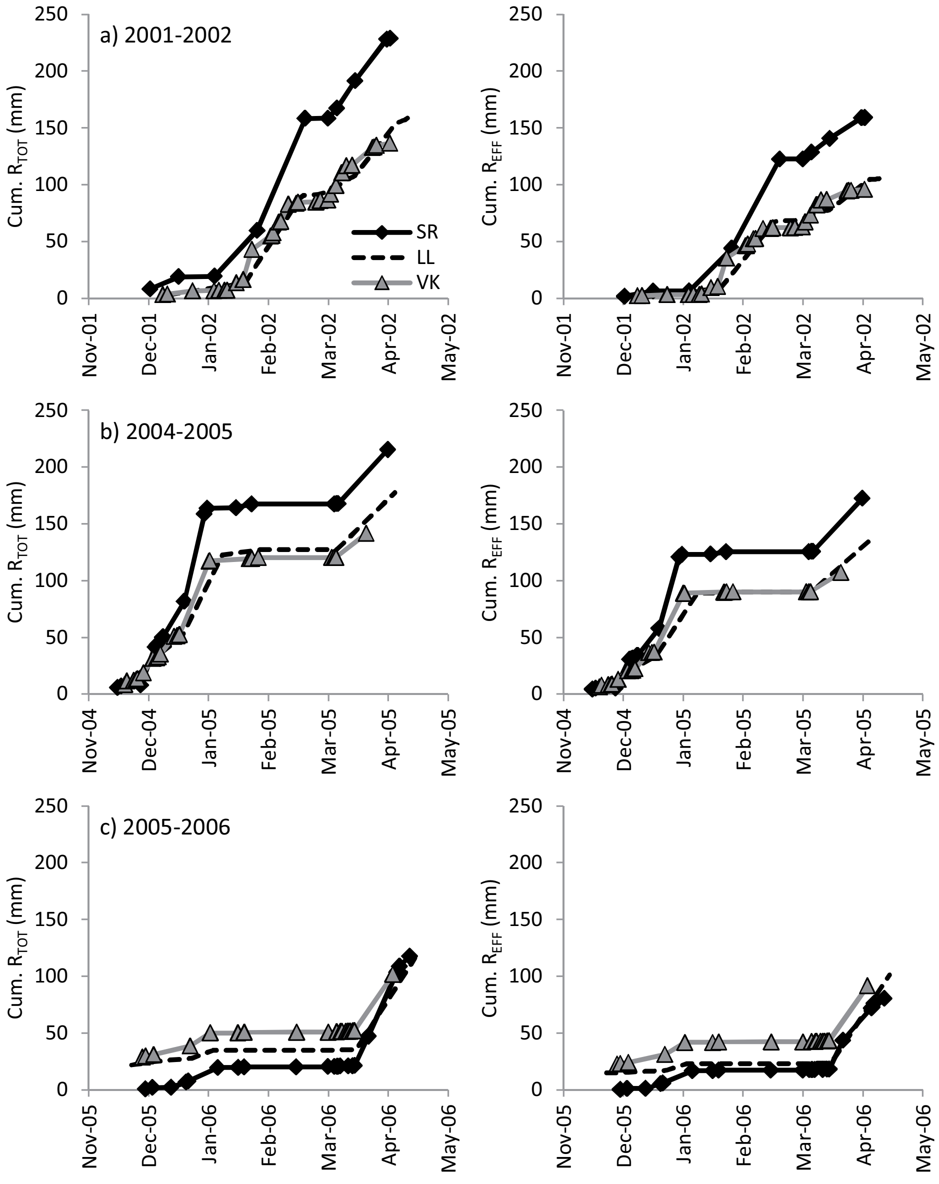


Figure 49. Cumulative event runoff during three cold periods: a) 2001-2002, b) 2004-2005, and c) 2005-2006. R_{TOT} is event total runoff (mm) and R_{EFF} event direct runoff (mm). The time axis shows the end date of an event.

Table 31. Summary of the end date of direct runoff and the number of events for each cold period in the event analysis.

	End of the direct runoff			Number of events		
Season	SR	LL	VK	SR	LL	VK
2001-2002	April 4	April 16	April 4	10	21	31
2004-2005	April 21	April 21	April 6	17	9	23
2005-2006	April 23	April 26	April 15	22	13	18

Significant differences in runoff event characteristics between the winter periods were observed in R_{DUR} (p=0.031, the Kruskal-Wallis test) for LL (Figure 50a) and in R_{MEAN} for both LL and VK (the Kruskal-Wallis test, p=0.025 for LL in Figure 50b; p=0.004 for VK in Figure 51b). These differences resulted from the varying weather patterns during the different years; in Figure 50, the most pronounced feature for LL was the events of a longer duration and with higher runoff volumes during the winter of 2004-2005. For VK, the smaller R_{MEAN} during the last winter, 2005-2006, was caused by smaller event runoff depths (Figure 51b).

For SR, only R_{DUR} (Figure 52a) showed a temporal pattern that did not correspond to those visually observed at the control catchments based on the box plots. Also, the changes in R_{TOT} (Figure 52c) and R_{EFF} (Figure 52d) appeared to be more pronounced for SR compared with VK: as the box plots illustrate the fact that the medians of R_{TOT} and R_{EFF} in the winter 2001-2002 exceeded the 75th percentiles of the latter two winter periods for SR. Statistically significant differences between the periods were observed for R_{DUR} (p=0.011, the Kruskal-Wallis test) and R_{TOT} (p=0.028).

Based on the above results, urbanization clearly impacted R_{DUR} by reducing the duration of the cold period events. This agreed with the findings that the event count was higher in the more urbanized conditions at VK than at LL (Table 31) without there being large differences in the cumulative event runoff volumes at the control catchments (Figure 49). The impact of urbanization on runoff volumes and peak flows was not detected in the three periods used in the analysis. A decreasing pattern in R_{TOT} was only found for SR, supporting the idea that the snowmelt runoff separated into more frequent events with a shorter duration and smaller event runoff depths than before urbanization. Statistically significant differences between the catchments were only observed in R_{DUR}: SR had longer R_{DUR} than VK during the first winter, 2001-2002 (p=0.003, the Mann-Whitney U test). During the cold period of 2004-2005, LL had longer events than SR and VK (p<0.001 for LL and VK, p=0.011 for LL and SR, the Mann-Whitney U test), whereas no similar difference in R_{DUR} was observed during the last cold period.

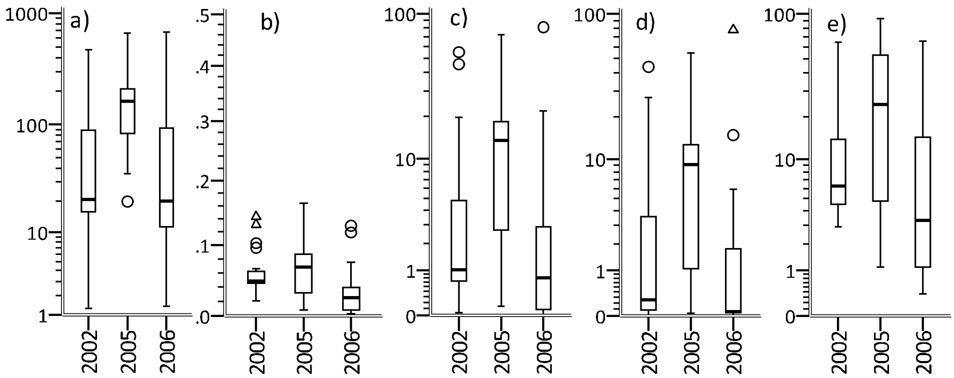


Figure 50. Box plots of the event runoff characteristics during the cold period at the low-density LL catchment: a) runoff event duration R_{DUR} (h), b) mean runoff intensity R_{MEAN} (mm/h), c) total runoff depth R_{TOT} (mm), d) direct runoff depth R_{EFF} (mm), and e) peak flow Q_{MAX} (l/s). Circles and triangles illustrate mild and severe outliers, respectively, as defined in Chapter 2.4.3.

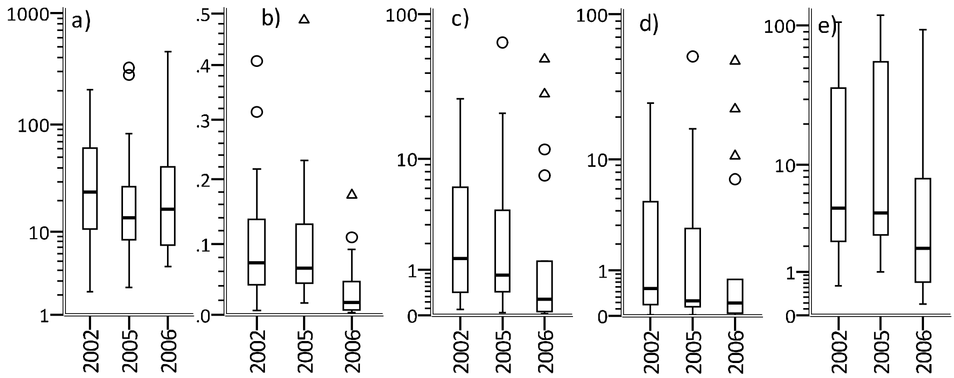


Figure 51. Box plots of the event runoff characteristics during the cold period at the medium-density VK catchment: a) R_{DUR}, b) R_{MEAN}, c) R_{TOT}, d) R_{EFF}, and e) Q_{MAX}.

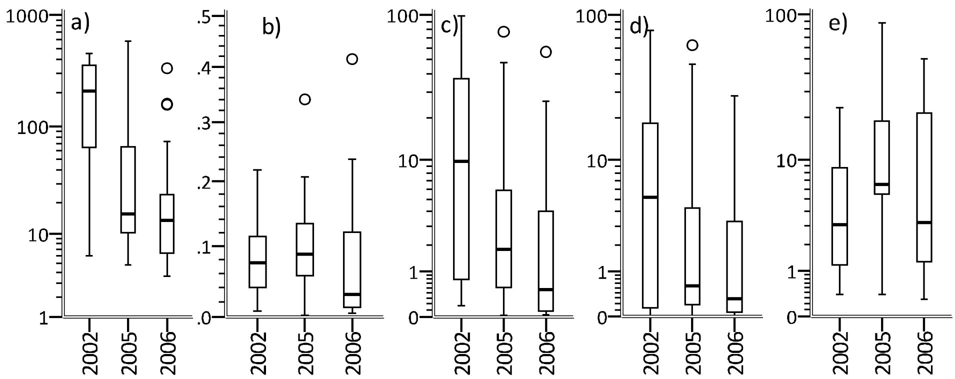


Figure 52. Box plots of the event runoff characteristics during the cold period at the developing SR catchment: a) R_{DUR}, b) R_{MEAN}, c) R_{TOT}, d) R_{EFF}, and e) Q_{MAX}.

When the results from the cold period runoff events are compared with those from the warm period events, the changes occurring during the cold period were less distinct than the changes during the warm period runoff events (Section 5.1.2). While the duration of the warm period runoff events did not change significantly during the development owing to their strong linkage to the rainfall event duration, R_{DUR} most strongly indicated the impacts of urbanization during the cold period runoff events. Although the results from the cold period were masked by the high degree of variability in the runoff characteristics, the direction of change looked different between the warm and cold periods: urbanization caused an increase in the key runoff characteristics during the warm period events, but the key characteristics during the cold period decreased, such as the event runoff volumes and event durations, or remained unchanged. A common feature of the warm and cold period events was the fact that the runoff response to varying weather conditions was more visible for LL (Figure 50) than for VK (Figure 51).

5.1.5 Multiple linear regression analysis of runoff event variables

Model-building procedure

The purpose of the multiple linear regression (MLR) analysis was not to produce predictive models, but to identify the key hydrological variables describing the runoff mechanisms for the study catchments. The variables that are most relevant from a stormwater management and planning point of view are the total event runoff (R_{TOT}), direct runoff (R_{EFF},), event peak flow (Q_{MAX}), and volumetric runoff coefficient (C_{VOL}). The explanatory variables were the rainfall characteristics and the antecedent conditions (Table 7 in Section 2.4.3). The variables describing the catchment conditions included the total impervious area (TIA) and the effective impervious area (EIA). The way in which the EIA is determined is described later in Section 5.1.6. For the developing SR catchment, the data from Phase 1 (2001-2003) and Phase 3 (2005-2006) were used to illustrate the changes between the two periods; only the data from Phase 3 were used in the combined models.

Before starting the model-building procedure, the Pearson correlations were calculated to detect simple relationships between the event characteristics. The correlation matrices are presented in Appendix E. Because the variables had skewed distributions, they were log-transformed. Usually, the normality assumption was accepted for transformed variables (the Kolmogorov-Smirnov test), or at least it improved the symmetry of the distributions towards the normal distribution. In particular, the distributions for the preceding 1-7 day precipitation sums (PREC1-PREC7) did not improve as much within the symmetry of the distributions after the log-transformation as did the other variables.

All of the models and the regression coefficients discussed here are statistically significant at $p<0.001$, if not mentioned otherwise. In the following section, one or more MLR equations are provided for each catchment and for all of the catchments combined. The different model versions are numbered, starting from the simplest model version. Some models are marked by a) and b) to illustrate two alternatives having an equal number of independent variables. Scatter plots of the predicted values vs. observed are illustrated in Appendix F for the best models reported later in Tables 32-37.

Key variables in the MLR models

The most important variables in the MLR models for R_{TOT} and R_{EFF} were event precipitation (P_{TOT}) and imperviousness (TIA or EIA). Precipitation alone explained 87-98% of the variation in runoff volumes in most of the catchment models (Table 32). The combined runoff models revealed the importance of imperviousness (Table 33): while P_{TOT} alone explained 71-76% of the variance in runoff volumes in the combined runoff models, the use of TIA and EIA increased the R^2 values to more than 90%. When using EIA, slightly smaller SEEs were achieved; however, no major differences between TIA and EIA as explanatory variables were observed.

Table 32. MLR models for log(R_{TOT}) and log(R_{EFF}) including regression coefficients for log-transformed variables, coefficients of determination (R^2) and the standard error of the estimate (SEE). The model numbers (1-3) indicate different versions of the same model for each catchment.

	Model	Constant	P_{TOT}	P_{DUR}	P_{MAX}	DAYS	R^2	SEE
R_{TOT}, Total event runoff (mm)								
LL	1	-1.131	1.266				*0.87*	*0.252*
	2	-1.131	1.049	0.183			*0.88*	*0.242*
	3	-1.051	1.011	0.185		-0.147	*0.89*	*0.232*
VK	1	-0.545	1.173				*0.94*	*0.136*
	2	-0.527	1.170			-0.077	*0.95*	*0.128*
SR: Phase 1	1	-1.455		0.934			*0.72*	*0.433*
SR: Phase 3	1	-0.705	1.142				*0.98*	*0.076*
R_{EFF}, Direct runoff (mm)								
LL	1	-1.623	1.551				*0.93*	*0.218*
	2	-1.557	1.521			-0.121	*0.94*	*0.211*
VK	1	-0.668	1.245				*0.95*	*0.136*
	2	-0.656	1.243			-0.052	*0.95*	*0.133*
SR: Phase 1	1	-0.133	0.414				*0.51*	*0.192*
SR: Phase 3	1	-0.828	1.146				*0.98*	*0.060*

Table 33. Combined MLR equations for log(R_{TOT}) and log(R_{EFF}): models with a) TIA and b) EIA. All variables are log-transformed. Letters (a) and (b) illustrate two alternatives for the models having an equal number of independent variables.

Model	Constant	P_{TOT}	TIA	EIA	DAYS	R^2	SEE
R_{TOT}, Total event runoff (mm)							
1	-0.720	1.130				*0.76*	*0.293*
2a	-2.762	1.208	1.296			*0.91*	*0.179*
2b	-1.878	1.209		0.813		*0.91*	*0.179*
3a	-2.631	1.194	1.265		-0.139	*0.92*	*0.173*
3b	-1.769	1.194		0.794	-0.138	*0.92*	*0.172*
R_{EFF}, Direct runoff (mm)							
1	-.955	1.255				*0.71*	*0.374*
2a	-3.853	1.366	1.84			*0.94*	*0.177*
2b	-2.600	1.367		1.156		*0.94*	*0.175*
3a	-3.754	1.355	1.816		-0.105	*0.94*	*0.173*
3b	-2.518	1.356		1.141	-0.104	*0.94*	*0.172*

The Phase 1 model for determining R_{TOT} for SR was an exception among the runoff volume models because the best MLR equation was achieved using P_{DUR} as the only explanatory variable (Table 32). P_{DUR} explained 72% of the variations in R_{TOT}, while P_{TOT} alone could only have explained 64% of the variations. The Phase 1 models for both R_{TOT} and R_{EFF} had lower R^2 values than for the other catchments owing to the large number of events, which consisted mainly of baseflow and, sometimes, non-existent direct runoff. Similarly to the Phase 1 results for SR, P_{DUR} was included in more complex models for the low-density LL catchment in Table 32. Thus, P_{DUR} had a more pronounced effect on R_{TOT} in less developed catchment conditions most likely as a result of longer concentration times and larger rainfall losses compared with the more developed catchment conditions.

The event peak flows (Q_{MAX}) proved to have a more site-specific and complex nature than R_{TOT} and R_{EFF}, which can be seen in the form of lower R^2 values in Table 34 compared with Table 32. The order of importance of the main explanatory variables differed among the different study catchments and construction phases. The three most important variables were the maximum 10-minute intensity (P_{MAX}), TIA and P_{TOT}. The catchment models (Table 34) showed that P_{TOT} was the primary explanatory variable for Q_{MAX} in the less developed catchment conditions (LL and Phase 1 at SR), whereas P_{MAX} was in the more developed catchment conditions (VK and SR Phase 3 at SR) — this was also noticed based on the bivariate correlations in Appendix E and the scatter plots in Figure 53. Based on Figure 53, it is obvious that the scatter plots for VK and Phase 3 for SR resemble each other (smaller scatter in Q_{MAX} in relation to P_{MAX} than in

P_{TOT}), while Q_{MAX} correlates more highly with P_{TOT} than with P_{MAX} for LL and Phase 1 for SR.

Table 34. MLR models for log(Q_{MAX}) for individual catchments. All variables are log-transformed.

	Model	Constant	P_{TOT}	P_{MAX}	P_{MEAN}	DAYS	PREC5	R^2	SEE
Q_{MAX}, Peak flow (l/s)									
LL	1	0.274	0.979					*0.80*	*0.255*
	2	0.430	0.746	0.448				*0.85*	*0.218*
	3	0.478	0.731	0.432		-0.098		*0.86*	*0.214*
VK	1	1.754		1.032				*0.70*	*0.236*
	2	1.627	0.185	0.894				*0.72*	*0.228*
	3	1.598	0.248	0.786	0.216			*0.74*	*0.218*
SR: Phase 1	1	-0.512	0.696					*0.38*	*0.419*
	2	-0.678	0.628				0.303	*0.45*	*0.399*
SR: Phase 3	1	1.703		1.169				*0.84*	*0.167*
	2	1.693		1.111	0.144			*0.86*	*0.160*

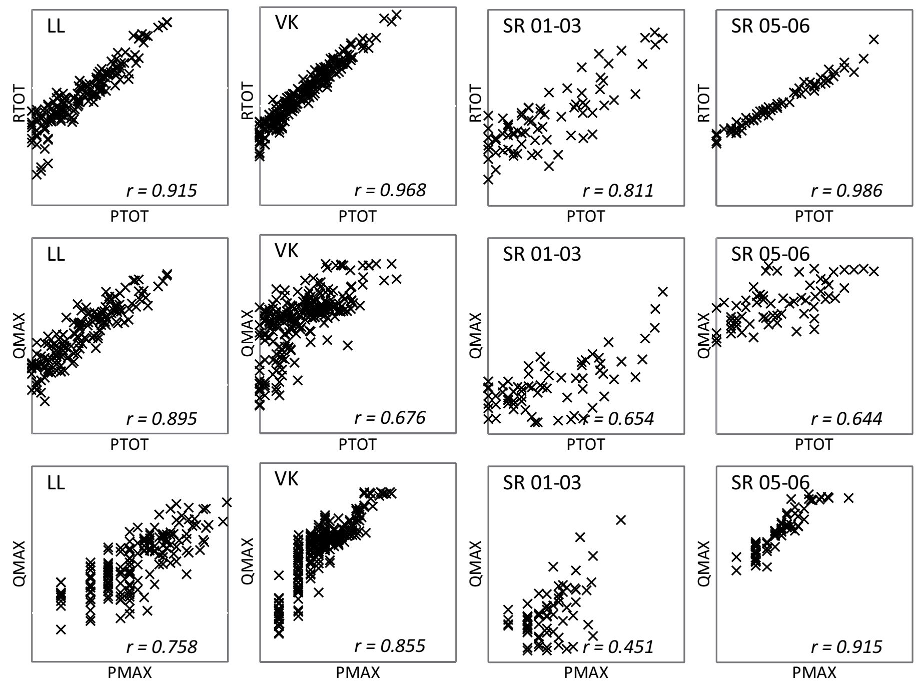


Figure 53. Scatter plots of the log-transformed Q_{MAX}, P_{MAX}, R_{TOT} and P_{TOT} with the Pearson correlation coefficients (*r*).

In the combined model for Q_{MAX} (Table 35), the peak flows were averaged over the total catchment areas in terms of units [*l/s/ha*]. Without the unit transformation, the best model would have had a slightly lower R^2 value, 0.79. In the models, the role of catchment imperviousness was even more important than in the R_{TOT} and R_{EFF} models (Table 33): TIA and EIA were the first variables chosen for the model and they explained 47% of the variations in the event peak flows. However, P_{MAX} was needed for there to be a considerable increase in the R^2 value. By adding P_{TOT}, a 4% increase in the R^2 value was achieved. Hence, all three parameters were incorporated for an adequate model for Q_{MAX}, and still the coefficient of determination remained lower than it did for the R_{TOT} and R_{EFF} models (Table 33).

Table 35. Combined MLR models for log(Q_{MAX}). All variables are log-transformed.

Model	Constant	P_{TOT}	P_{MAX}	TIA	EIA	R^2	SEE
Q_{MAX}, Peak flow (l/s/ha)							
1a	-3.685			2.533		0.47	0.491
1b	-1.970				1.599	0.47	0.488
2a	-4.209		1.053	2.892		0.78	0.313
2b	-2.250		1.055		1.826	0.79	0.307
3a	-4.545	0.387	0.741	2.933		0.82	0.282
3b	-2.560	0.39	0.741		1.852	0.83	0.275

The catchment models for the volumetric runoff coefficient, C_{VOL}, had only moderate R^2 values at best (Table 36), but the combined models achieved an R^2 of 0.80 (Table 37). TIA and EIA alone explained more than 60% of the variations in the event, C_{VOL}s. P_{TOT} was an important variable both in the combined model and in the catchment models, and it had the highest bivariate correlation with C_{VOL} based on Appendix E. Also, P_{MAX} had statistically significant correlations with C_{VOL}, but it was only included as the first explanatory variable in the Phase 3 model for SR: for SR, P_{TOT} and P_{MAX} showed equivalent correlations with Q_{MAX} in Phase 3, while during Phase 1 and in the control catchments C_{VOL} always had a higher degree of correlation with P_{TOT} than with P_{MAX} (Appendix E).

Table 36. MLR models for log(C_{VOL}) in individual catchments. All variables are log-transformed. For SR Phase 1, an alternative model 1b is shows, how the removal of rainfall events P_{TOT} < 5 mm affected the model results.

	Model	Constant	P_{TOT}	P_{DUR}	P_{MAX}	DAYS	R^2	SEE
C_{VOL}, Volumetric runoff coefficient (-)								
LL	1	-1.608	0.539				0.64	0.641
	2	-1.551	0.514			-0.107	0.67	0.662
VK	1	-0.672	0.258				0.40	0.137
	2	-0.659	0.256			-0.056	0.43	0.134
	3	-0.631	0.219		0.076	-0.057	0.44	0.132
SR: Phase 1	1a	-0.004		0.024			0.42	0.021
	1b	-0.098	0.113				0.59	0.027
SR: Phase 3	1	0.075			0.029		0.48	0.010
	2	0.069	0.009		0.022		0.51	0.010

Table 37. Combined MLR models for log(C_{VOL}). All variables are log-transformed.

Model	Constant	P_{TOT}	TIA	EIA	DAYS	R^2	SEE
C_{VOL}, Volumetric runoff coefficient (-)							
1a	-3.385		1.698			*0.61*	*0.245*
1b	-2.226			1.066		*0.61*	*0.244*
2a	-3.857	0.366	1.842			*0.80*	*0.178*
2b	-2.602	0.367		1.157		*0.80*	*0.177*
3a	-3.758	0.355	1.819		-0.106	*0.80*	*0.175*
3b	-2.520	0.356		1.142	-0.105	*0.81*	*0.173*

Impact of antecedent conditions on runoff generation

Especially in less developed catchment conditions (LL and SR Phase 1), the variables describing antecedent conditions had statistically significant ($p<0.05$) but weak correlations ($r<0.40$) with R_{TOT}, R_{EFF} and Q_{MAX} (Appendix E). Overall, it seemed that the impact of the antecedent conditions was masked by the variations in other, stronger explanatory variables. Based on the correlations alone, the link between the variables describing the antecedent conditions and runoff was not strong, but the multiple regression analysis showed significant relationships between the antecedent conditions and all of the studied runoff variables, yet their impact on the model's performance was not as important as that of the other variables. Based on the combined models, the preceding dry period (DAYS) in particular had a decreasing effect on R_{TOT} and R_{EFF} (Table 33), as well as on C_{VOL} (Table 37).

Unstable regression coefficients, multicollinearity and other residual considerations

A strong correlation between the independent variables may cause multicollinearity in the MLR models. For every model, multicollinearity statistics (tolerance and VIF) were checked and suspicious parameters were removed from the models to readdress their impact on the variable selection and regression coefficients. Multicollinearity mostly affected P_{TOT} and P_{DUR}, which had a strong, positive bivariate correlation with each other (Appendix E). However, both P_{TOT} and P_{DUR} were included as explanatory variables in the R_{TOT} model for LL: it can be assumed that both larger event precipitation and longer duration promoted the generation of higher runoff volumes owing to both larger pervious surfaces and a longer time of concentration. In this case, a large degree of multicollinearity was not observed based on the tests conducted, despite the strong (r=0.85) bivariate correlation between P_{TOT} and P_{DUR}.

For each model, the residuals were inspected as plots against the predicted values and normal P-P plots of the residuals. Often few outliers had to be removed from the data based on the residual plots. Additionally, the Q_{MAX} model for the medium-density VK catchment did not fulfil the residual assumptions as the residuals revealed a nonrandom U shape against the predicted values (see Appendix F). This indicates that the model structure or functional form were not optimal, but a better model was not achieved e.g. with other independent variables. The residual plots for the Phase 1 models for SR were affected by the highly nonlinear runoff response to rainfall, especially during minor rainfall events (see Appendix F). The removal of the smallest events from the SR Phase 1 data would have improved the residual plots and the R^2 values of the models. For example, the removal of events with P_{TOT}<5 mm would have increased the R^2 values in the SR Phase 1 runoff models (R_{TOT} and R_{EFF}) to 0.76-0.78 and for C_{VOL} to 0.59 (see example in Table 36), but it would have decreased the sample size from the original 73 events to only 28 events. In fact, linear or log-linear regression did not seem to be appropriate for estimating runoff characteristics for a wide range of events in the predevelopment conditions — in this case, the regression was merely used to identify the differences between the construction phases and the study catchments.

5.1.6 Rainfall losses and runoff-contributing area

Initial rainfall losses and the hydrologically active area in each catchment were determined by fitting a linear regression line between the event rainfall, P_{TOT}, and direct runoff, R_{EFF}. In this way, the intercept on the rainfall axis gave an estimate for the initial loss and the slope of the regression equation yielded the proportion of the effective impervious area (EIA) in relation to the total catchment area. To demonstrate the differences in runoff generation during small/moderate and large rainfall events, a regression line was applied for two event groups: minor rainfall events (P_{TOT} ≤ 15 mm) and major rainfall events (P_{TOT} > 15 mm). Seven minor events were excluded from the analysis of the medium-density VK catchment owing to high runoff coefficients (C_{VOL}>0.55), implying the presence of runoff generation outside the impervious areas. Six of these events (P_{TOT} 4.6...13.4 mm) occurred during late spring, in May. Eight events at VK that exceeded full pipe capacity were also removed from the analysis of major events (P_{TOT} 14.6-103.6 mm). All of the regression models shown here were statistically significant at p<0.01.

Hydrologically active area and initial losses during minor storms

The plots of minor rainfall events (P_{TOT} ≤ 15 mm) for the study catchments are shown in Figure 54. For the LL and VK control catchments (Figure 54a-b), the data points were well described using linear regression lines (R^2 0.87 and 0.91). For the developing SR catchment (Figure 54c), large scatter existed in the data for all minor events and, therefore, a linear regression line was separately inserted into the data for Phases 1 and 3 (Figure 55). During Phase 1, minor rainfall events at SR often generated only small amounts of direct runoff, and a higher variation in R_{EFF} was observed in comparison to the control catchments: COV values for direct runoff during minor events were 1.7 for SR and 1.2 for LL and VK. This appeared as a poorer fit for the regression line (R^2 0.52) during Phase 1 for SR (Figure 55a). During Phase 3, a linear relationship (R^2 0.95) was also established for SR (Figure 55b).

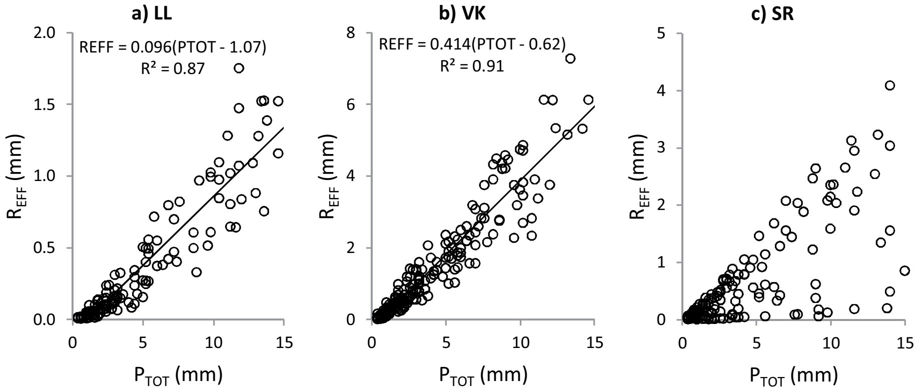


Figure 54. Scatter plots of event rainfall (P_{TOT}) and direct runoff (R_{EFF}) for minor rainfall events (P_{TOT} ≤ 15 mm) during the years 2001-2006 at a) the low-density LL catchment, b) the medium-density VK catchment, and c) the developing SR catchment. In VK, seven events with C_{VOL}>0.50 were excluded.

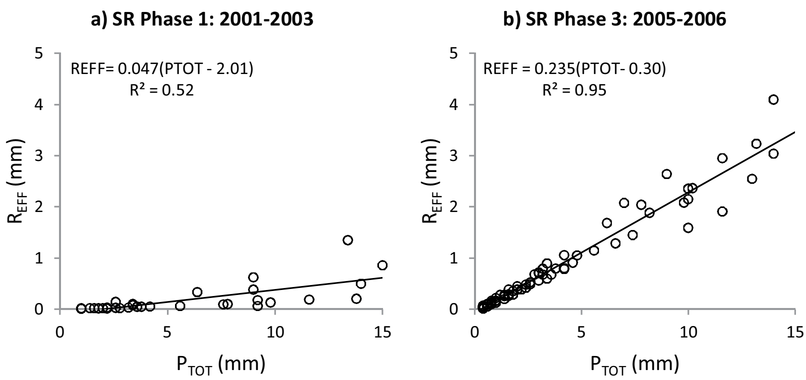


Figure 55. Event rainfall (P_{TOT}) and direct runoff (R_{EFF}) at the developing SR catchment during a) Phase 1 and b) Phase 3.

For VK and LL, the EIA was 41% and 10%, respectively, of the total catchment area (Figure 54a-b). For SR, the EIA during Phase 3 was approximately 24% (Figure 55b). Hence, for the control catchments and for SR during Phase 3, the EIA comprised only a part of the TIA, and the impervious surfaces became more efficient as the catchment TIA increased: the proportion of EIA in relation to TIA was 48% for LL, 64-74% for SR and 83% for VK. During Phase 1 for SR, however, the hydrologically active area comprised about 5% of the total catchment area (Figure 55a), which exceeded the TIA estimate of only about 1.5% (Table 2 in Section 2.2). This showed that direct runoff was also generated outside of the impervious surfaces, which was visually observed throughout the monitoring period as surface runoff on pervious areas, especially on slopes and in piles of soil without vegetation and with direct access to sewer inlets (Figure 56a-b).

Figure 56. Examples of surface runoff from pervious surfaces at the developing SR catchment: a) surface runoff from pervious surface near manhole in July 2004, b) soil and newly sowed grass seeds were washed off from a compacted pervious slope during a rainfall event after landscape works in May 2006.

Urban development decreased the initial losses: the initial losses accounted for the first 1.1 mm at LL (Figure 54a) and 2.0 mm of the event precipitation at SR during Phase 1 (Figure 55a), whereas at VK and SR during Phase 3 the corresponding amounts of initial loss were 0.6 mm (Figure 54b) and 0.3 mm (Figure 55b), respectively.

Hydrologically active area during major storms

Major rainfall events (P_{TOT} > 15 mm) represented approximately 9% of all events at VK and SR during Phase 3, and 20-23% at LL and SR during Phase 1. The differences in the sample sizes were caused by the differences in the duration of the hydrograph recession limb and the catchment lag (see Section 5.1.3), but not by differences in the weather conditions. The linear regression models for the major events for the control catchments (Figure 57a-b) and Phase 3 for SR (Figure 57d) had high R^2 values (>0.80). Again, the model for Phase 1 had lower R^2 values than the other models (Figure 57c), but the R^2 values for major events (0.66) were slightly better than the R^2 values for minor events during Phase 1 (0.52 in Figure 55). It should be noted that the SR data did not include events having as high a magnitude as in the control catchments because the wet year of 2004 was excluded from the SR data.

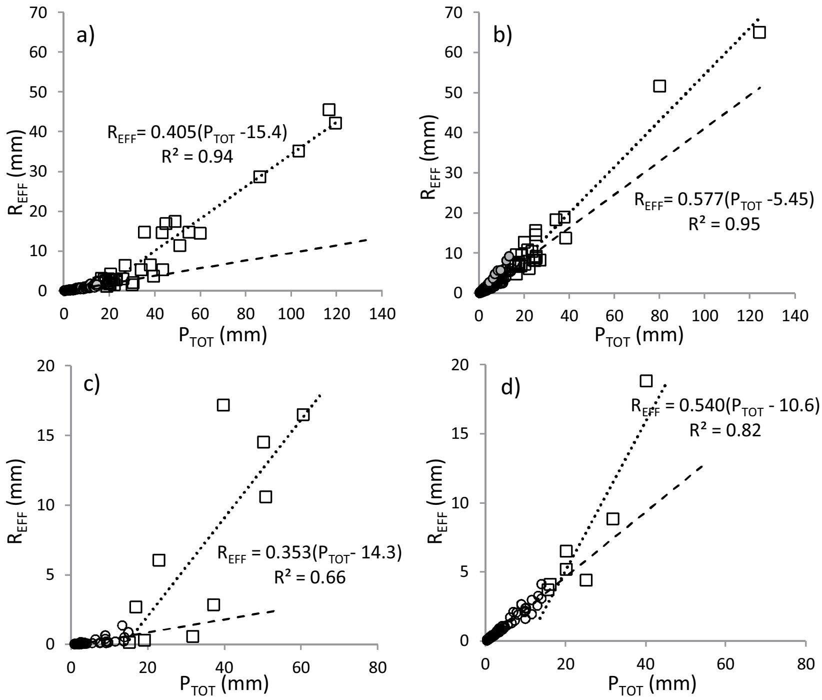


Figure 57. Comparisons of linear regression lines for major rainfall events with >15 mm of rain (dotted lines) and minor rainfall events (dashed lines) at a) LL, b) VK, c) SR during Phase 1 (2001-2003), and d) SR during Phase 3 (2005-2006). Number of events (minor/major): LL 137/35, VK 256/26, SR 34/10 (Phase 1) and 75/7 (Phase 3).

Following the same assumption about the determination of the hydrologically active area during minor events, the regression coefficients for P_{TOT} that exceeded the TIAs of each catchment (Figure 57) indicated that direct runoff was also generated from pervious surfaces during major rainfall events. The difference in the runoff responses to rain storms between the minor and major rainfall events was tested by including a dummy GROUP variable and an interaction term, P_{TOT} × GROUP, into the regression models in order to combine all events (Table 38). The regression coefficients for both variables were statistically significant at $p<0.01$ for all catchments and during both periods for SR, indicating a significant difference in the runoff response between the minor and major rainfall events. Table 38 shows the intersection between the separate regression lines as an approximate threshold for rainfall depth, which corresponds to a P_{TOT} range of 17-20 mm for urbanized catchments (LL, VK and SR during Phase 3), after which the runoff response changes and, hence, the contributing area expands.

The difference in runoff generation between the minor and major rainfall event groups diminished as the catchment TIA increased: based on the slopes of the regression lines shown in Figure 57, the runoff producing area during major events was 41%, 300% and 130% larger than the EIA during minor rainfall events at VK, LL and SR during Phase 3, respectively.

Table 38. Combined regression models for R_{EFF}, the corresponding R^2 values, and the threshold P_{TOT} between minor and major rainfall events. All models are statistically significant at p<0.001.

Catchment	Regression model	R^2	Threshold P_{TOT} (mm)*
LL	$0.405P_{TOT} + 6.131GROUP - 0.309P_{TOT} \times GROUP - 6.234$	0.96	19.8
VK	$0.577P_{TOT} + 2.882GROUP - 0.163P_{TOT} \times GROUP - 3.140$	0.97	17.7
SR Phase 1	$0.353P_{TOT} + 4.953GROUP - 0.306P_{TOT} \times GROUP - 5.047$	0.82	16.2
SR Phase 3	$0.540P_{TOT} + 5.630GROUP - 0.304P_{TOT} \times GROUP - 5.702$	0.93	18.5

GROUP = 1, when $P_{TOT} \leq 15$ mm

GROUP = 0, when $P_{TOT} > 15$ mm

*) Threshold P_{TOT} as the intersection of the regression models for minor/major rainfall events

5.1.7 Volumetric runoff coefficients in relation to the event rainfall depth

The changes in the runoff-contributing area implied that the volumetric runoff coefficients, C_{VOL}, must increase as the event precipitation increases. In fact, based on the multiple regression analysis presented in Section 5.1.5, the main factors affecting the C_{VOL}s were the catchment imperviousness and the event precipitation, P_{TOT}. For instance, P_{MAX} had weaker, although statistically significant, correlations with C_{VOL} than P_{TOT} (Appendix E). P_{MEAN} correlated with C_{VOL} only in less developed catchment conditions (LL and SR Phase 1), but the correlations were rather weak and had a negative sign (*r* -0.32 through -0.40) because events with a higher P_{TOT} had longer durations and, thus, a lower P_{MEAN}. Based on the correlations in Appendix E, C_{VOL} had statistically significant (p<0.001) positive correlations with both R_{EFF} (*r*=0.72...0.97) and Q_{MAX} (*r*=0.70-0.87) at all catchments.

Figure 58 illustrates the increase in C_{VOL} as a function of the rainfall event magnitude and reveals large C_{VOL} variations in events with similar rainfall depths. Despite the variation, the highest C_{VOL} coefficients were observed for catchments with a higher TIA and a higher P_{TOT}. The largest differences between the catchments were observed during smaller rainfall events. The more developed catchments (VK in Figure 58b and SR Phase 3 in Figure 58d) exhibited a pronounced increase in C_{VOL} for rainfall events greater than 1 mm, while for the low-density LL catchment (Figure 58a) the observed pattern was similar to Phase 1 for SR (Figure 58c), even though the average C_{VOL} for the smallest rains (1...5 mm) at LL were four times greater than for Phase 1 at SR.

C_{VOL} increased in all rainfall groups during the construction works at SR (Figure 58c-d), but the largest changes were observed in the runoff response of minor rainfall events (Table 39). The average C_{VOL} increased more than the largest observed C_{VOL} in each event group. For the three largest event groups in Table 39 (P_{TOT} > 15 mm), the greatest per cent change occurred in the smallest observed C_{VOL} because, during Phase 1, C_{VOL}s as low as 0.01 were observed for rainfall events of 15-25 mm.

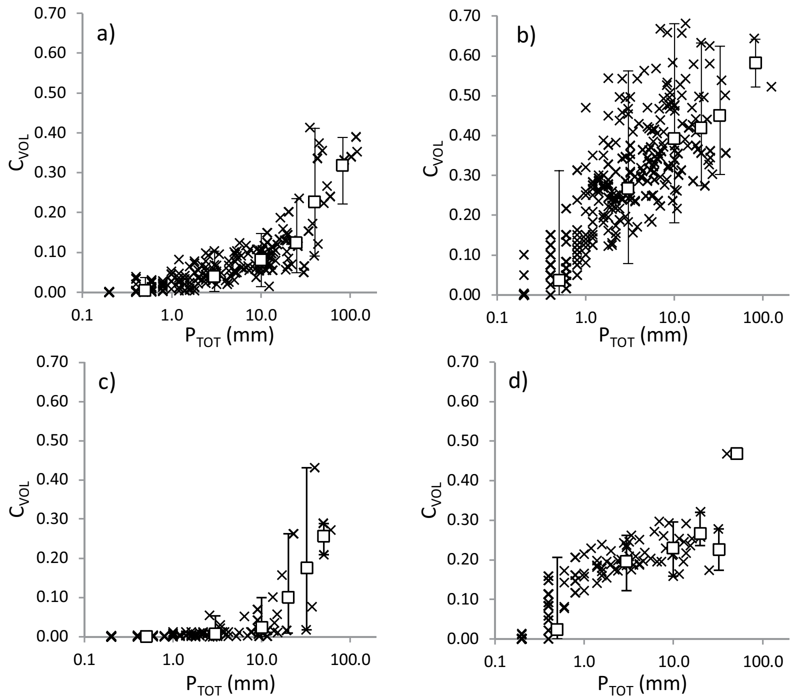


Figure 58. Variations in volumetric runoff coefficients (C_{VOL}) in relation to the event precipitation sum (P_{TOT}) at a) LL, b) VK, c) SR during Phase 1 (2001-2003), and d) SR during Phase 3 (2005-2006). Average values for each rainfall event class are shown with boxes and minimum and maximum values as whiskers.

Table 39. Percentual increase in C_{VOL} for different rainfall event categories for SR between Phase 1 (2001-2003) and Phase 3 (2005-2006). During Phase 3 only one event at SR exceeded P_{TOT} 40 mm.

P_{TOT} (mm)	< 1	1...5	5...15	15...25	25...40	> 40
Mean C_{VOL}	*8458 %*	*1858 %*	*1048 %*	*167 %*	*26 %*	*80 %*
Min C_{VOL}	-	-	-	*2262 %*	*769 %*	*123 %*
Max C_{VOL}	*6688 %*	*423 %*	*196 %*	*23 %*	*-35 %*	*61 %*

Based on Table 40, the average C_{VOL} for all of the urbanized catchments was less than the TIA, which is in accordance with the results presented in Section 5.1.6: for most events, the area contributing to direct runoff is much smaller than the total impervious area of the catchment. Owing to the large number of small events, especially those at VK, the average C_{VOL} for all runoff-producing events was even less than the estimated EIA. A feature common to all catchments and both phases for SR is that the 80^{th} percentile of all rainfall events that produced direct runoff roughly equalled the previously estimated EIAs as well as the average C_{VOL}s for the P_{TOT} group, i.e. the group ranging from 5 to 15 mm (Table 40). However, C_{VOL}s exceeding the TIA were observed at all catchments: hence, pervious areas also generated direct runoff. For the event group with 5-15 mm, which is below the threshold precipitation presented in Table 38, the maximum observed C_{VOL} exceeded the catchment TIA only at VK.

Table 40. Summary of the volumetric runoff coefficients (C_{VOL}) and the catchment characteristics, total impervious area (TIA) and effective impervious area (EIA).

	Imperviousness		All events producing direct runoff			P_{TOT} 5...15 mm	
	EIA	TIA	Mean C_{VOL}	Max. C_{VOL}	80th*	Mean C_{VOL}	Max. C_{VOL}
LL	0.10	0.20	0.08	0.41	0.11	0.08	0.15
VK	0.41	0.50	0.28	0.68	0.42	0.39	0.68
SR Phase 1	0.05	0.02	0.06	0.43	0.06	0.02	0.10
SR Phase 3	0.24	0.32...0.37	0.19	0.47	0.24	0.23	0.30

*) 80th percentile

5.1.8 Multiple linear regression analysis of EMCs and EMLs

Prior to the multiple linear regression (MLR) analysis, the Pearson correlations were calculated to identify simple relationships between the event characteristics, the event mean concentrations (EMCs) and the event mass loads (EMLs). The correlation matrices are presented in Appendix G. Statistically significant correlations between the water quality variables and other event characteristics were found for the LL and VK control catchments, but strong correlations ($r>0.80$) were rare, especially between EMCs and the event variables. In the regression for the developing SR catchment, additional variables were introduced to describe the ongoing construction activities (Table 41): EARTH, HOUSE, PAVING and WASTE. These variables described the progression of the construction works based on the discussion in Section 2.2, and they were treated as dummy variables having values of 0 or 1 depending on their completion in the catchment. Also the changing proportion of TIA was used as an additional independent variable. The first regression attempts without these variables produced only mediocre models at best.

The MLR models for LL and VK are presented in Table 42 (EMCs) and Table 43 (EMLs), and for SR in Table 44. Different model versions for the same pollutant are marked a) and b): b) models are shown when the replacement of the rainfall event characteristics as explanatory variables together with the runoff variables produced a better model than the a) version, which only took into account rainfall event characteristics and antecedent conditions. In the case of the EMC models in particular, other combinations of explanatory variables could have been used, and therefore, the selected models were not the only options. Few individual events were excluded from the regression data as outliers because, otherwise, they clearly distorted the regression results: the highest TP EML for LL and the two highest TSS EMCs for SR. Scatter plots of the predicted values vs. observed are illustrated in Appendix H for the best water quality models reported in Tables 42-44. In general, all presented models yielded adequate residual plots after the removal of outliers.

Table 41. Description of the independent variables describing construction activities at SR.

Variable	Description	Dummy	Values
EARTH	Periods with earth-moving works	yes	From 2001 to May 2006: 1 Later: 0
HOUSE	Periods with building construction	yes	The years 2001-2002: 0 Later: 1
PAVING	Periods before and after major asphalt works	yes	The years 2001-2003: 1 Later: 0
WASTE	Periods with assumed wastewater discharges	yes	August-September 2001: 1 Summer 2003: 1 July- September 2004: 1 Other: 0
TIA	The amount of impervious surfaces as a percentage of the total catchment area (%)	no	The years 2001-2003: 1.5 The year 2004: linearly interpolated monthly values from 19.3 (May) to 31.6 (September) May-July 2005: 31.6 August-September 2005: 36.5 May-July 2006: 36.5 August-October 2006: 37

Table 42. MLR-models for the log-transformed EMCs for the LL and VK control catchments. All independent variables are log-transformed.

	Model	Constant	P_{TOT}	R_{TOT}	P_{MAX}	Q_{MAX}	P_{DUR}	P_{MEAN}	DAYS	PREC*	R^2	SEE
TSS, Total suspended solids												
LL	a	1.667			0.942		-0.196				0.62	0.242
VK	a	2.494	-0.626		0.961					-0.288	0.47	0.337
	b	0.250		-0.617		1.083				-0.237	0.53	0.317
TP, Total phosphorus												
LL	a	-1.022			0.556		-0.095		0.140		0.60	0.155
VK	a	-0.178	-0.457		0.490					-0.321	0.48	0.244
	b	-1.467		-0.434		0.596				-0.299	0.57	0.220
TN, Total nitrogen												
LL	a	-0.048	0.078		0.145				0.052		0.35	0.104
VK	a	0.645	-0.313		0.209					-0.198	0.40	0.179
COD, Chemical oxygen demand												
LL	a	0.889			0.269						0.38	0.117
VK	a	1.649			0.396		-0.443	-0.426		-0.286	0.57	0.188
	b	0.645		-0.412		0.438				-0.256	0.59	0.184

*PREC is PREC5 for TN and PREC7 for TSS, TP, and COD.

Table 43. MLR-models for the log-transformed EMLs for the LL and VK control catchments. All independent variables are log-transformed.

	Model	Constant	P_{TOT}	R_{TOT}	R_{EFF}	P_{MAX}	Q_{MAX}	DAYS	PREC*	R^2	SEE
TSS, Total suspended solids											
LL	a	-0.089	1.180			0.789				0.86	0.298
	b	-0.160		0.336			1.088			0.88	0.275
VK	a	1.042	0.544			0.861			-0.251	0.62	0.373
	b	-0.573			0.382		1.056		-0.226	0.72	0.317
TP, Total phoshorus											
LL	a	-2.745	1.313			0.306				0.92	0.204
	b	-1.415			0.849	0.397				0.96	0.142
VK	a	-1.671	0.751			0.384			-0.270	0.69	0.269
	b	-2.309			0.545		0.581		-0.259	0.78	0.226
TN, Total nitrogen											
LL	a	-1.782	1.477							0.89	0.235
	b	-0.435		1.066						0.97	0.124
VK	a	-0.832	0.915						-0.175	0.74	0.228
	b	-0.750		0.739			0.198		-0.186	0.84	0.182
COD, Chemical oxygen demand											
LL	a	-0.917	1.484							0.90	0.226
	b	0.380		1.015		0.257				0.97	0.118
VK	a	0.173	0.746			0.291			-0.246	0.75	0.220
	b	-0.176		0.609			0.384		-0.235	0.84	0.172

*PREC is PREC5 for TN and PREC7 for TSS, TP, and COD.

Based on the performance of the MLR models in Tables 42-44, it is easier to predict EMLs than EMCs. The EML models reached R^2 values ranging from 0.62 to 0.97, thus producing clearly better outcomes than the EMC models (R^2 0.35-0.62). In the EML models, one variable always explained at least 50% of the variation observed in the event loads, while in the EMC models one variable usually explained less than 50% of the variation in the EMCs. For SR, no acceptable model for TN EMCs was found (Table 44) because the residual assumptions of normality and homoscedasticity were not fulfilled. Nevertheless, rainfall depth or total runoff volume also explained 66% and 78%, respectively, of the observed variance in TN EML for SR.

A typical feature in the water quality MLR models was that they consisted of three (LL and VK) or four (SR) key variable types: 1) a volume variable, 2) an intensity variable, 3) a variable describing the antecedent conditions, and 4) for SR, a variable describing the catchment conditions during the construction works:

1) The volume variables included the event rainfall depth (P_{TOT}), rainfall event duration (P_{DUR}), total runoff volume (R_{TOT}) and direct runoff volume (R_{EFF}). Increasing runoff volumes increased the EMLs but diluted the EMCs. An exception to this rule was observed in the TN EMC model for LL (Table 43): this seems to be related to the fact that the dilution effect during a long recession phase was not as distinct for TN, which is also transported via subsurface runoff in dissolved form, while the more particle-bound pollutants were mainly transported by surface runoff (see also Section 3.1.6);
2) The intensity variables included the maximum rainfall intensity (P_{MAX}) and peak flow rate (Q_{MAX}), which correlated positively with both the EMCs and EMLs. This likely relates to the energy of rain and the flow to washoff particles from the impervious and pervious surfaces and from the conveyance systems used for drainage. Especially at SR, event intensity was associated with the erosion of disturbed soil surfaces;
3) Antecedent conditions had site-specific differences in their role in the MLR models: for LL, the antecedent dry period (DAYS) was chosen for the EMC models of nutrients, while for VK an antecedent precipitation sum (PREC5 for TN and PREC7 for other pollutants) was included in all MLR models. For SR, PREC7 was included only in the COD EMC and EML models. If added to a model, the longer antecedent dry period appeared as a higher EMC, and wet preceding conditions decreased both the EMCs and EMLs;
4) For SR, additional site variables increased the R^2 values by 1-18% depending on the model. The role of the additional variables varied between the models, as illustrated by the different variable combinations and the changing signs of the regression coefficients, depending on the pollutant.

The event characteristics describing the same variable type (1-3 above) usually had moderate or strong, statistically significant correlations with each other (Appendix E). The importance of the different variable types varied according to the model and pollutant, e.g. P_{MAX} in the EML models was more important for the particulate bound pollutants than for the TN models.

It cannot be assumed that the same variables that have important roles in the runoff models (Section 5.1.5) also best define the water quality for a given catchment or pollutant. For instance, for LL the role of P_{MAX} in the runoff models was not important, while it was the first variable chosen for the EMC models in Table 42. The role of the antecedent conditions was clearly stronger in the water quality models than in the runoff models. The importance of the antecedent conditions in the runoff models (Section 5.1.5) was small, especially for the urbanized catchments with the highest TIA, whereas in the EMC models for VK the antecedent precipitation sum was the first variable included in the models for TP, TN and COD. For SR, PREC7 alone explained 15% of the observed variations in COD EMCs, but it increased R^2 values by only 1% in the EML model while the total runoff explained 90% of the variations in event loads.

Table 44. The log-transformed EMC and EML models for the developing SR catchment. All independent variables are log-transformed, except TIA and the dummy variables HOUSE, PAVING and WASTE.

Model	Constant	P_{TOT}	P_{MAX}	R_{TOT}	R_{EFF}	Q_{MAX}	TIA	HOUSE	PAVING	R^2	SEE
TSS, Total suspended solids											
EMC											
a	1.759	-0.499	0.898					0.420		0.38	0.339
b	1.115				-0.463	0.901			-0.804	0.48	0.312
EML											
a	-0.256	0.842	0.908				0.020			0.69	0.403
b	0.368		0.799		0.681			0.645		0.78	0.337
TP, Total phoshorus											
EMC											
a	-0.948	-0.201*					-0.024	1.118		0.43	0.334
b	-1.246		0.503		-0.323		-0.015	0.961		0.46	0.327
EML											
a	-3.003	0.897	0.537					0.805		0.66	0.352
b	-2.371			0.613		0.422	-0.031	1.095		0.72	0.323
TN, Total nitrogen								WASTE			
EML											
a	-2.191	1.397					0.576	0.540		0.80	0.325
b	-0.648			1.038			0.165	0.494		0.86	0.266
COD, Chemical oxygen demand					PREC7			HOUSE			
EMC											
a	1.570	-0.230	0.218		-0.149		-0.008			0.37	0.154
b	1.523	-0.258			-0.160	0.208	-0.016			0.44	0.147
EML											
a	-0.753	1.178						-0.486	0.654	0.80	0.265
b	0.276			0.944	-0.134					0.92	0.169

*P_{DUR} instead of P_{TOT}

The use of additional variables in the models for the developing SR catchment showed that during the construction works, both the changes in runoff generation and in the ongoing construction activities had a major impact on runoff quality (Table 44). However, these variables were ambiguous, i.e. they behaved differently depending on the pollutant and often did not provide straightforward clues about the underlying mechanisms. The variables TIA, HOUSE and PAVING for the most part behaved similarly in the different models, except for in the TP models. In the TSS and TN models, increasing TIAs and the building construction period led to higher EMCs and EMLs compared with the first years of the development, which, along with the increasing runoff volumes, can be explained by the erosion of disturbed soil surfaces that occurred in the catchment throughout the monitoring period. However, the extra variables could not reflect the fact that some events during the years 2002 and 2003 produced high TSS EMCs for events with larger rainfall depths, runoff volumes and long durations, indicating high erosion rates prior to the increase in TIA. For COD, the negative signs for TIA and HOUSE can be interpreted as a reflection of both the stabilization of surfaces and the dilution effect of increasing runoff volumes during the later years of development. The TP models showed the conflicting sides of the same phenomenon owing to the opposite signs of TIA and HOUSE: HOUSE indicated higher TSS EMCs and EMLs because of the increasing runoff volumes, peak flows and erosion, but, at the same time, the EMCs and EMLs decreased as the increasing TIA stabilized the catchment surfaces. In the case of TN, the periods marked by the WASTE variable produced higher TN EMLs: this variable indicated possible wastewater discharges, but these periods also included other TN sources, as discussed previously in Section 3.2.2.

5.1.9 Comparisons of seasonal event water quality

Event water quality was examined from two perspectives: water quality was examined during the 'common' events using statistical comparison tests, whereas the occurrence of the 'worst' events was examined using probability plots. As was summarized in Sections 1.3.1 and 3.2.3, conclusions about water quality in recent studies are often based on EMCs. Hence, it is important to compare the event water quality in Espoo with other studies reporting EMCs in cold climates, and also to compare it with the results obtained from the long-term water quality analysis presented in Chapter 3 utilizing different techniques.

Based on Table 45, the cold period EMLs were usually higher than the warm period EMLs. However, the seasonal differences in EMCs between the study catchments were not entirely consistent. For the LL and VK control catchments, the TP and COD EMCs were higher during the warm period than during the cold period, while the reverse was true for TN. Although the Mann-Whitney U test showed differences in seasonal TN EMCs for LL, the absolute difference was small (Table 26), which supports the discriminant analysis results presented in Section 3.1.6, where no distinct seasonal pattern was found for TN at LL.

For LL, the TSS EMCs were higher during the warm period than during the cold period (Table 45). The probability plots of the TSS EMCs showed that, unlike the consistent difference between the two seasons at LL (Figure 59a), the intersecting TSS probability plots for VK (Figure 59b) illustrated higher EMCs during the warm period only for high TSS EMCs, but lower EMCs for the values at and below the median EMC.

For SR, only the TSS EMCs showed a concentration difference between the seasons and was higher during the cold period (Table 45). Both seasons had overlapping probability distributions over the whole range of EMCs for TP (Figure 60a) and COD (Figure 60b), but again, intersecting probability curves for the two seasons were observed for the TN EMCs (Figure 60c).

Table 45. Seasonal differences between the warm period (w) and the cold period (c) EMCs and EMLs. Bolded comparisons are statistically significant at p<0.05; p-values in the parenthesis (the Mann-Whitney U test).

		TSS	TP	TN	COD
LL	EMC	**w > c (0.000)**	**w > c (0.000)**	**c > w (0.006)**	**w > c (0.000)**
	EML	c > w (0.066)	**c > w (0.022)**	**c > w (0.000)**	**c > w (0.001)**
VK	EMC	c > w (0.233)	**w > c (0.001)**	**c > w (0.001)**	**w > c (0.000)**
	EML	**c > w (0.001)**	c > w (0.059)	**c > w (0.000)**	**c > w (0.035)**
SR	EMC	**c > w (0.044)**	w = c (0.862)	w = c (0.984)	w = c (0.533)
	EML	**c > w (0.000)**	**c > w (0.000)**	**c > w (0.000)**	**c > w (0.000)**

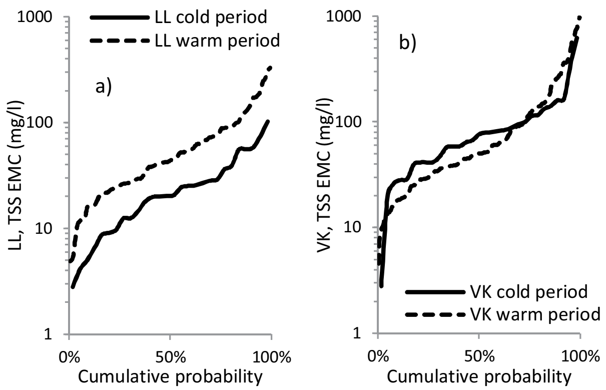


Figure 59. Seasonal EMC probability plots of TSS for a) the low-density LL catchment and b) the medium-density VK catchment.

The box plot comparison of the warm and cold period EMCs (Figure 61) and EMLs (Figure 62) pointed out how the differences between the catchments were more distinct during the cold period than during the warm period. In particular, the warm period box plots included several outliers as a reflection of the highly skewed water quality data. The results from the statistical comparison tests supporting the box plots are shown in Table 46.

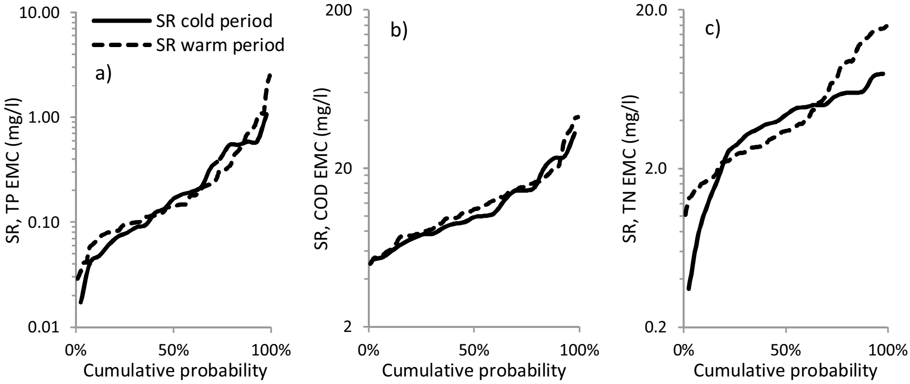


Figure 60. Seasonal EMC probability plots for the developing SR catchment for a) TP, b) COD, and c) TN.

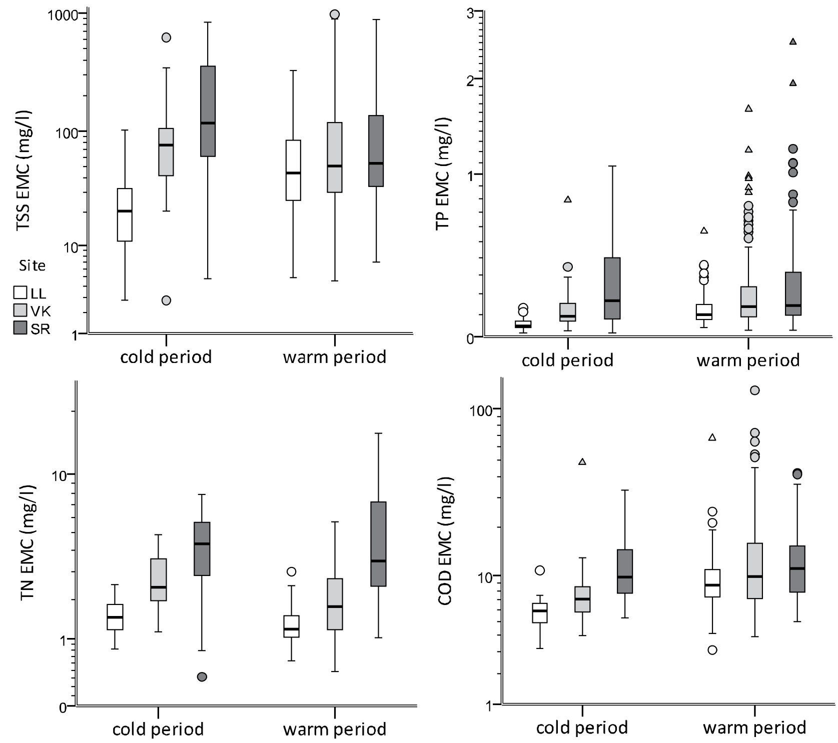


Figure 61. Box plots of the cold and the warm period EMCs. Circles and triangles illustrate mild and severe outliers, respectively, as defined in Chapter 2.4.3.

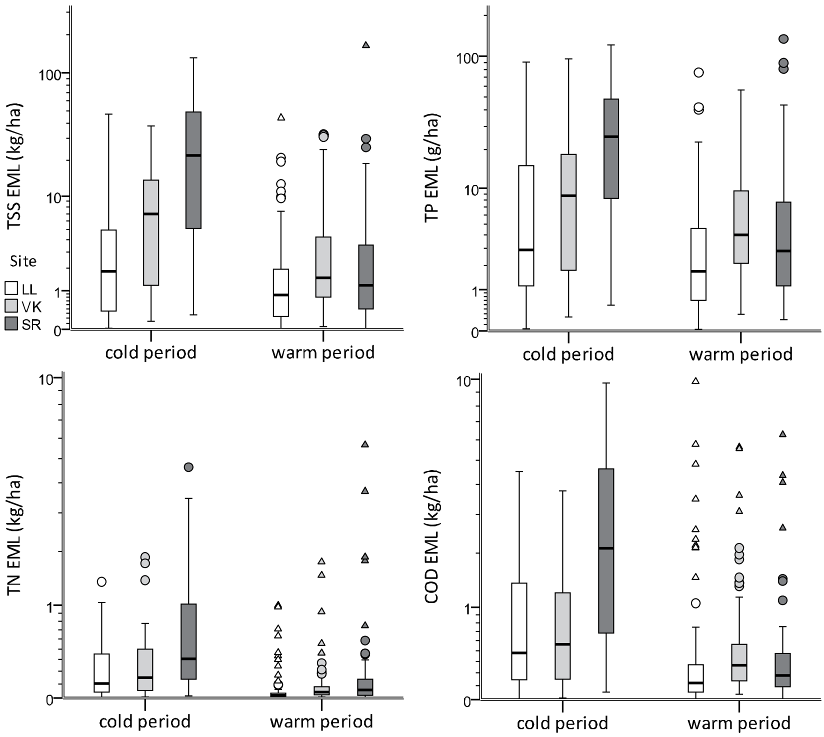


Figure 62. Box plots of the cold and the warm period EMLs. Circles and triangles illustrate mild and severe outliers, respectively, as defined in Chapter 2.4.3. Note the different unit (*g/ha*) of TP EML.

Table 46. Statistically significant differences (p<0.05) in seasonal EMCs and EMLs between the study catchments (the Kruskal-Wallis and the Mann-Whitney U tests).

		TSS	TP	TN	COD
EMC	warm	-	SR > LL, VK > LL	SR > VK > LL	SR > LL
	cold	SR > LL, VK > LL	SR > LL, VK > LL	SR > VK > LL	SR > VK > LL
EML	warm	VK > LL	SR > LL, VK > LL	SR > VK > LL	VK > SR
	cold	SR > VK > LL	SR > VK, SR > LL	SR > VK, SR > LL	SR > VK, SR > LL

In Table 46, statistically significant differences between the catchments were observed for all pollutants and seasons except for the warm period TSS EMCs. The lowest EMCs (Figure 61) and EMLs (Figure 62) were typically observed at LL and the highest at SR; however, only the TN EMCs and EMLs were significantly higher for SR than in the control catchments for both seasons (Table 46). The differences between the catchments were less distinct particularly for the warm period TSS and COD EMLs: VK seemed to produce the highest EMLs owing to the largest warm period runoff volumes. Also, the cold period EMLs reflected the differences in event runoff volumes: the highest EMLs were produced by SR, although the SR events did not always have significantly higher EMCs compared with VK (Table 46). Furthermore, the higher EMCs during the cold period events at

VK compared with LL only resulted in higher cold period EMLs in the case of TSS.

In some cases, when significant differences between the catchments were not observed based on the statistical comparison tests (Table 46), then probability plots (Figure 63) provided useful information about the differences within the total range of observed variables. For instance, SR showed higher EMCs than VK for the cold period TSS (Figure 63a) and TP (Figure 63b) for the most part in the cumulative EMC probability distributions. Similarly, SR and VK had higher TSS EMCs than LL in the upper end of the warm period probability plots (Figure 63c).

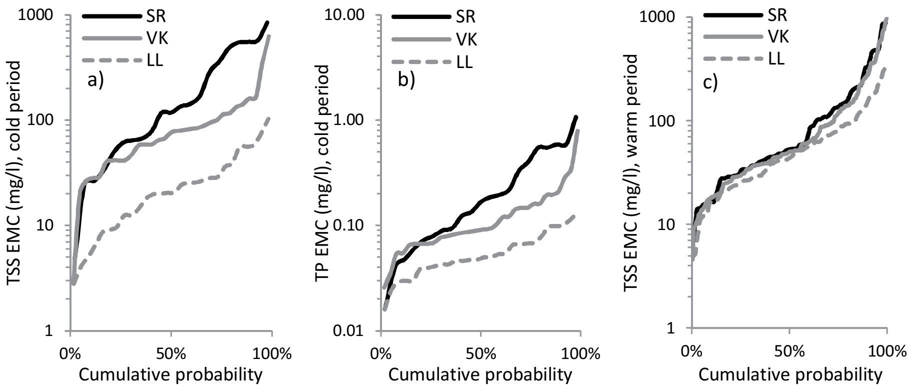


Figure 63. Comparison of cumulative EMC probabilities of a) the cold period TSS, b) the cold period TP, and c) the warm period TSS.

In addition to the seasonal and site-specific differences in the average concentration and load levels, the occurrence of the highest values differed between the catchments. Table 47 lists the exceedance probabilities above the water quality thresholds reported by Stockholm Vatten (2001). These thresholds represent the moderate (C_M) and high (C_H) concentration classes, which were earlier compared in Section 3.2.4 to the average annual and seasonal pollutant concentrations.

The probability of the EMCs reaching the threshold of high concentrations was at least double for VK in comparison to LL, and even higher for SR, especially during the cold period and for the warm period TN EMCs (Table 47). While the threshold for moderate EMCs (C_M) was more often exceeded by the warm period TSS and TP at LL, at VK and SR the majority of events exceeded the moderate threshold during both seasons. At LL and VK, the threshold of high concentrations (C_H) was exceeded most likely by TSS and TP during warm period rainfall events, while at SR exceedances above C_H were observed for both seasons. When the NOEL concentration for TSS (25 mg/l, Table 47) was used as a threshold, the majority of events were found to exceed the threshold at all catchments except for the cold period TSS EMCs at LL.

Table 47. Probability of exceedance for select water quality thresholds.

		TSS			TP		TN	
		EMC ≥ NOEL	EMC ≥ C_M	EMC ≥ C_H	EMC ≥ C_M	EMC ≥ C_H	EMC ≥ C_M	EMC ≥ C_H
LL	warm period	75%	46%	8%	51%	15%	46%	-
	cold period	43%	18%	-	10%	-	75%	-
VK	warm period	83%	51%	16%	69%	34%	75%	2%
	cold period	93%	69%	8%	43%	14%	97%	-
SR	warm period	86%	54%	22%	70%	38%	99%	35%
	cold period	94%	79%	36%	64%	40%	88%	37%

C_M, C_H = thresholds for moderate and high stormwater concentrations (Stockholm Vatten, 2001)

NOEL = no observable effects limit, 25 mg/l (Ellis and Mitchell, 2006)

5.2 Discussion

5.2.1 Impacts of urbanization on event runoff generation

Changes in runoff event characteristics during rainfall events

In the experimental setup for the current study, the change in the catchment hydrology occurred almost abruptly as a step change rather than gradually. Gradual changes are typical for studies on the effects of urbanization in large catchments that span a period of several decades (e.g. Changnon et al., 1996; Beighley and Moglen, 2002; Dougherty et al., 2007; Huang et al., 2008; Cheng et al., 2010); hence, the cause-effect relationships in Espoo can be more easily identified. In addition, the current results are more straightforward and in-depth than those obtained only by catchment comparisons (e.g. Rao and Delleur, 1974; Melanen and Laukkanen, 1981; Driver and Troutman, 1989; Brezonik and Stadelmann, 2002; Burns et al., 2005). In this way, this thesis responds to the need for studies that track the hydrological effects of urbanization in a more detailed manner, starting from the undeveloped conditions of a catchment, during the development process. This need has been previously noted by, for example, Burns et al. (2005), Shuster et al. (2005) and Dietz and Clausen (2008). Although the impacts of urbanization have been widely documented, to the best of the author's knowledge there are not many similar studies on a small catchment scale.

The most pronounced changes were observed in C_{VOL}, Q_{MAX} and R_{MEAN} during minor rainfall events (P_{TOT} < 16 mm), but for major events statistically significant changes were only observed for Q_{MAX} and R_{MEAN} (Section 5.1.2). These findings support the earlier results suggesting that during minor rainfall events, often only a small part of the catchment (namely, the effective impervious area (EIA)) can be considered the primary contributing area, whereas the total area may be critical for large storms (Pitt, 1987; Novotny, 2003; Lee and Heaney, 2003). The distinct changes observed during minor events support the management strategy to control the more common minor storms rather than the infrequent major storms if the aim of urban stormwater management is to maintain the predevelopment conditions of catchment hydrology — this is a concept that is promoted by several authors, such as Pitt (1987, 1999), Roesner (1999), Pitt and Clark (2003) and Burns et al. (2012). However, results concerning major rainfall events should be treated with caution since fewer of them have been studied compared with the minor events.

Changes in runoff events during the cold period of the year

Previous studies on the impacts of urbanization on runoff event characteristics under wintry conditions are scarce. In Finland, Laiho (1980) compared flow data for one spring from seven urban catchments (4-25 events per site) from southern to northern Finland and concluded that the smallest event runoff volumes were observed in two city centre catchments owing to the transport of snow. The available data did not support any detailed examination of the differences between the catchments. Several studies on urban hydrology in cold region have been conducted at the urbanizing Kawarta Heights catchment (0.97 km^2) in Ontario, Canada (Taylor, 1977, 1982; Buttle and Xu, 1988; Buttle, 1990). Buttle (1990) analyzed the impacts of urbanization on event runoff characteristics during snowmelt using data from a period of 14 years and Tukey's multiple comparison test. Based on the existing literature pertaining to the typical changes resulting from urbanization, Buttle (1990) anticipated that urbanization would increase event direct runoff volumes and peak discharge and reduce travel times during snowmelt events, but he observed significant changes only in the recession constants, indicating a steepening of the recession limb of the hydrographs.

The present study extends the results of Buttle (1990) to a different set of snowmelt event characteristics: total event runoff (R_{TOT}), direct runoff (R_{EFF}), runoff event duration (R_{DUR}), mean runoff intensity (R_{MEAN}) and peak flow (Q_{MAX}). In Section 5.1.4, significant differences were observed, especially in R_{DUR}, between the study catchments; significant differences were also observed in R_{TOT} between the study years at the developing SR catchment. This demonstrates that as a consequence of urbanization, the cold period runoff became separated into more frequent events of a shorter duration (R_{DUR}) and smaller event runoff depths (R_{TOT}).

The observed decrease in the cold period event durations at the study catchments in Espoo implies that the recession of snowmelt-driven runoff events becomes steeper, as observed in Canada by Buttle (1990), as a result of the impervious surfaces and an efficient drainage system. However, both the results from Espoo and those reported by Buttle (1990) reveal no significant changes in direct runoff volumes or peak discharge during construction activities. Previously, the conflicting findings reported in the existing literature about the changes in cold period events resulting from urbanization (Taylor, 1977, 1982; Buttle and Xu, 1988; Matheussen, 2004) were discussed in Sections 1.2.4 and 3.2.1: the present study, together with Buttle's (1990) study, did not find evidence for substantial increases in snowmelt-induced event peak flows, as previously suggested by Taylor (1977), who compared urban and rural runoff responses for one spring season.

The transport of snow from urban catchments reduces runoff volumes, as observed by Laiho (1980). The impact of this factor on snowmelt runoff is more pronounced in densely built areas where there is not enough space available for snow storage, whereas at the residential catchments of the present study, the amount of transported snow had only a small impact on long-term runoff generation. In Section 4.1.1, for example, the low-density LL catchment generated about 9 mm more runoff than the medium-density VK catchment during the snow study period: this runoff excess can be explained by the small volumes of transported snow from VK (about 3-7 mm of runoff) and the higher contributions from subsurface runoff at LL.

The results of the current study (Section 5.1.4) confirmed Buttle's (1990) findings in Canada that urbanization increases the number of runoff events during the cold period. One important factor that increases the event count and is highly site-dependent is the use of road salt for de-icing, which triggers small, chemically-driven melt events from road surfaces (Oberts, 1994). At the current study catchments, road salt and sand were used for road safety. In addition to de-icing, the number of events is also influenced by other factors that enhance snowmelt in an urban environment, such as the changed radiation balance as a result of the construction of buildings, the urban surface types and the lowered albedo of urban snow (Buttle and Xu, 1988; Bengtsson and Westerström, 1992; Semádeni-Davies and Bengtsson, 1998; Semádeni-Davies and Bengtsson, 2000; Semádeni-Davies et al., 2001; Ho and Valeo, 2005). The impact of more intensive snowmelt on runoff in Espoo was seen in the form of a shorter melt season at VK in comparison with LL (Section 5.1.4): Buttle and Xu (1988) compared the runoff response to snowmelt in suburban and rural parts of the Kawartha Heights catchment for two springs and noted that urbanization led to accelerated snowmelt in suburban areas combined with a rapid conveyance of runoff in the urban drainage system. Based on a modelling study of a residential catchment in Trondheim, Norway, Matheussen (2004) concluded that the major effect of urbanization on winter runoff was the earlier and enhanced melt rates, which led to higher runoff generation during the winter months in comparison to April. As previously discussed in Section 3.1.2, the evenly distributed monthly runoff pattern at VK, without a distinct runoff peak in April, also reflected an earlier snowmelt in comparison to LL.

Buttle (1990) concluded that the changes in runoff event characteristics resulting from urbanization are more subtle under wintry conditions than the changes during the warm period. The results from the study catchments in Espoo also revealed that i) the impacts of urbanization during the cold period are evident in different runoff characteristics than during the warm period and ii) the direction of change during the cold period may be opposite to that observed during the warm period. In fact, the catchments in Espoo showed that although urbanization increased runoff volumes and peak flows during the warm period (Section 5.1.2), the opposite was observed for event runoff volumes during the cold period, and the possible changes in peak flows are not distinct enough to be statistically significant for the cold period (Section 5.1.4). Although urbanization increases the number of runoff events during both warm and cold seasons, it does not necessarily increase cumulative volume over the entire cold period. The most pronounced impact of urbanization during the cold period was the shorter duration of runoff events, whereas the event duration during the warm period runoff was insensitive to change.

5.2.2 Impacts of urbanization on direct runoff hydrographs

In Section 5.1.3, the changes in the shape of the direct runoff hydrographs and in the catchment lag (the mean transit time, MTT) were investigated using instantaneous unit hydrographs (IUHs) that were based on a two-parameter gamma distribution defined by the shape parameter, α, and the scale parameter, β. Unit hydrograph methods are a common tool in hydrological analysis, modelling and design, even though examples of their use in hydrological analysis are more numerous in rural catchments than in urban catchments (Rabuñal et al., 2007).

In the present study, IUHs were introduced to illustrate and quantify the changes in the hydrograph shape for warm period events during urbanization (Section 5.1.3). The impacts of urbanization on the hydrograph shape, i.e. the steeper rising limb, the higher peak flows, the shorter recession limb and the shorter catchment lag, resulted from the changes in the drainage networks and impervious coverage. These changes in the shape of the direct runoff hydrograph were observed at all study catchments, which had a TIA ranging from 20% to 50%, but the shortest lag time and the steepest IUH shape was attributed to the developing catchment SR, which had a TIA of 34% owing to its steep topography. This result supports the findings by Burns et al. (2005) that the TIA is not solely responsible for the changes in the runoff hydrograph: in their study, which was conducted in New York State, a catchment with a TIA of 6.2% had the longest time lag in comparison to an undeveloped catchment and a catchment with a TIA of 11% owing to detention caused by a headwater wetland. These results partly explain the multiple linear regression analysis findings presented in Section 5.1.5, where the event peak flows had more complex and site-specific features than the models for runoff volumes, which are more directly controlled by TIA. Additionally, the changes in non-paved areas, such as the compaction of soils and the loss of vegetation as discussed in Section 3.2.1, likely affected the hydrograph shape during the construction works.

Rao and Delleur (1974) studied the impact of urbanization on runoff generation by comparing the IUHs of several urban and rural catchments in Indiana and Texas and concluded that the lag time depend on both the rainfall event and the catchment characteristics, such as area and TIA, and for this reason the catchment lag varies from event to event. The present study found (Section 5.1.3) that urbanization reduces the event-to-event variation in the hydrograph's shape and the catchment lag. This finding is consistent with the observations revealing that a linear relationship between precipitation and direct runoff is established after urbanization and that the runoff-contributing area for the most part remains constant during minor storms (Section 5.1.6).

Recent studies on changes in IUHs resulting from urbanization include those by Cheng and Wang (2002), Huang et al. (2008) and Cheng et al. (2010). These studies discussed changes in the unit hydrographs during urbanization at the 204 km^2 Wu-Tu catchment in Taiwan, where the climatic conditions differ greatly from those at the catchments in the current study owing to a high and unevenly distributed annual precipitation. Based on their results, urbanization decreased the shape of the IUH parameter α, but the scale parameter β remained constant; hence, the change in α was associated with the increase in TIA. In the present study, α tended to decrease during urbanization, but only the decrease in β and MTT was statistically significant owing to a more pronounced change in the parameter values in comparison to α, as described in Section 5.1.3. At least for the conditions in Espoo and at the small catchments, the results disagree with the finding presented by Cheng et al. (2010), which suggest that α is more sensitive to urbanization than β.

It is likely that the discordance between the findings by Cheng et al. (2010) and those of the present study result from the large differences in the spatial scale of the study catchments. In addition, the rather small changes in imperviousness (from 5% to 13%) and the high range of event rainfall depths (50-1600 mm) at the Wu-Tu catchment were quite different from those at the developing SR catchment in Espoo: the TIA changed from 1.5% to 37% and the rainfall depths from 2 to 14 mm.

The higher rainfall depths easily mask the changes in the shape of the hydrograph caused by urbanization: in Sections 5.1.2 and 5.1.7, it was observed that the change in the hydrological variables was larger during minor rainfall events than during major events. For instance, Hood et al. (2007) observed significantly longer lag times for a LID site in Connecticut compared with a site provided with a conventional pipe system during minor rainfall events (< 25 mm) but not during major events (> 25 mm). Hence, the runoff response during small events used in the IUH analysis better reflects the change in the catchment conditions, since runoff is mainly produced from the effective impervious surfaces, while the runoff-contributing area may expand into pervious areas during larger events (Section 5.1.6).

The runoff response to rainfall in large catchment areas with a relatively low TIA is not as sensitive to the changes caused by urbanization as runoff in small catchments, which can easily experience large relative changes in TIA. Hrachowitz et al. (2010) studied rural catchments (0.4-9.6 km^2) in Scotland, and like Cheng et al. (2010), they related α to the catchment characteristics, especially to soil type and drainage density, because of the small temporal variability in α and its lack of a relationship with rainfall intensity. Hrachowitz et al. (2010) then associated β to precipitation intensities exceeding the catchment-specific thresholds. This result is in line with the findings of Kokkonen et al. (2004) from two small rural catchments (0.18 and 0.63 km^2) in Finland and Oregon, where β showed a strong, negative correlation with event peak flow, while α did not correlate with the peak flow. However, because urbanization especially increases peak flow rates during rainfall events, as reported in Section 5.1.2, one would expect that β would be influenced by urban development. Perhaps, the increase in TIA in the study by Cheng et al. (2010) was not large enough to influence β or else the large size of the catchment masked the dependences that can be observed in small catchments. For example, Kokkonen et al. (2004) did not find strong relationships between β and peak flow rates for two larger catchments (58 and 1235 km^2) in southern Finland. In fact, the current study suggests (Section 5.1.3) that the catchment lag at the developing SR catchment had a strong positive correlation with α during the first years of construction, but a strong positive correlation with β during the later years. Hence, the IUH parameter having a stronger impact on the catchment lag changed during the course of the construction work. These correlations should be interpreted with caution, however, because they also showed site-specific differences and should be verified against data from a larger number of events and sites.

5.2.3 Key variables affecting event runoff generation

Several studies have applied multiple linear regression analysis to study the characteristics of urban runoff events, e.g. Melanen and Laukkanen (1981), Pitt (1987), Driver and Troutman (1989), Liscum (2001) and Brezonik and Stadelmann (2002). Although different sets of independent variables were used in the previous studies, the results concerning the most important variables are rather similar. These included event precipitation (P_{TOT}), the maximum rainfall intensity (P_{MAX}) and the catchment imperviousness either as total impervious area (TIA) or as effective impervious area (EIA), which were also the key variables affecting runoff generation in the current study (Section 5.1.5). The previous regression studies mainly focused on catchment comparisons instead of investigating the changes occurring in an urbanizing catchment.

The most important variables for predicting event runoff depths were P_{TOT} and TIA, of which P_{TOT} alone can explain more than 90% of the variance in the event runoff volumes (Section 5.1.5). This result agrees with the models for total event runoff proposed by Pitt (1987) for residential/commercial and industrial areas in Toronto, Canada and by Driver and Troutman (1989) and Brezonik and Stadelmann (2002) for total runoff in different geographic regions of the US, as well as the models for direct runoff proposed by Melanen and Laukkanen (1981) for several catchments in Finland and by Liscum (2001) for catchments in the Houston metropolitan area in Texas. Both Melanen and Laukkanen (1981) and Pitt (1987) concluded that rainfall alone explained runoff volumes to such an extent that other variables do not have practical importance in the estimation of runoff volumes.

Pitt (1987) obtained more site-specific equations for peak discharge rates than for total runoff volumes and suggested that the simplest equations either use only P_{MAX} or a combination of P_{TOT} and P_{MAX}. In the peak flow models for Finnish catchments (Melanen and Laukkanen, 1981), the first variable in the MLR equations was again P_{MAX} together with TIA, and other independent variables included the preceding dry period and the accumulated rainfall volume prior to the occurrence of P_{MAX}. Melanen and Laukkanen (1981) did not include P_{TOT} as an alternative independent variable in their peak flow MLR analysis, because they theoretically related peak flow rates to short summer rainfalls with a high P_{MAX}. In the study by Liscum (2001), the peak discharge rate was explained without including the maximum rainfall intensity by catchment area and by using an index describing the extent of the drainage features, event precipitation and an antecedent rainfall index. Compared with the above previous studies, the current regression analysis results for peak flows (Section 5.1.5) mainly resemble those provided by Pitt (1987) owing to the similar selection of independent variables: TIA or EIA, P_{MAX} and P_{TOT}. The regression models for peak flows lack the unanimous consistency of the runoff volume models discussed earlier, which is reflected by the various forms of the regression equations for the different catchments.

In the study by Brezonik and Stadelmann (2002), volumetric runoff coefficients were not correlated with rainfall characteristics, but, rather, with land use variables such as TIA (r=0.35). In the current study (Section 5.1.5), imperviousness was the most important variable in the C_{VOL} models; it accounted for more than 60% of the observed variance between events. Both EIA and TIA were strong explanatory variables in the MLR models describing runoff coefficients (C_{VOL}), and only slightly smaller SEEs were observed for the models using EIA instead of TIA. Similar to the present study, Melanen and Laukkanen (1981) observed that the site-specific MLR models for C_{VOL} did not achieve such high R^2 values as the combined model for all catchments (R^2 0.45-0.64 for individual models, 0.71 for the combined model), where an important independent variable was TIA. Since Melanen and Laukkanen (1981) did not use P_{MAX} as an independent variable in the C_{VOL} models, the additional explanatory variables included the duration of the rainfall events (P_{DUR}), mean rainfall intensity (P_{MEAN}) and the preceding dry period. At the current study catchments, P_{MAX} was also identified as an important variable in some of the site-specific regression models (see Table 36).

Antecedent conditions are mentioned as an influencing factor affecting runoff generation in urban areas and are included as a parameter in some of the design methods, e.g. in the UK (Butler and Davies, 2004) and in the US (Walesh, 1989). In the present study, however, the antecedent conditions were of little practical relevance in runoff estimation. In the local climate conditions of Espoo, rainfall is rather evenly distributed throughout the year and prolonged dry periods rarely occur, which likely reduces the importance of antecedent conditions in the regression equations. Neither Pitt (1987) nor Brezonik and Stadelmann (2002) included the antecedent dry period in their MLR models. Based on their studies and the current study, it can be concluded that variables describing antecedent conditions have practically no value in the MLR runoff models and that simpler models can often be regarded as sufficient for runoff estimation.

The problem with MLR models that combine several catchments is that they provide a unified relationship between runoff and explanatory variables, and thus, they do not provide insight into the differences between catchments representing different stages of urbanization. The previous studies cited above improved the performance of the model by grouping catchments according to soil properties (Liscum, 2001), land use and catchment area (Brezonik and Stadelmann, 2002), and mean annual rainfall (Driver and Troutman, 1989), but not by TIA (or EIA). Based on the current study, differences in the influencing variables between the study catchments can be explained by the level of urbanization and by the subsequent differences in impervious areas, rainfall losses and time of concentration. For instance, antecedent conditions have a stronger impact on peak discharge and event runoff depths in less developed catchment conditions (TIA 1.5% and 20%) based on larger, statistically significant bivariate correlations (Appendix E) in comparison to a more developed catchment (TIA ~34% and 50%). Also in less developed catchment conditions, the duration of the rainfall event seems to increase the total runoff depths. In more developed catchment conditions (TIA ~34% and 50%), the catchments had a more pronounced response to the maximum rainfall intensity than in less developed conditions (TIA 1.5% and 20%), especially in the case of Q_{MAX} and C_{VOL}. Hence, in more developed catchments high rainfall intensities can produce high peak flows even when the total rainfall depth is low.

5.2.4 Impacts of urbanization and event magnitude on the runoff-contributing area and volumetric runoff coefficients

Effective imperviousness and initial losses in Finnish urban catchments

The main driver for the hydrological change caused by urbanization is the construction work done on impervious surfaces. Based on review of the existing literature by Schueler et al. (2009), impervious cover is used as a key variable and a compliance measure, e.g. in the prediction of future downstream hydrology, in the design of stormwater management practices and zoning and in the assessment of water quality standards and stream health by watershed planners, stormwater engineers, water quality regulators, economists and ecologists. Uncertainties in the estimates of catchment imperviousness or its surrogates cause substantial errors in runoff modelling (Pitt, 1987; Lee and Heaney, 2003; Park et al., 2009). Owing to the important role of imperviousness, its characteristics should be well understood and methods for its estimation should be available locally.

Earlier results suggest that the extent of surfaces contributing direct runoff during rainfall events is often less than the estimated amount of total impervious area (TIA) in an urban catchment (Melanen and Laukkanen, 1981; Arnell, 1982; Radojković and Maksimović, 1986; Boyd et al., 1993; Becciu and Paoletti, 1997; Chiew and McMahon, 1999; Lee and Heaney, 2003). Varying terminology has been used to define the hydrologically active (runoff-producing) area: e.g. *effective impervious area* (EIA) or *directly connected impervious area* (DCIA). Also, at the study catchments in Espoo the EIA comprised only a part of the TIA (Section 5.1.6). Combined with the previously studied urban catchments in Finland (Melanen and Laukkanen, 1981), the relationship between TIA and EIA is well described as a linear regression (Figure 64a), which is statistically significant at a 99% confidence level. Thus, in urban catchments with a TIA within the range of 20-70%, reasonable EIA estimates can be achieved using the simple linear regression equation given in Figure 64a. A similar range of EIA proportions from the catchment area in Espoo can be found elsewhere: in Sweden, Arnell (1982) reported that the effective area comprised 49 to 91% of TIA for catchments representing TIAs ranging from 19 to 57%.

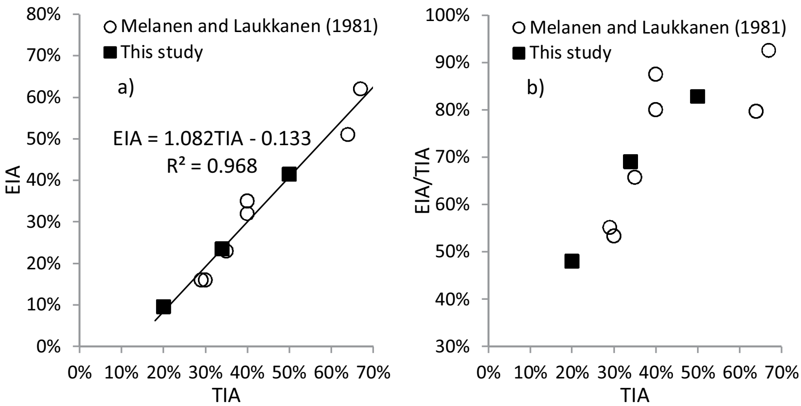


Figure 64. Relationship between the TIA and EIA (a) and the proportion of EIA in relation to TIA (b) at Finnish urban catchments.

Based on the data from the Finnish catchments, Melanen and Laukkanen (1981) concluded that the EIA is between 50 and 80% of the TIA in residential catchments and between 80 and 90% in the city centres and at industrial catchments. The results from the Espoo catchments reinforce the previous Finnish observations illustrating that impervious surfaces become more effective, i.e. the EIA approaches the TIA as the TIA increases. Figure 64b demonstrates that there is a nearly linear increasing pattern in the effective part of the TIA as the catchment becomes more impervious (TIA <40%), but after the TIA reaches about 40%, the relationship disappears. On average, the EIA covered 58% of the TIA in low- to medium-density catchments (TIA <40%, n=5) and 85% in medium- to high-density catchments (TIA ≥40%, n=5). In addition to the linear relationship, a nonlinear form ($EIA=A(TIA)^B$) was proposed by Sutherland (2000) and Said and Downing (2010) for the estimation of EIA. The nonlinear equation incorporates the idea that impervious surfaces become more efficient in terms of EIA as the TIA increases. For the Finnish catchments in Figure 64a, the nonlinear form would have yielded the same R^2-value as the linear equation. The form of the EIA equation, or a combination of linear equations, should be further examined, especially when data from catchments with a higher TIA become available.

In addition to analysing the EIA extent in the study catchments, estimates for initial losses were obtained (Section 5.1.6). Initial losses of less than 2 mm are typically observed at urban catchments (see Figure 65), although, according to Pitt (1987), initial losses may account for up to 5-10 mm of rain. Even though the absolute volume of initial losses is low in comparison to major rain intensities, the initial losses constitute a significant portion of the precipitation during small, frequently occurring storms (Field and Sullivan, 2003). Hence, the initial losses have a practical importance when the amount of direct runoff has to be accurately estimated during small rainfall events. The estimates for the initial losses from the current study catchments fall well within the range of those for other urban catchments in Finland and abroad (Figure 65a). The estimates from three catchments compiled by Boyd et al. (1993) are not shown in Figure 65a owing to their large initial losses (1.3-6.1 mm) in relation to their high EIAs (48-96%). The reasons for these high initial losses were not discussed by Boyd et al. (1993). It should be noted that the initial loss estimates are affected by the accuracy of monitoring during small events and, hence, are subject to potentially large relative errors.

Melanen and Laukkanen (1981) suggested that the initial loss is a decreasing function of the catchment slope and the percentage of paved surfaces, although these relationships were not clear based on their data (Figure 65b). Current results (Section 5.1.6) indicated that the age of the surfaces likely influences the amount of initial losses in addition to the TIA. The estimated losses for the low-density LL catchment (TIA 20%), the medium-density VK catchment (TIA 50%) and the developing SR catchment having a TIA of only 1.5% decrease with an increasing TIA, as suggested by Melanen and Laukkanen (1981), but the smallest losses were observed at SR after construction works with a recently established impervious areas (TIA ~34%). Pitt (1987) found that the initial losses from smooth street surfaces were less than the losses from rough street surfaces, and Shuster et al. (2005) concluded, based on a review of the existing literature, that the weathering of roadways will impact the effectiveness and connectiveness of impervious surfaces. Melanen and Laukkanen (1981) estimated smaller initial losses for two catchments with low EIAs (16%), but it was not explained whether this was caused by the type or the age of the drainage network. Owing to the high variability of the initial losses in

Figure 65a-b, more data from catchments with different characteristics in Finland would be required to establish a more detailed model for estimating the initial losses.

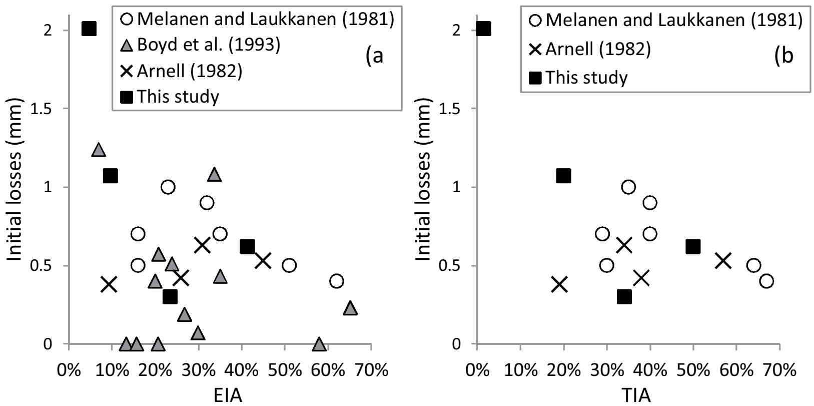


Figure 65. Relationship between the initial losses and (a) EIA and (b) TIA at various catchments in Finland and abroad (Australia, Canada, Denmark, Great Britain, Hungary, Italy, Norway, Sweden, USA, and former Yugoslavia) for catchments having total area of 60 ha or less.

Variations in direct runoff generation according to the rainfall event magnitude

The degree of effectiveness, i.e. the direct runoff-producing area, is typically assumed to be directly related to the TIA (Brabec et al., 2002; Shuster et al., 2005; Said and Downing, 2010). However, the rainfall event magnitude also has a strong impact on the runoff-producing area (Sheeder et al., 2002; Said and Downing, 2010). Previously, Lee and Heaney (2003) argued that a threshold of storm intensity able to produce runoff outside the effective impervious area is needed in order to prorate the cost of stormwater systems and water quality management for major and minor storms. The present study (Section 5.1.6) responded to this need by establishing a precipitation threshold that separates minor and major events based on the change occurring in the runoff response to rainfall depth. The threshold forms a hydrological criterion in the local climate for separating rainfall events based on their runoff-contributing area and management purpose. This finding was in line with the results of the MLR analysis discussed in Section 5.1.5, where the key variables describing event runoff coefficients were TIA and P_{TOT}.

At the Espoo catchments, a statistically significant change in the runoff response to rainfall occurred after the event rainfall depth exceeded 17-20 mm (Section 5.1.6). The threshold identified in Espoo seems realistic in comparison to the examples found from international references, despite the differences in local conditions. Pitt (1987) studied the urban rainfall-runoff process using catchment-scale models in Toronto, Canada, and found that pervious surfaces produce substantial amounts of runoff and pollutants above rainfall depths of about 10-25 mm. Based on a study of catchments in Florida, Said and Downing (2010) suggested, that rainfall depths greater than 25 mm cause a notable increase in the directly connected impervious area in relation to the TIA.

The difference in runoff-contributing surfaces between minor and major rainfall events may not be distinct for catchments with TIAs that exceed those of this study (TIA > 50%). Boyd et al. (1993) compared the regression lines of event rainfall and runoff depths for several countries and observed that urban catchments with extensive sewer systems tend to produce runoff only from impervious areas. Also in Espoo, the difference in the runoff response to rainfall between minor and major events decreased as the catchment TIA increased (Figure 57 in Section 5.1.6), which can be explained by the increasing effectiveness of the TIA, as shown in Figure 64b. It should be noted that the linear rainfall-runoff relationship indicating a constant runoff-producing area for minor storms discussed in Section 5.1.6 was established after the catchment contained a noticeable amount of impervious surfaces: in the predevelopment stage, the hydrologically active area in the developing SR catchment comprised small, directly connected paved surfaces (TIA 1.5%) and disturbed soil surfaces with direct access to sewer manholes, which is in accordance with the findings by Line and White (2007) previously discussed in Section 3.2.1.

Volumetric runoff coefficients in Finland for different design purposes

The recently published national stormwater manual for Finland (Association of Finnish Local and Regional Authorities, 2012) recommends taking a more integrated and sustainable approach to stormwater management in Finland. International theories regarding varying design goals and events are included in the manual to outline a methodology for minimizing the adverse impacts of urbanization on water cycle and for improving water quality along with flood protection. However, the lack of published research on local conditions has led to a situation in which the design guidance principles are based on literature from abroad or else on traditional sewer design, which is not directly transferable to other design purposes. Several authors (e.g. Pitt, 1999; Roesner, 1999; Lee and Heaney, 2003; Liu, 2011; Burns et al., 2012) have pointed out the importance of small- and medium-sized storms to stormwater runoff quality management and to the management of a large spectrum of design events for restoring predevelopment hydrology and water quality. The current results emphasize the importance of minor storms: during the construction works, the largest relative changes occurred in runoff coefficients during minor storms (Section 5.1.7) and no statistically significant changes in runoff coefficients during major storms were observed (Chapter 5.1.2). For minor events, most of the pervious areas are not hydraulically active and the initial rainfall losses are larger compared with major storms. Thus, smaller runoff coefficients should be used, for example in design tasks aiming at water quality control (Pitt, 1987; Roesner, 1999). Pitt (1987) estimated that the use of constant, large runoff coefficients for all storm events results in runoff prediction errors greater than 25%. For the same reason, the conventional stormwater models intended for flood control should be used with caution in runoff prediction for small- and medium-sized storms (Field and Sullivan, 2003; Pitt and Vorhees, 2003). Hence, local information based on monitoring and modelling is urgently needed for updating and refining the design principles.

Figure 66 summarizes the observed runoff coefficients at the current study catchments together with the previously studied Finnish catchments (Melanen and Laukkanen, 1981). Two regression lines are shown: 1) for the estimation of an average runoff coefficient (C_{VOL}) and 2) for the maximum observed runoff coefficients ($C_{VOL,\ max}$). The regression lines use either TIA (Figure 66a) or EIA (Figure 66b) as the measure of imperviousness. It should be noted that the equation for $C_{VOL,\ max}$ is based on only one event per catchment. Behind the C_{VOL} equation, the number of runoff events (71-168 per catchment) in Melanen and Laukkanen's (1981) study is comparable to the number of events in the current study (82-298 per catchment). The combined events from the two studies are considered sufficient for providing generalized estimates of average runoff coefficients across a wide range of imperviousness.

The average C_{VOL}s from the Espoo catchments are all located above the regression lines for the mean runoff coefficients for Finnish catchments (Figure 66). The likely reason for the slightly higher runoff coefficients compared with Melanen and Laukkanen's (1981) results has to do with the different methods used for the rainfall measurements. Melanen and Laukkanen (1981) used a Hellman-type pluviograph, which they suggested had an approximate measurement error of 10%. In the present study, no additional precipitation correction was applied for the tipping-bucket rain gauges based on the field calibrations (Section 2.3.1). The method used for the baseflow separation was the same for both studies: the use of different methods would have precluded intercomparison of the different catchments (Blume et al., 2007).

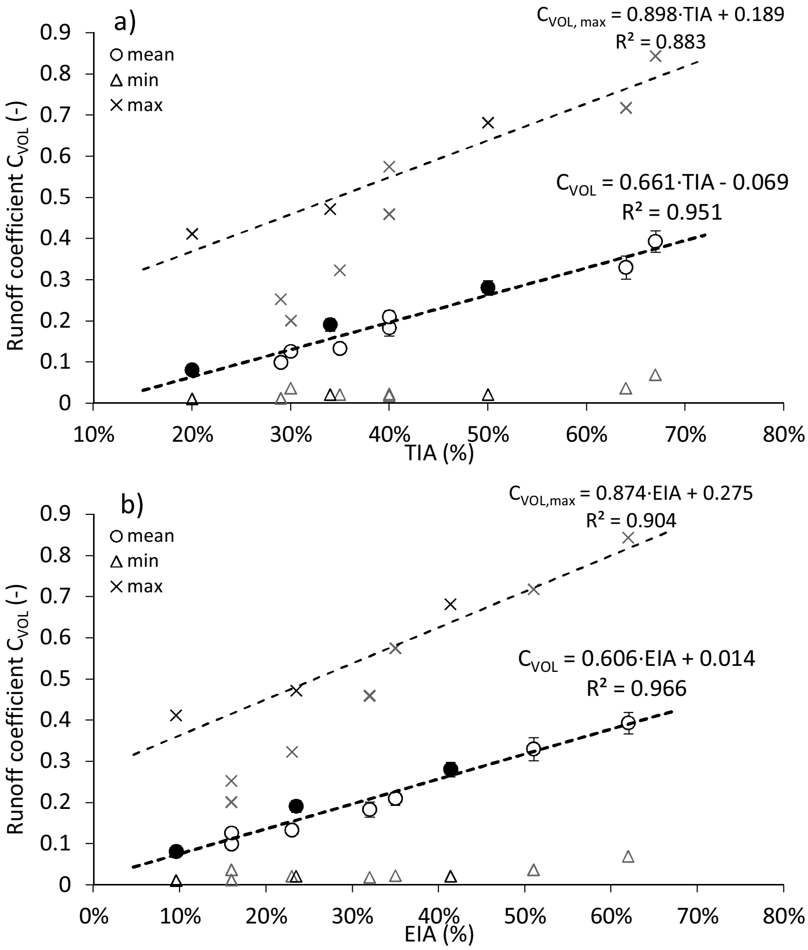


Figure 66. Mean runoff coefficients with the 95% confidence intervals and the minimum and maximum values for the study catchments (black circles) and white circles representing urban catchments studied by Melanen and Laukkanen (1981) according to (a) the TIA and (b) EIA. All of the equations are statistically significant at 95% level of confidence.

As illustrated in Figure 66, an average runoff coefficient is directly proportional to the TIA and EIA, as suggested by many authors (e.g. Schueler, 1994; Goldshleger et al., 2009). A large difference exists between the largest observed runoff coefficients and the average runoff coefficients (Figure 66), illustrating that the runoff coefficient is not constant for a particular catchment. This fact has been observed in previous studies as well. For instance, Pitt (1987, 1999) used runoff coefficients to demonstrate that the runoff generation from different types of impervious surfaces is similar after the rain depth exceeds 80 mm, but the differences for smaller rainfall events can be very large.

A comparison of the runoff coefficient model in Figure 66 to other studies reveals the importance of the locally derived data. In the US, a regression equation for small storm runoff coefficients was developed by Urbonas et al. (1990), which takes the following form (Equation 9):

$$C = 0.858i^3 - 0.78i^2 + 0.774i + 0.04 \quad (9)$$

where C is the runoff coefficient and i is the TIA (dimensionless, per cent value divided by 100) based on data from more than 60 catchments (WEF-ASCE, 1998). Compared with the regression equations in Figure 66a, Equation (9) overestimates the runoff coefficients and does not appear to be applicable to Finnish catchments. As shown in Figure 67, the equation developed for the US overestimates the runoff coefficients for low development densities: for catchments with a TIA greater than 40%, the estimates for the US are approximately 20-30% higher than those in Finland, whereas for catchments with a TIA less than 40%, the difference are from 40% to 170%. Goldshleger et al. (2009) presented a modified model for runoff coefficients that combined data from the US, Australia and Israel. In their model, the runoff coefficients were equal to zero for catchments with a TIA of up to 20%; the runoff coefficients increased linearly when the TIA increased from 20% to 40% and were equal to the TIA for catchments with a TIA greater than 40%. This model would underestimate the runoff coefficients for Finnish catchments with a low TIA and overestimate them in the case of a high TIA. However, Goldshleger et al. (2009) did not especially introduce minor storms as a design event; instead, they focused more on urban flooding. It is difficult to accurately determine what factors cause such differences between the present study and those from abroad: in addition to differences in climatic conditions and the type of infrastructure, the methods used for analysing the data may explain some of the differences between the results.

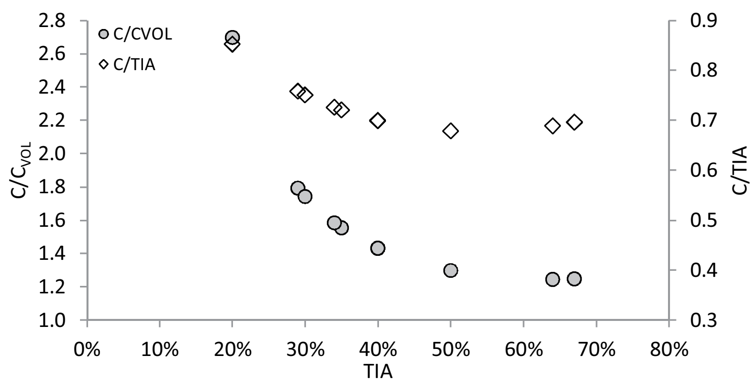


Figure 67. Comparisons of runoff coefficients C for small storms in the US and average runoff coefficients (C_{VOL}) for Finnish catchments based on the equation in Figure 66(a).

In Figure 68, the measured runoff coefficients from the study catchments (Section 5.1.7) and those determined based on the Finnish stormwater manuals (*Manuals 1-2* in Figure 68) are compared. The EIA is also included because it can be considered a surrogate for the runoff coefficient (e.g. Lee and Heaney, 2003). The manual coefficients were originally meant for sewer design and are high in comparison with the observed coefficients for most events. Yet, the manual coefficients are exceeded by the maximum observed C_{VOL}s (*All events max* in Figure 68) for all study catchments. In fact, the upper end of the runoff coefficients based on Manual 2 is of a similar magnitude as the maximum observed C_{VOL}s. Based on the results, the estimated runoff coefficients in the sewer design seem to be adequate for the design tasks aiming at flood control.

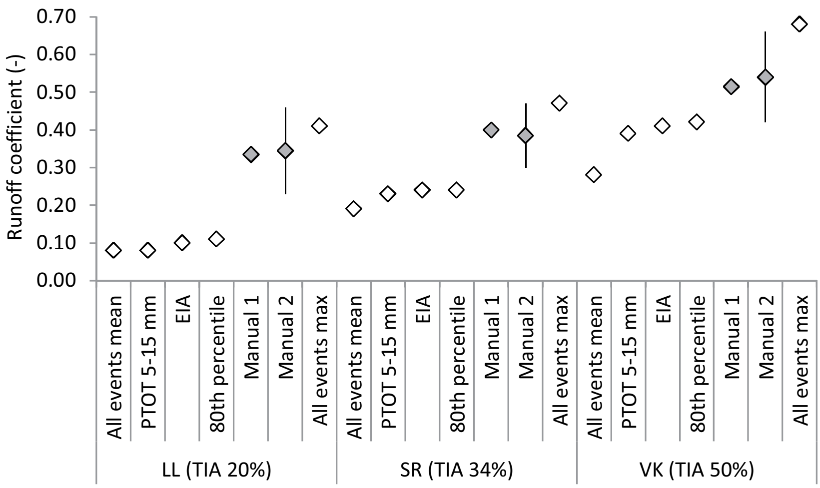


Figure 68. Comparisons of observed runoff coefficients, EIA, and runoff coefficients recommended for sewer design. Manual 1 refers to coefficients given in RIL (2004) by the Association of Finnish Civil Engineers and Manual 2 to Tielaitos (1993) in the national stormwater manual (Association of Finnish Local and Regional Authorities, 2012). For Manual 2, a range of coefficients was calculated with the lowest and the highest values for each surface type. White symbols represent values based on the monitoring data, grey symbols the literature coefficients.

Several suitable runoff coefficients can be given for common, minor storms; these runoff coefficients are notably lower than the manual coefficients and could be utilized in design tasks aiming at, for example, water quality control or groundwater recharge. These coefficients are illustrated in Figure 68 as 1) an average coefficient for all runoff producing events, 2) an average coefficient for events within the precipitation depth range of 5 to 15 mm, 3) the 80th percentile runoff coefficient for all events producing direct runoff, and 4) the EIA. All of these coefficients describe events that generate runoff mostly from the effective impervious area and that fall below the threshold rainfall depth of 17-20 mm. When space is limited and the overflows are safely conveyed, any of these measures for the runoff coefficient can be used instead of the large runoff coefficients that are used for flood control and infrequent events. The results also support the idea that the EIA is a surrogate runoff coefficient, as suggested by Lee and Heaney (2003). In the present study, the EIA was determined based on the monitored rainfall-runoff data, which Shuster et al. (2008) recommended as the best means for assessing effective imperviousness. If runoff measurements are not available, the equation in Figure 64a can be used to determine the EIA based on the TIA. This method may not be accurate in those cases when the effectiveness of impervious surfaces is notably reduced in comparison to a traditional development, e.g. at LID sites. Also, the regression equations in Figure 66 can be used to determine the average runoff coefficient for common storms; they give slightly lower estimates for the study catchments in comparison to the measured average of all runoff-producing events in Figure 68 owing to the combined data from the present study and the one by Melanen and Laukkanen (1981).

The results discussed here about the changing extent of the runoff-contributing area, the precipitation threshold (Section 5.1.6) and the runoff coefficients for different event magnitudes (Section 5.1.7) lend support to the recent approaches in urban runoff management, which are based on classifying rainfall events according to the management goal and event size. For example, the Norwegian water guideline from the year 2008 recommends that municipalities should retain and infiltrate rainfall events less than 20 mm (Nie et al., 2011), which corresponds to the upper end of the precipitation threshold determined in the present study. In Minnesota, the sizing of stormwater practices aims at managing the whole spectrum of rainfall events by dividing the events into management zones based on their relative frequency (Minnesota Stormwater Manual, 2008). Similar approaches are utilized, for example, in Connecticut, (Connecticut Stormwater Quality Manual, 2004), and Toronto, Canada (Toronto Water, 2006). The refinement of design criteria to serve a variety of management aims in Finland needs further analysis based on both monitoring and modelling, but the hydrological principles established in the current study provide a starting point for such work.

5.2.5 Key variables affecting event water quality

A common feature of stormwater quality data is the non-normality and skewness of pollutant distributions and, as such, logarithmic transformations are often preferred (Driver and Troutman, 1989; Brezonik and Stadelmann, 2002; McLeod et al., 2006; Kayhanian et al., 2007; Helmreich et al., 2010), even though the supremacy of the log-distribution over other distributions should not be taken for granted (Hall et al., 1990; Van Buren et al., 1997; Maestre et al. 2005). In this study, the log-transformation provided a reasonable fit to the normal distribution for all of the studied constituents; hence, there was no need to further examine the other data processing methods for the key water quality variables. However, because the accuracy of log-normal distributions for illustrating the extreme values is questionable (Maestre et al., 2005; McLeod et al., 2006), the probability of the exceedances of threshold concentrations were examined using the probability plots of the observed values.

The key variables describing EMCs and EMLs

Several studies can be found in the existing literature that use multivariate statistical techniques, especially multiple linear regression analysis (MLR), to investigate event variables and their impact on event water quality in urban catchments (e.g. Melanen and Laukkanen, 1980; Melanen, 1981; Driver and Troutman, 1989; LeBoutillier et al., 2000; Brezonik and Stadelmann, 2002; McLeod et al., 2006; Kayhanian et al., 2007; Maniquiz et al., 2010). Not all of the previous studies discuss both the event mean concentrations (EMCs) and the event mass loads (EMLs), but those that do so report that loads are easier to predict than concentrations (e.g. Brezonik and Stadelmann, 2002; Maniquiz et al., 2010). The complexity of predicting the EMC stems from the fact that there are several influencing factors, and none of them explains the majority of the observed event-to-event variance. Based on the results of the MLR analysis for EMCs and EMLs presented in Section 5.1.8, water quality was explained by four main variables for all of the studied catchments: 1) a volume variable, 2) an intensity variable, 3) antecedent conditions and 4) variables describing construction works. In practice, this means that major rainfall events produce more diluted concentrations but larger pollutant loads than minor storms; greater rainfall intensities increase both the concentrations and event loads, but the role of antecedent conditions in particular depends on the site and pollutant in question.

For EML, the rainfall depth is reported as being the single most important variable for various pollutants. Driver and Troutman (1989) developed regression equations for event pollutant loads by combining several urban catchments from different parts of the US and concluded that the most important variable was rainfall depth (P_{TOT}) in addition to such catchment variables as total area, impervious area and land use. McLeod et al. (2006) studied four urban sites in Saskatoon, Canada, where the single most important explanatory variable for EML was rainfall depth, but they also observed catchment-specific differences in explanatory variables. In another residential catchment in Saskatoon, LeBoutillier et al. (2000) concluded that the TSS load was best explained by P_{TOT} and mean rainfall intensity (P_{MEAN}). Brezonik and Stadelmann (2002) conducted an MLR analysis to predict both the EMC and EML for 43 sites around Minnesota, in the US, and mentioned P_{TOT} and P_{MEAN} as the most useful variables for predicting EMLs in addition to the catchment area. In Finland, a detailed analysis of event loads has not been conducted before. The results of the present study (Section 5.1.8) support the volume-dependence of EMLs; for instance, rainfall depth explained approximately 90% of the observed variance in TN and COD loads at the low-density LL catchment. P_{TOT} was always the first variable chosen for EML models, except for the TSS EML models for the medium-density VK catchment and the developing SR catchment, for which the maximum 10-minute rainfall intensity (P_{MAX}) was chosen before P_{TOT}. In Section 5.1.8, the inclusion of P_{MAX} was explained by the energy of the rain and flow to wash off particles from both impervious and pervious catchment surfaces and from the conveyance system itself. Hence, based on the results, the event pollutant loads were strongly dictated by the amount of precipitation and runoff, but differences can be expected between particulate and more soluble pollutants. It should be noted that although the use of three variable types (volume, intensity and antecedent conditions) in the EML models (Section 5.1.8) did not produce R^2 values that were as high as those for the runoff volumes presented in Section 5.1.5, the coefficients of determination at all of the study catchments (R^2 0.62-0.97) were higher than the values previously reported by LeBoutillier et al. (2000) (R^2 0.14-0.53), Brezonik and Stadelmann (2002) (R^2 0.33-0.57) and Maniquiz et al. (2010) (R^2 0.44-0.55).

The previous studies on predicting the EMC yield more varied results than those for predicting the EML, but some generalizations can be made from the case studies despite the different explanatory variables. In Gold Coast, Australia, Liu (2011) concluded, based on bivariate correlations and principal component analysis, that events with a high average rainfall intensity (P_{MEAN}) and a long antecedent dry period (DAYS) increase the EMC and that rainfall events of a longer duration (P_{DUR}) produce lower EMCs. In climatic conditions more similar to the study catchments in Espoo, Brezonik and Stadelmann (2002) included P_{MEAN} and DAYS with positive regression coefficients into their best model for TSS EMC and P_{DUR} with a negative coefficient together with DAYS into their COD EMC model for residential sites in Minnesota. Brezonik and Stadelmann (2002) actually used the same variables as Liu (2011), but instead of P_{MEAN}, they ranked P_{DUR} and DAYS as the most useful variables in the EMC models (data from 65 sites). Based on the correlations presented by Melanen and Laukkanen (1980) for six urban catchments in Finland, the relationships between the pollutant concentrations and the variables characterizing volume, intensity and antecedent conditions appeared to be similar to both the studies cited above and the current study despite the different selection of explanatory variables. However, Melanen and Laukkanen (1980) mentioned the maximum 5-minute rainfall intensity (P_{MAX}) as the most important variable in the EMC models. The EMC models presented in Section 5.1.8 are good in comparison to those in other studies despite the rather low R^2 values (0.35-0.62): for example, the regression models for Finnish catchments provided by Melanen and Laukkanen (1980) explained between 30 and 40% of the variations in EMC (TSS, TP, TN and COD_{Cr}). The feature common to all of the regression models is the dilution effect observed in EMCs as the rainfall depths increase.

Based on the results presented in this thesis and in the previous studies, the role of maximum rainfall intensity (P_{MAX}) and antecedent conditions require further clarification. The use of P_{MEAN} in many earlier studies is understandable, as it can easily be calculated using P_{TOT} and P_{DUR}, whereas the use of P_{MAX} requires an analysis of the individual observations within an event, which may not be available. For this reason, Brezonik and Stadelmann (2002) used only P_{MEAN} and not P_{MAX} in their analysis. However, in some cases, P_{MAX} has been rejected from MLR analysis based on bivariate correlations: Liu (2011) excluded P_{MAX} owing to its strong correlation with P_{MEAN}, and for the same reason removed P_{TOT} but not P_{DUR}. Kayhanian et al. (2007), who studied EMC data from 34 highway sites in California, excluded P_{MAX} owing to its moderate correlations with P_{TOT} and possible multicollinearity, in addition to the fact that it was less important in the EMC models. In the present study, both P_{TOT} and P_{MAX} were needed to construct the water quality models.

The importance of antecedent conditions in the urban water quality models seems to be unclear based on the previous research. Similar to P_{MAX}, the data for antecedent conditions is not always available (e.g. Driver and Troutman, 1989) or else the variables describing the antecedent conditions are considered unimportant based on weak bivariate correlations (e.g. Helmreich et al., 2010; Maniquiz et al., 2010). In the case of the load models provided by McLeod et al. (2006) for urban sites in Saskatoon, Canada, the antecedent dry period had no statistical significance. Conversely, despite the rather weak bivariate correlations, Brezonik and Stadelmann (2002) mentioned the preceding dry period as a useful parameter in some EML and EMC models. In addition to the most commonly used antecedent dry period, the preceding precipitation sums were used in the present study to describe antecedent conditions. Based on the results presented in Section 5.1.8, both periods can be significant variables in the regression models depending on the site and the pollutant. For instance, the longer dry period increased the nutrient EMCs at the low-density LL catchment, indicating a build-up process, while at the medium-density VK catchment the antecedent five- or seven-day precipitation sums were especially important in the EMC models, and significant also in the EML models with negative regression coefficients. This, in turn, can be explained as a washoff mechanism showing that larger amounts of precipitation eventually start depleting the available pollutant storage. However, because neither the one-day nor three-day precipitation sums were included in the models, this apparently required relatively large amounts of precipitation. This supports the previous conclusions by Chiew et al. (1997) and Deletic et al. (1998) that pollutant washoff is rarely limited by the amount of pollutants and that there is usually enough of a pollutant mass available for washoff for the total duration of common rainfall events. These findings, combined with the observed dilution of EMCs in the regression models, support the general idea of the importance of minor rainfall events in urban runoff quality management (e.g. Pitt, 1999; Roesner, 1999; Lee and Heaney, 2003; Liu, 2011; Burns et al., 2012) in local conditions, when the treatment of all runoff may not be a feasible or cost-effective solution.

The key variables affecting water quality during construction works

Previous studies attribute sediment yields from construction sites to both event runoff volumes and rainfall energy. Daniel et al. (1979) studied three residential construction sites in Wisconsin: using simple linear regression analysis with data from one year, they found that sediment loads were best explained by the product of total runoff volume and peak flow (r^2 0.62), with runoff volume being the most important variable. Walling (1974) applied multiple linear regression analysis to a 26 ha developing residential catchment in Exeter, England, again using data from one year during the building construction phase. He concluded that sediment concentrations and loads were best explained by a measure describing the rainfall energy, either by the kinetic energy or its product with a maximum 30-min intensity of rainfall. Nelson (1996; as cited in Burton and Pitt, 2002) related the increase in TSS concentrations to rainfall intensities at construction sites in Alabama, whereas Schueler (2000) related increases in TSS concentrations in sediment traps and basins to rainfall depth at construction sites in Maryland. According to the current results presented in Section 5.1.8, the basic mechanisms affecting the EMC and EML were the same at the developing SR catchment and the control catchments when only rainfall or runoff event characteristics were considered. Thus, in contrast to the results presented by Schueler (2000), the EMC models in this study showed dilution during large events of longer duration. Nevertheless, it should be noted that the basic mechanisms described here failed to explain TSS EMCs during some events during the construction works; likewise, the extra variables also connected higher EMCs and EMLs to the later phases of development in the TSS, TP and TN models, which contradicts the dilution effect resulting from increased runoff volumes. Hence, it can be concluded that during different phases of construction works, the mechanisms affecting the changes in pollutant concentrations varied and the dilution effect was not as distinct at the construction sites as it was at the developed residential catchments.

Schueler (2000) noted how difficult a target a construction site is for monitoring changes in the catchment conditions on a month-to-month basis. The previous studies cited above have not usually considered how variables describing the temporal changes in the construction activities or in the impervious area coverage affect the water quality. Based on the results presented in Section 5.1.8, the different phases of the construction works and the changes in the runoff-contributing area (TIA) clearly influenced the EMCs and EMLs. Hence, additional variables that describe catchment conditions during the construction works are needed to raise the coefficient of determination to the same level with the developed control catchments, when the gathered data presents longer time periods containing different construction phases. Previously, Atasoy et al. (2006) and Dougherty et al. (2006b) considered the rate of land conversion and construction activities in their analysis of water quality, but on a coarser spatial and temporal scale than the analysis carried out in the present study. In a multiple linear regression analysis of an urbanizing 127 km^2 Cub Run catchment in Washington D.C., Dougherty et al. (2006b) used the change in the impervious area as a measure of urban soil disturbance associated with urban development. They observed that in addition to the precipitation depth, urban soil disturbance increased the loads of all of the studied pollutants (TP, TN, TSS) together with their agricultural sources. Atasoy et al. (2006) used spatially autoregressive models to study how rainfall depth, point pollution sources, the total residential area and changes in the residential area impacted monthly pollutant loads from 20 monitoring stations in the larger Neuse River Basin, in North Carolina. Atasoy et al. (2006) discovered that both the extent of the residential development and its changes (i.e. construction) adversely affected the pollutant loads, with the latter being the most influential variable. The TP and TN loads were affected by both the extent of the residential development and its changes, but TSS had a statistically significant relationship only with the developing area and not the residential area, which was explained by the stabilization of the catchments after the initial construction phase. However, they noted that other factors also affect water quality and that there was a need to reduce the spatial scale of their study. In the present study, the additional construction and catchment variables revealed different mechanisms related to the changes in the catchment conditions and the construction activities, but these variables were also ambiguous and demonstrated pollutant-dependent behaviour (Section 5.1.8). For all of the pollutants, the impact of construction variables was different, either indicating an increase or decrease in the EMCs or EMLs as construction works progressed. For TN, the periods with possible wastewater discharges increased the event loads, but not all of the TN sources were accurately described and a model for TN EMC could not be constructed with the available variables.

In the present study, the availability of more detailed process descriptions would have enabled more detailed results regarding the pollutant transport mechanisms, e.g. by using more detailed measures for the amount of disturbed soil surfaces or construction activities influencing the pollutant sources. However, the results show that in addition to the recommendation by Schueler (2000) that sediment removal is needed the most during larger storms that occur in the later stages of construction, all construction phases should be considered important in pollution mitigation, as was previously suggested based on the long-term water quality results presented in Section 3.2.4.

5.2.6 Seasonal differences in event water quality

Many previous studies compare seasonal urban runoff quality on a street-level scale (Sansalone and Buchberger, 1997; Bäckström et al., 2003; Westerlund et al., 2003; Westerlund and Viklander, 2006; Hallberg et al., 2007; Westerlund, 2007; Helmreich et al., 2010), but catchment-scale studies of urban runoff quality under cold climate conditions are scarce (Semádeni-Davies and Titus, 2003). Previous studies that included catchment monitoring (discussed in Section 3.2.3) revealed site-specific results on the magnitude of seasonal differences in the concentrations of different pollutants (Oberts, 1990; Pitt et al., 1996; Brezonik and Stadelmann, 2002; Semádeni-Davies and Titus, 2003), and these differences also depend on the TIA based on present (Section 3.1.6) and past Finnish studies (Melanen, 1980; Kotola and Nurminen, 2003). At the LL and VK control catchments, significantly higher EMCs for the cold period events were only observed for TN (Section 5.1.9); this differs from the rather straightforward results presented in road runoff studies, which usually report higher EMCs for winter than for summer runoff (Westerlund et al., 2003; Bäckström et al., 2003; Hallberg et al., 2007). At the developing SR catchment, significant differences between seasonal EMCs were observed only for TSS, which supports the discriminant analysis results presented in Section 3.1.6, where seasonal patterns explained only 40% of the variations in monthly concentrations during construction works in contrast to nearly 90% at the residential control catchments.

A common approach in the previous cold climate studies has been to study the seasonal water quality differences by comparing EMCs from only two periods: cold and warm (e.g. Brezonik and Stadelmann, 2002;

Westerlund et al., 2003; Semádeni-Davies and Titus, 2003; Hallberg et al., 2007). When the results of the two-period EMC comparisons presented in Section 5.1.9 are compared with the seasonal concentration patterns established in Section 3.1.6, which are based on discriminant analysis (DA), it is evident that the two-period event approach in some cases masked the seasonal concentration patterns. Thus, cold climate urban runoff studies have not yet explored the seasonal variations in urban runoff quality in enough detail to reveal the key features of small urban catchments representing different levels of TIA. At LL for all of the studied pollutants and at VK for TN, DA showed divisions based on the two periods, warm and cold, whereas at VK the pollutants other than TN followed a pattern where spring produced equal or higher concentrations than summer and autumn. In the latter case, the two-period EMC comparisons masked the underlying seasonal patterns at VK, particularly by indicating significantly higher TP and COD concentrations during the warm period.

Melanen (1981) found no differences in EMCs between suburban residential catchments (TIA 29-40%) during the warm period rainfall events. Also, according to Laiho (1980), the quality of snowmelt events was similar at all suburban catchments, but poorer in the city centre areas (Laiho, 1980; Melanen, 1980). In the present study (Section 5.1.9), however, significant differences between the catchments were usually observed for both EMCs and EMLs, reflecting higher pollutant concentrations and loads at the medium-density VK catchment and the developing SR catchment in comparison to the low-density LL catchment. The differences between LL and VK can to a large extent be explained by the differences in TIA and traffic-related sources, which in Section 4.1.4 appeared as a notably higher pollutant mass accumulated in the snow per unit area at VK than at LL. The lack of significant differences in the study by Melanen (1981) likely results from the smaller TIA difference between suburban study catchments (29-40%) compared with the current study (20-50%).

Although the developing SR catchment always yielded the highest median EMCs for all pollutants and seasons, significant differences between SR and the control catchments in EMCs and EMLs were not always observed (Section 5.1.9). The individual EMCs and EMLs were not evenly distributed throughout the different construction periods and monitoring years; hence, the extent and timing of the impacts of the construction works on water quality are more clearly reflected by the results of the long-term analysis presented in Chapter 3.

Harremoës (1988) divided the water quality impacts of urban runoff into two categories, acute and chronic, of which chronic impacts are more common. The present study aims to provide a comprehensive view of urban runoff and, thus, the seasonal occurrence of high pollutant concentrations was also studied. This revealed a distinct, seasonal feature, one which has not been explored in previous cold climate studies: high EMCs occurred more likely during the warm period than during the cold period both at LL and VK (Section 5.1.9); thus, if acute impacts and the violations of concentration criteria are of importance, the exceedances of EMC concentration criteria are expected to occur more frequently during summer and autumn than during winter and spring. Construction works, however, increased the occurrence of high concentrations in both seasons in comparison to the developed urban catchments. In addition, the probability of high EMCs was much higher at VK (TIA 50%) than at LL (TIA 20%).

Although in Espoo the cold period events did not always yield notably higher EMCs in comparison with the warm period events (Section 5.1.9), significantly higher event loads were always observed for the cold period. Previously, Westerlund et al. (2003) found statistically significant difference in TSS EMCs between rainfall and snowmelt events in road runoff in Luleå, Sweden, but not in the event loads; yet, the cumulative mass load of all of the sampled events was higher for snowmelt events than for rainfall events. Hallberg et al. (2007) explained the elevated pollutant loads during snowmelt in motorway runoff in Stockholm, Sweden only by referring to the higher pollutant concentrations. Although this is not the only reason behind the larger loads during the cold period events in the present study, in Section 4.2.3 it was concluded that ploughed snow along roadsides and deposited particles and other pollutants from soil and road surfaces increased the pollutant concentrations in runoff during spring; this, however, is not strongly reflected by the seasonal EMC comparisons in the present study. Despite the higher event loads, spring did not account for a substantially high proportion of annual loads (Section 3.1.7); this is explained by the smaller number of events during the cold period (Section 5.2.1) and the increased contribution of the growing season to annual loads after urbanization (Section 3.2.3).

Owing to the chronic nature of water quality impacts associated with urban runoff, annual or seasonal loads are often of most concern in water quality studies. Annual loads should be evaluated using distributions of the annual mean concentrations (Marsalek, 1991), but, owing to the lack of long-term annual water quality records, constant mean EMC or SMC (*site mean concentration* as a flow-weighted mean EMC) are used in the estimation of loads (e.g. Chiew and McMahon, 1999; Mitchell, 2005; Mourad et al., 2005; Ellis and Mitchell, 2006; McLeod et al., 2006). For this reason, it is important to compare the measured annual concentrations with those determined based only on the EMCs. Figure 69 illustrates the SMCs for each catchment in Espoo together with the annual average concentrations (Section 3.1.5).

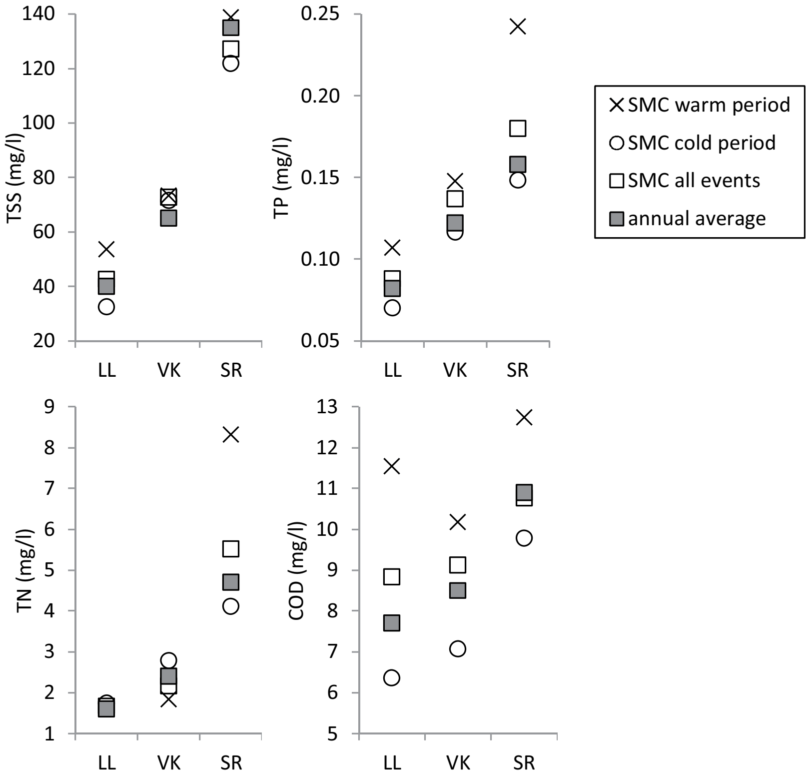


Figure 69. Site mean concentrations (SMC) as a flow-weighted average EMC of all events and of warm and cold period events, in comparison with average annual concentrations from Chapter 3.1.5 for the low-density LL catchment, the medium-density VK catchment and the developing SR catchment.

If the low-density LL catchment and the medium-density VK catchment are examined, the equality of the SMC and the long-term average depend on the magnitude of the seasonal variations. When large, significant seasonal differences are observed, the monitoring of a single season likely results in large errors in the long-term average. In Figure 69, this concerns most of the pollutants: TSS, TP and COD concentrations at LL and TP, TN and COD concentrations at VK. The seasonal SMCs differed from the annual average concentrations by 30-50% (warm period) and 15-19% (cold period) at LL. At VK, the corresponding percentages were 20-23% and 4-17%. If all of the events are combined (*SMC all events* in Figure 69), the errors are naturally smaller, 5-15%. In the case of TN at LL and TSS at VK, only small differences in the SMCs between the two periods exist in Figure 69 and, thus, the sampling of a single season does not cause such a large bias in the estimation of the annual average concentrations. However, because the EMCs do not take into account the baseflow between events, the TSS SMCs at VK were systematically 10-13% higher than the long-term average.

Previously, Modaresi et al. (2010), for instance, noted that using a constant EMC for both rainfall and snowmelt runoff is not a realistic assumption in load modelling, but they also observed a lack of seasonal values for several land use types in a city-scale load modelling study done in Luleå, Sweden. Also, Westerlund (2007) concluded, based on a study of road runoff quality in Luleå, that using separate pollutant concentrations for rainfall events and snowmelt events instead of a single concentration value would improve the classification of standard concentrations for road runoff given by the Swedish Road Administration. Based on the results from the study catchments in Espoo (Figure 69), the largest errors are associated with SMCs based only on the warm period rainfall events.

In Figure 69, some of the largest differences between SMCs and annual average concentrations were observed for the developing SR catchment: usually the warm period SMCs overestimate the annual average concentrations and cold period SMCs underestimate the annual average concentrations. The large differences between seasonal SMCs first seem surprising in light of the insignificant comparison results with the statistical tests presented in Section 5.1.9. However, the elevated warm period SMCs at SR are affected by events that produced both high runoff depths and EMCs during the construction works as opposed to the common dilution effect observed at the control catchments (Section 5.2.5). Thus, the seasonal differences in EMCs seem rather different at SR regardless of whether medians or SMCs are compared.

In the US, some studies have reported that the recent EMC data are lower than those obtained in earlier studies, such as the NURP study conducted in 1978-1983 (Smullen and Cave, 2003; Park et al., 2009), however, trends have not been observed in all studies or for all pollutants (Pitt and Maestre, 2005). The EMCs observed in the current study (Table 26 in Section 5.1.1) are lower than the standard values for pollutant concentrations (suburban areas) provided by Melanen (1980, 1982) separately for rainfall-runoff and snowmelt events for urban runoff calculations done in Finland (Table 1 in Section 1.3.1). Also, the COD_{Mn} concentrations for snowmelt provided by Laiho (1980) for two urban catchments were high (17 mg/l) in comparison with those in the present study (<10 mg/l). These results are consistent with the differences observed in Section 3.2.2, when the annual pollutant export and concentrations reported in the present study were compared with those reported by Melanen (1981). In Section 3.2.2, the main causes for the differences between the past and present studies were the different methods for calculating annual pollutant loads and monitoring, although changes in laboratory standards may have also affected the comparisons. However, changes in pollution sources over a period of three decades also may explain the improved water quality. Considering the recent results from the US, a similar need for updated water quality data for the purposes of planning and modelling exists in Finland because, together with the runoff coefficient, the EMC is a key variable in many land use-based urban runoff models (Park et al., 2009).

5.2.7 Sources of error

Uncertainties related to the experimental work and reported in Section 3.2.5 are also relevant from the viewpoint of the results discussed in Chapter 5. One of the uncertainties has to do with the change in the temporal monitoring resolution from ten to two minutes during the study period: the changes in the monitoring resolution are especially apparent in the analysis of the unit hydrographs in Section 5.1.3. Obviously, all of the data analysis would have benefitted from a more frequent monitoring interval already at the beginning of the study. Owing to the coarser monitoring interval at the beginning of the study, in addition to the exceedances of the flow monitoring capacity, especially at the medium-density VK catchment, the emphasis of the analysis lies on the determination of runoff volumes and the influencing factors and hydrological and water quality impacts of urbanization instead of the prediction of high-flow rates. At VK, the full pipe capacity was exceeded eight times, for which a flow rate equivalent to a water depth of 500 mm (342.6 l/s) was used to give an approximation of the event runoff volume. During these events, the event runoff volumes and event pollutant mass loads (EMLs) were underestimated; the event mean concentrations (EMCs), however, were probably overestimated.

Especially at the developing SR catchment, the number of events in the water quality analysis is small during the early years of monitoring, which is a result of data breaks and a smaller number of samples due to small runoff volumes. It should be noted that for the years 2001-2003, the monitoring programme was not particularly planned for an event-scale analysis, but, instead, for the determination of long-term pollutant loads (Kotola and Nurminen, 2003); thus, the use of composite samples covering runoff periods longer than just a single event reduced the number of events in the water quality analysis. For this reason, the long-term results presented in Sections 3.1.5-3.1.7 should be considered alongside the event-scale comparison. Also, based on the results presented in Section 5.2.5, more accurate information about the changes in the catchment characteristics and the ongoing construction activities would have been valuable in the analysis of the water quality at the construction site. At all catchments, the comparisons between minor and major rainfall events should be treated cautiously owing to the small number of major events during the study years.

In the analysis of the event data, nonparametric comparison tests were used to detect shifts in the mean ranks of the time series, even though this set of data may be affected by serial correlation, which violates the test assumptions about the independence of the data (Yue and Wang, 2002a). Yue and Wang (2002b) demonstrated that in contrast to a common conception, the Mann-Whitney U test is sensitive to many other properties of the tested time series, and they further recommended that it is advisable to conduct an analysis of both statistical and practical importance of the shifts or differences observed between the samples. For this reason, in this thesis statistical comparison tests were used to support the comparisons of the time series, but the results do not solely rely on statistical testing. The use of these tests for similar purposes as in the present study is not uncommon, as mentioned in Section 2.4. Thus, the assumption that event data are independent seems to be widely utilized and, hence, supports the choice of methods in this study. The serial correlation existing in the time series was reduced in the current study by the choice of events in the analyses: first, the water quality events comprised only a small part of all events, and second, runoff events represented only the events that produced measurable direct runoff. Hence, many storms were well separated in time. However, it should be noted that strong assumptions were made in order to conduct the data analyses.

The variety of methods used in this thesis also gave strength to the analysis. Goonetilleke et al. (2005) have argued that the common outcomes in urban water quality studies, which obtain pollutant loadings for different land use types, lack the ability to derive statistically significant results owing to their sole dependency on univariate methods. In the present study, an attempt was made to provide a large suite of methods in order to investigate the impacts of urbanization, including both long-term and event data analysis supported by visual, univariate and multivariate statistical methods.

6. Conclusions

This thesis investigated the impacts of urbanization on runoff generation and water quality in residential catchments in southern Finland. The study aimed to achieve a broad, comprehensive view of the urban runoff phenomena at a small catchment scale, and it includes an analysis of five-year runoff and water quality monitoring data and a snow monitoring study. Based on the results about the type and extent of the observed changes and the seasonal patterns in runoff generation and water quality, the results provide a hydrological basis for strategies aiming to reduce the adverse impacts of urbanization and maintain the predevelopment hydrology.

Based on the findings of this study, urbanization resulted in significant increases in runoff depth, volumetric runoff coefficients, long-term runoff ratios, peak flows, mean runoff intensities and reduced catchment lag during the warm period of the year (*the objectives 1a and 3a*). At the urban catchments, the highest peak flows occurred during rainfall events in summer and autumn (*1a*). Urbanization did not cause notable changes in total runoff generation during the cold period, but affected its temporal occurrence: the snowmelt period became separated into more numerous runoff events of a shorter duration and with smaller runoff volumes (*1a, 3a*). Earlier snowmelt and the increased contribution of the warm period to annual runoff generation also caused a shift towards an evenly distributed runoff pattern throughout the year. Urbanization had a pronounced impact on areal snow properties owing to the redistribution of urban snow (*2a*), which results in higher spatial and temporal variability in snow properties, particularly in the SWEs of ploughed snow (*2a*).

Urbanization caused the greatest changes in the runoff response during minor, frequently occurring rainfall events (*1a, 3a*). Additionally, urbanization reduced the event-to-event variations in the shape of the direct runoff hydrographs and the catchment lag (*3a*). The most important variables affecting the runoff response during rainfall events included the event rainfall depth, maximum rainfall intensity and catchment imperviousness (*3b*). In a local climate, antecedent conditions seemed to have only little practical relevance for the event runoff estimation. At the urban study catchments, a statistically significant change in the runoff response to rainfall occurred when event rainfall depths exceeded an approximate threshold of 17-20 mm (*3c*). Minor rainfall events produced runoff mainly from the effective impervious surfaces, but the largest events also produced runoff from the pervious surfaces. The runoff coefficients in Finnish stormwater design manuals at present are high in comparison to the observed coefficients for most rainfall events.

Urbanization increased the pollutant concentrations and export rates (*1b*). The study revealed significant seasonal variations in long-term pollutant concentrations; at the residential urban catchments, these variations depended on catchment imperviousness and the type of pollutant. On a seasonal scale, the average concentrations observed for summer and autumn exceed those of the cold period at the low-density urban catchment, but spring yielded the highest seasonal concentrations at the medium-density catchment. The distinct differences between catchments, especially in pollutant concentrations in spring, are explained by the results from the snow surveys: snow-free impervious areas decrease areal SWEs, but other urban sources increase pollutant accumulation in terms of snow per unit area (*2b*). At the low-density catchment, the larger proportion of untouched, cleaner snow diluted the pollutant concentrations in comparison to the medium-density catchment. During the cold period, however, enhanced runoff generation also increased pollutant export at a lower land use density. If only individual runoff events are considered, the mean event loads were significantly higher during the cold period than during the warm period at all of the studied catchments regardless of whether or not seasonal differences in EMCs were observed (*3d*). However, on a longer timescale, no single season was responsible for a notably higher average proportion of annual pollutant export, which emphasized the increased importance of the growing season for diffuse pollution in urban areas (*1b*).

In addition to seasonality, several other factors affected water quality during rainfall events. At the low- and medium-density residential catchments, the events with higher precipitation depths produced more diluted concentrations but larger pollutant loads than minor storms, and higher rainfall intensities increased both pollutant concentrations and event loads, but in particular the role of antecedent conditions depended on the site and pollutant in question (*3b*). Also, the snow quality observations provided information about the sources and the spatial distribution of pollutants within the catchment, which are not directly related to imperviousness: traffic load, type of snow (untouched/ploughed), type of street (street with/without vehicular traffic), the distance from the traffic (snow pile located directly along the vehicular road or behind an elevated pavement), other anthropogenic activities (road maintenance, pets) and airborne pollution (*2a*).

The study revealed that construction works have a profound impact on water quality depending on the ongoing construction activities, regardless of the catchment TIA, which masks the seasonal patterns observed in mature urban catchments (*1b, 3b, 3d*). The export peaks of sediments and associated pollutants occurred together with the periods of greatest soil disturbance, but a lag exists in the transport of TN, which can be explained by the release of nitrogen from the soil, pumping from the construction sites and additional discharges, such as wastewater discharges or explosives used during the construction works (*1b*). High EMCs were observed more frequently at the developing urban catchment compared with the developed residential urban catchments (*3d*).

The importance of urban runoff as a diffuse pollution source depended on the chosen water quality criteria and pollution control objectives (*1c*). If chronic, long-term concentrations are considered, a year-round reduction in nitrogen may be needed as well as in particle-bound pollutants, especially during spring and summer. The concentration criteria were exceeded during all of the construction phases (*1c, 3c*). The probability for the occurrence of acute water quality impacts increases during the warm period of the year in comparison to the cold period, as the catchments become more impervious, and during construction works (*3d*); however, this result is only based on the comparisons of the observed EMCs to the water quality criteria and not on an analysis of the actual receiving water impacts. Because of the lack of established concentration criteria for urban runoff, the large variation observed in concentrations and the combined influence of runoff volumes, the concentrations alone are not reliable indicators of pollution potential (*1c*). If the aim of urban runoff management is to minimize the adverse impacts of urbanization, then all of the studied urban land use types should be considered as pollution sources that require treatment based on the comparisons of annual export rates with rural land uses. More importantly, the greatest impacts of urbanization on receiving waters could result from the seasonal increases in pollutant export during the growing season, which cannot be evaluated based solely on the magnitudes of the annual pollutant export.

The concentrations of ploughed snow were high in comparison to the stormwater quality criteria (*2b*). The treatment of ploughed snow could have an especially significant impact on TP and TSS loads due to their abundance in snow, and because they will likely remain in a snowpack longer than more soluble pollutants (*2b*). The treatment of snow probably will not result in as large of a reduction in runoff loads as could be estimated based on the areal snow storage because the bulk of pollutants also originate outside snow storage sites (*2b*). However, the comparisons between snow and runoff measurements should be interpreted with caution because uncertainties are related to the spatial and temporal representativeness of snow observations owing to the large degree of heterogeneity observed at the urban sites.

A major finding of this study is that the changes in runoff generation resulting from urbanization were sometimes difficult to detect, they only persist during a limited period of time within a year and they are easily masked by other factors affecting runoff generation (*1a*). Based on the results, it is recommended that the impact of urbanization on runoff generation is best detected based on measures that quantify the maximum flow rates (monthly high-flow rates or event peak flow rates) or are expressed as a ratio of a runoff variable and another variable that is not changed by urbanization, such as volumetric runoff coefficients, mean runoff intensities (*3a*) or six-month warm period runoff ratios (*1a*). Simultaneous measurements from appropriate control catchments are essential (*1a*).

Of the studied pollutants, TSS, TP and TN were the most susceptible to urbanization. Differences in temporal behaviour were observed between TN and other, more particulate pollutants, which should be understood when designing monitoring studies (*1b*). The monitoring of a single season results in biased estimates for annual concentrations depending on the magnitude of the seasonal variations: in this study, the largest errors were observed with estimates that were based only on the warm period rainfall events (*3d*). At the developing catchments, monitoring should be representative of different construction phases and catchment conditions (*1b*, *3d*). Although the monitoring of snow requires less intensive monitoring than for runoff, the pollutant export cannot be estimated solely based on snow measurements (*2b*).

The findings of this study have a number of important implications for future practice, e.g. the need for water quality treatment was discussed from different perspectives. One objective of sustainable urban runoff management is to prevent and mitigate the changes that occur as a result of urbanization. The results showed that the greatest changes in the local climate occur in the runoff response to frequently occurring rainfall events during the warm period of the year and in the pollutant accumulation and areal distribution of snow. The frequent, minor storms were also related to the highest pollutant concentrations. Hence, infiltration and treatment of common minor storms seems to be a promising approach for maintaining the predevelopment hydrology and reducing urban pollutant loads. The thesis proposes ways to determine runoff coefficients for different management purposes. In the cold period, the focus should be aimed at reducing the wintertime pollution sources and the appropriate storage and treatment of snow. Finally, construction sites should be included in controlled activities in order to protect the environment and water resources, e.g. by means of legislation, environmental permits and stormwater management guidance.

The originality of the thesis arises from the lack of documented local monitoring data and comprehensive catchment-scale studies on seasonal urban runoff generation and water quality in cold climate conditions. The study established benchmark data for conditions characteristic of boreal region in Fennoscandinavia. The experimental setup of the thesis provides results for the timing and magnitude of the changes caused by urbanization, which are more straightforward to interpret and in-depth than those obtained in studies of urbanization over a period of several decades at large catchments or only by conducting catchment comparisons. To the best of the author's knowledge, studies similar to the current thesis are rare. Also, studies on the impact of different construction activities, especially in cold climates, are scarce. The findings of the study improve our understanding of the types of changes observed in cold period runoff, especially considering the fact that previous studies present conflicting results. The study also revealed new aspects about the changes occurring in the gamma unit hydrographs resulting from urbanization. The results revealed significant seasonal concentration patterns, which have not been documented in previous studies. The author was unable to find studies from similar climates that would document the precipitation thresholds, the division of minor and major rainfall events and varying runoff coefficients for further management purposes. The snow study confirms the previous findings about the impacts of urbanization on point snow properties and provides additional evidence about urban snow properties and treatment needs by extrapolating the results and applying them to a wider catchment perspective. The division of ploughed snow into two groups (streets with/without vehicular traffic) provided new insights into snow pollution, as previous studies have mainly focused on the impact of traffic loads and wintertime maintenance on snow quality.

The results of this thesis are limited to the land use types and pollutants studied. The limitations related to the gathered data include the less frequent monitoring resolution at the beginning of the monitoring study, the incomplete data sets for the cold period due to freezing problems, the accuracy of the peak flow measurements, the spatial representativeness of the point snow measurements and the lack of temporal representativeness of event water quality data during the different construction phases. The study would have also benefitted from more detailed documentation of the catchment conditions during the construction works. Uncertainties related to some statistical methods used in the study have been openly addressed in the discussion.

In the future, the seasonal aspects and especially the role of cold seasons in urban runoff management still remain an important research topic. Especially from the point of view of pollution mitigation and the detention of larger runoff volumes within the urban catchment, the cold period events may be important design events. The data presented in this thesis can be further extended e.g. to physically based modelling of runoff generation and to the examination of water quality changes within individual events. There is a great need to gather and update the basic information about urban runoff characteristics, such as EMCs for a broader range of pollutants, for the purposes of planning and modelling. The research so far in Finland also lacks data from densely build areas (TIA > 60%) and from construction sites and urbanizing catchments. Based on the results of this study, it is hypothesized that incorporating seasonal information about, for example, pollutant concentrations would improve the estimation of pollutant loads in local climates. The development of the catchment-scale assessment and monitoring of urban snow could be useful when studying the urban pollutant sources and pollutant transport within a catchment and the management possibilities for urban snow. In the future, it is important that researchers make the effort to apply their results to the practical context of stormwater management, as science-based information is urgently needed to aid in the shift required for successful, sustainable urban drainage systems.

References

Arnell, V. 1982. Estimating runoff volumes from urban areas. Water Resources Bulletin, 18(3): 383-387.

Arnold, C.L. Jr, Gibbons, C.J. 1996. Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association. 62(2):243-259.

Asadian, Y., Weiler, M. 2009. A new approach in measuring rainfall interception by urban trees in Coastal British Columbia. Water Quality Research Journal of Canada, 44(1): 16-25.

Ashley, R., Jones, J., Ramella, S., Schofield, D., Munden, R., Zabatis, K., Rafelt, A., Stephenson, A., Pallett, I. 2007. Delivering more effective stormwater management in the UK and Europe – lessons from the Clean Water Act in America. In: Proc. Novatech 2007, pp. 1697-1704.

Association of Finnish Local and Regional Authorities. 2012. Stormwater manual (in Finnish). Helsinki. 298 p. ISBN 978-952-213-896-5.

Atasoy, M., Palmquist, R.B., Phaneuf, D.J. 2006. Estimating the effects of urban residential development on water quality using microdata. Journal of Environmental Management, 79: 399-408.

Bannerman, R., Baun, K., Bohn, M., Hughes, P.E., Graczyk, D.A. 1983. Evaluation of urban nonpoint source pollution in Milwaukee County, Wisconsin: Volume 1: Urban stormwater characteristics, sources, and pollutant management by street sweeping. Wisconsin Department of Natural Resources, Madison, USA. 206 pp.

Bartošová, A., Novotny, V. 1999. Model of spring runoff quantity and quality for urban watersheds. Water Science and Technology, 39(12): 249-256.

Becciu, G., Paoletti, A. 1997. Random characteristics of runoff coefficient in urban catchments. Water Science and Technology. 36(8-9): 39-44.

Beck, H.J., Birch, G.F. 2012. Metals, nutrients and total suspended solids discharged during different flow conditions in highly urbanized catchments. Environmental Monitoring and Assessment, 184: 637-653.

Bedan, E.S., Clausen, J.C. 2009. Stormwater runoff quality and quantity from traditional and low impact development watersheds. Journal of the American Water Resources Association, 45(4): 998-1008.

Beighley, R.E., Moglen, G.E. 2002. Trend assessment in rainfall-runoff behavior in urbanizing watersheds. Journal of Hydrologic Engineering, 7(1): 27-34.

Bengtsson, L. 1984. Modeling snowmelt induced runoff with short time resolution. In: Proc. 3rd Int. Conf. Urban Storm Drainage, Vol. 1, Analysis and design of stormwater systems. Pp. 305-314. ISBN 91-7032-128-0.

Bengtsson, L., Semádeni-Davies, A. 2000. [Chapter 1:] Theoretical background. In: Maksimovic, C. (Ed.) et al. Urban drainage in specific climates, Vol 3: Urban drainage in cold climates. IHP-V, Technical documents in hydrology, No. 40, Vol. 2, UNESCO, Paris. Pp. 23-40.

Bengtsson, L., Westerström, G. 1992. Urban snowmelt and runoff in northern Sweden. Hydrological Sciences, 37:263-275.

Blume, T., Zehe, E., Bronstert, A. 2007. Rainfall-runoff response, event-based runoff coefficients and hydrograph separation. Hydrological Sciences Journal, 52(5): 843-862.

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

Boyd, M.J., Bufill, M.C., Knee, R.M. 1993. Pervious and impervious runoff in urban catchments. Hydrological Sciences Journal. 38(6): 463-478.

Boyd, M.J., Bufill, M.C., Knee, R.M. 1994. Predicting pervious and impervious storm runoff from urban drainage basins. Hydrological Sciences Journal. 39(4): 321-332.

Brabec, E., Schulte, S. Richards, P.L. 2002. Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. Journal of Planning Literature, 16(4): 499-514.

Brezonik, P.L., Stadelmann, T.H. 2002. Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota, USA. Water Research, 36: 1743-1757.

Burian, S.J., Nix, S.J., Durrans, S.R., Pitt, R.E., Fan, C.-Y., Field, R. 1999. Historical development of wet-weather flow management. Journal of Water Resources Planning and Management, 125(1): 3-13.

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

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., Kendall, C. 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. Journal of Hydrology, 311: 266-281.

Burton, G.A., Pitt, R.E. 2002. Stormwater effects handbook: A toolbox for watershed managers, scientists, and engineers. CRC Press. 929 p. ISBN 0-87371-924-7.

Butler, D., Davies, J.W. 2004. Urban drainage. 2nd ed. Spon Press, London. ISBN 0-415-30607-8.

Buttle, J.M. 1990. Effects of suburbanization upon snowmelt runoff. Hydrological Sciences Journal, 35: 285-302.

Buttle, J.M., Xu, F. 1988. Snowmelt runoff in suburban environments. Nordic Hydrology, 19: 19-40.

Bäckström, M., Nilsson, U., Håkansson, K., Allard, B., Karlsson, S. 2003. Speciation of heavy metals in road runoff and roadside total deposition. Water, Air, and Soil Pollution, 147: 343-366.

Campbell, N., D'Arcy, B. Frost, A. Novotny, V., Sansom, A. 2004. Diffuse pollution: An introduction to the problems and solutions. IWA Publishing, London. ISBN 1 900222 53 1. 322 s.

Campbell Scientific Ltd. 1998. ARG100 Tipping bucket raingauge: User guide. Campbell Scientific Ltd, Shepshed, Leicestershire, UK.

Changnon, D., Fox, D., Bork, S. 1996. Differences in warm-season, rainstorm-generated stormflows for northeastern Illinois urbanized basins. Water Resources Bulletin, 32(6): 1307-1317.

Charbeneau, R.J., Barrett, M.E. 1998. Evaluation methods for estimating stormwater pollutant loads. Water Environment Research, 70(7): 1295-1302.

Cheng, S.-j., Wang, R.-y. 2002. An approach for evaluating the hydrological effects of urbanization and its application. Hydrological Processes, 16: 1403-1418.

Cheng, S.-j., Lee, C.-f., Lee, J.-h. 2010. Effects of urbanization factors on model parameters. Water Resources Management, 24: 775-794.

Chiew, F.H.S., Duncan, H.P., Smith, W. 1997. Modelling pollutant buildup and washoff: Keep it simple. In: Smaill, A. (Ed.) Proc. 24th Int. Hydrology and Water Resources Symposium, Auckland, New Zealand. pp. 131-136.

Connecticut Stormwater Quality Manual, 2004. [Chapter 7:] Hydrologic sizing criteria for stormwater treatment practices. Vol. 2. pp. 1-13. Available at: http://www.ct.gov/deep /cwp/view. asp?a=2721&q=325704.

Cowen, W.F. & Lee, G.F. 1976. Phosphorus availability in particulate materials transported by urban runoff. Journal Water Pollution Control Federation, 48(3): 580-591.

Chiew, F.H.S., McMahon, T.A. 1999. Modelling runoff and diffuse pollution loads in urban areas. Water Science and Technology. 39(12): 241-248.

Daniel, T.C., McGuire P.E., Stoffel, D. & Miller, B. 1979. Sediment and nutrient yield from residential construction sites. Journal of Environment Quality, 8(3): 304-308.

Dietz, M.E., Clausen, J.C. 2008. Stormwater runoff and export changes with development in a traditional and low impact subdivision. Journal of Environmental Management, 87: 560-566.

Deletic, A. 1998. The first flush load of urban surface runoff. Water Research, 32(8): 2462-2470.

Dougherty, M. 2004. Quantifying long-term hydrologic and NPS pollutant response in an urbanizing watershed. Doctoral thesis, Virginia Polytechnic Institute and State University. 186 p.

Dougherty, M., Dymond, R.L., Grizzard, T.J., Godrej, A.N., Zipper, C.E. & Randolph, J. 2006a. Quantifying long-term NPS pollutant flux in an urbanizing basin. Journal of Environmental Engineering, April 2006, pp. 547-554.

Dougherty, M., Dymond, R.L., Grizzard, T.J., Godrej, A.N., Zipper, C.E., Randolph, J. & Anderson-Cook, C.M. 2006b. Empirical modeling of hydrologic and NPS pollutant flux in an urbanizing basin. Journal of American Water Resources Association, October 2006, p. 1405-1419.

Dougherty, M., Dymond, R.L., Grizzard, T.J., Godrej, A.N., Zipper, C.E. & Randolph, J. 2007. Quantifying long-term hydrologic response in an urbanizing basin. Journal of Hydrologic Engineering, January/February 2007, pp. 33-41.

Driver, N.E., Troutman, B.M. 1989. Regression models for estimating urban storm-runoff quality and quantity in the United States. Journal of Hydrology, 109: 221-236.

Duan, Q., Sorooshian, S., Gupta, v. 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resources Research, 28(4): 1015-1031.

Ellis, J.B, Mitchell, G. 2006. Urban diffuse pollution: key data information approaches for the Water Framework Directive. Water and Environment Journal, 20: 19-26.

Elvidge, C.D., Tuttle, B.T., Sutton, P.C., Baugh, K.E., Howard, A.T., Milesi, C., Bhaduri, B.L., Nemani, R. 2007. Global distribution and density of constructed impervious surfaces. Sensors, 7: 1962-1979.

Engelhard, C., De Toffol, S., Lek, I., Rauch, W., Dallinger, R. 2007. Environmental impacts of urban snow management – the alpine case study of Innsbruck. Science of the Total Environment, 382: 286-294.

Endreny, T.A., Hassett, J.M., Wolosoff, S.E. 2005. Robustness of pollutant loading estimators for sample size reduction in a suburban watershed. International Journal of River Basin Management, 3(1): 53-66.

Ferguson, B.K., Suckling, P.W. 1990. Changing rainfall-runoff relationships in the urbanizing Peachtree Creek watershed, Atlanta, Georgia. Water Resources Bulletin, 26(2): 313-322.

Field, R., Sullivan, D. 2003. [Chapter 1:] Management of wet weather flow in the urban watershed. In: Field, R., Sullivan, D. (Eds.) Wet-weather flow in the urban watershed: Technology and management. CRC Press LLC, Boca Raton, Florida, USA. ISBN 1-56676-916-7. pp. 1-41.

Førland, E.J., Allerup, P., Dahlström, B., Elomaa, E., Jónsson, T., Madsen, H., Perälä, J., Rissanen, P., Vedin, H., Vejen, F. 1996. Manual for operational correction of Nordic precipitation data. Nordic working group on precipitation. Norwegian Meteorological Institute, Oslo, Norway. 65 p.

Francey, M., Deletic, A., Duncan, H.P., Fletcher, T.D. 2004. An advance in modelling pollutant loads in urban runoff. In: Proc. Conf. Urban Drainage Modelling, Dresden, Germany.

Goldshleger, N., Shoshany, M., Karnibad, L., Arbel, S., Getker, M. 2009. Generalising relationships between runoff-rainfall coefficients and impervious areas: an integration of data from case studies in Israel with data sets from Australia and the USA. Urban Water Journal, 6(3): 201-208.

Goonetilleke, A., Thomas, E., Ginn, S., Gilbert, D. 2005. Understanding the role of land use in urban stormwater quality management. Journal of Environmental Management, 74: 31-42.

Gottschalk, L., Jensen, J.L., Lundquist, D., Solantie, R., Tollan, A. 1979. Hydrologic regions in the Nordic countries. Nordic Hydrology, 10: 273-286.

Granlund, K., Räike, A., Ekholm, P., Rankinen, K., Rekolainen, S. 2005. Assessment of water protection targets for agricultural nutrient loading in Finland. Journal of Hydrology, 304: 251-260.

Groffman, P.M., Law, N.L., Belt, K.T., Band, L.E., Fisher, G.T. 2004. Nitrogen fluxes and retention in urban watershed ecosystems. Ecosystems, 7: 393-403.

Grum, M., Aalderink, R.H., Lijklema, L., Spliid, H. 1997. The underlying structure of systematic variations in the event mean concentrations of pollutants in urban runoff. Water Science and Technology, 36(8-9): 135-140.

Gürer, I. 1975. Hydrometeorological and water balance studies in Finland. Doctoral thesis, Research papers 49, Helsinki University of Technology. 164 p.

Hall, M.J., Ellis, J.B., Brizio, M.G. 1990. On the statistical distributions of event mean concentrations of pollutants in stormwater runoff. In: Y. Iwasa, T. Suieshi (Eds.). Proc. 5th Int. Conf. Urban Storm Drainage, Osaka, Japan, Vol. 1. pp. 317-324.

Hallberg, M. 2007. Treatment conditions for the removal of contaminants from road runoff. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm, Sweden.

Hallberg, M., Renman, G., Lundbom, T. 2007. Seasonal variations of ten metals in highway runoff and their partition between dissolved and particulate matter. Water, Air, and Soil Pollution, 181:183-191.

Harbor, J. 1999. Engineering geomorphology at the cutting edge of land disturbance: erosion and sediment control on construction sites. Geomorphology, 31: 247-263.

Harremoës, P. 1988. Stochastic models for estimation of extreme pollution from urban runoff. Water Research, 22(8): 1017-1026.

Hatt, B.E., Fletcher, T.D., Walsh, C.J., Taylor, S.L. 2004. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. Environmental Management, 34(1): 112-124.

Hautala, E.-L., Rekilä, R., Tarhanen, J., Ruuskanen, J. 1995. Deposition of motor vehicle emissions and winter maintenance along roadside assessed by snow analyses. Environmental Pollution, 87: 45-49.

Helmreich, B., Hilliges, R., Schriewer, A., Horn, H. 2010. Runoff pollutants of a highly trafficked urban road –Correlation analysis and seasonal influences. Chemosphere, 80: 991-997.

Ho, C.L.I., Valeo, C. 2005. Observations of urban snow properties in Calgary, Canada. Hydrological Processes, 19: 459-476.

Hood, M., Clausen, J.C., Warner, G.S. 2007. Comparison of stormwater lag times for low impact and traditional residential development. Journal of the American Water Resources Association, 43(4): 1036-1046.

Hrachowitz, M., Soulsby, C., Tetzlaff, D., Malcolm, I.A., Schoups, G. 2010. Gamma distribution models for transit time estimation in catchments: physical interpretation of parameters and implications for time-variant transit time assessment. Water Resources Research, 46, W10536.

HSY, Helsinki Region Environmental Services Authority. 2011. [website:] Water management networks. Updated 15.12.2011. Available at: http://www.hsy.fi/en/waterservices/

Huang, H.-j., Cheng, S.-j., Wen, J.-c., Lee, J.-h. 2008. Effect of growing imperviousness on hydrograph parameters and peak discharge. Hydrological Processes, 22: 2075-2085.

Hur, J., Schlautman, M.A., Templeton, S.R., Karanfil, T., Post, C.J., Smink, J.A., Song, H., Goddard, M.A., Klaine, S.J., Hayes, J.C. 2008. Does current management of stormwater runoff adequately protect water resources in developing catchments? Journal of Soil and Water Conservation, 63(2): 77-90.

Hyvärinen, V. 1986. [Chapter 8.7:] Virtaamien arviointi (in Finnish). In: Mustonen, S. (Ed.) Sovellettu hydrologia. Vesiyhdistys r.y. pp. 205-225.

Jacks, G., Norrström, A.-C. 2004. Hydrochemistry and hydrology of forest riparian wetlands. Forest Ecology and Management, 196: 187-197.

Järvinen, J. 2007. [Chapter 4:] Runoff. In: Korhonen, J. (Ed.) 2007. Hydrological Yearbook 2001-2005. The Finnish Environment 44/2007, Finnish Environment Institute, Helsinki, Finland. ISBN 978-952-11-2930-8 (PDF). pp. 117-152.

Katko, T.S., Juuti, P.S. 2005. Finland. In: Juuti, P.S., Katko, T.S. (Eds.) Water, time and European cities: History matters for the futures. pp. 60-72.

Katko. T.S., Juuti, P.S., Pietilä, P.E. 2006. Key long-term strategic decisions in water and sanitation services management in Finland, 1860-2003. Boreal Environment Research, 11: 389-400.

Kaushal, S.S., Groffman, P.M., Band, L.E., Shields, C.A., Morgan, R.P., Palmer, M.A., Belt, K.T., Swan, C.M., Findlay, S.E.G., Fisher, G.T. 2008. Interaction between urbanization and climate variability amplifies watershed nitrate export in Maryland. Environmental Science & Technology, 42(16): 5872-5878.

Kayhanian, M., Suverkropp, C., Ruby, A., Tsay, K. 2007. Characterization and prediction of highway runoff constituent event mean concentration. Journal of Environmental Management 85: 279-295.

Koivusalo, H. 2002. Process-oriented investigation of snow accumulation, snowmelt and runoff generation in forested sites in Finland. Doctoral dissertation. Helsinki University of Technology, Water Resources Publications, TKK-VTR-6. 88 p. ISBN 951-22-6214-2.

Koivusalo, H., Kokkonen, T. 2002. Snow processes in a forest clearing and in a coniferous forest. Journal of Hydrology, 262: 145-164.

Kokkonen, T., Koivusalo, H., Karvonen, T., Croke, B., Jakeman, A. 2004. Exploring streamflow response to effective rainfall across event magnitude scale. Hydrological Processes, 18: 1467-1486.

Kortelainen, P., Mattsson, T., Finér, L., Ahtiainen, M., Saukkonen, S., Sallantaus, T. 2006. Controls on the export of C, N, P and Fe from undisturbed boreal catchments, Finland. Aquatic Sciences, 68: 453-468.

Kotola, J., Nurminen, J. 2003. Urban hydrology – runoff and pollution load in urban areas, Part 2: experimental study (in Finnish, abstract in English). Helsinki University of Technology Water Resources Publications 8. ISBN 951-22-6497-8. 203 p.

Krejci, V., Schilling. W. 1989. Urban hydrologists need meteorologists! In: Sevruk, B. (Ed.) Proc. WMO/IAHS/ETH Workshop, St. Moritz, Switzerland. pp. 371-376.

Kuichling, E. 1889. The relationship between the rainfall and the dischargeof sewers in populous districts. Trans. Am. Soc. Civ. Eng., 20: 1-56.

Kundzewicz, Z., Robson, A.J. 2004. Change detection in hydrological records – a review of the methodology. Hydrological Sciences Journal, 49(1): 7-19.

Kuusisto, E. 1980. On the intensity of rainfall in Finland. Aqua Fennica, 10: 3-11.

Kuusisto, E. 1986a. [Chapter 3:] Sadanta (in Finnish). In: Mustonen, S. (Ed.), Sovellettu hydrologia. Vesiyhdistys r.y. Helsinki.

Kuusisto, E. 1986b. [Chapter 4:] Lumipeite ja jääilmiöt (in Finnish). Mustonen, S. (Ed.), Sovellettu hydrologia. Vesiyhdistys r.y. Helsinki.

Laiho, L. 1980. Quality of melting water in urban areas (in Finnish, abstract in English). MSc thesis, Helsinki University of Technology. 91 p.

Landau, S., Everitt, B. 2004. A handbook of statistical analyses using SPSS. Chapman & Hall/CRC Press LLC. 354 p.

Laurén. A., Finér, L., Koivusalo, H., Kokkonen, T., Karvonen, T., Kellomäki, S., Mannerkoski, H., Ahtiainen, M. 2005. Water and nitrogen processes along a typical water flowpath and streamwater exports from from a forested catchment and changes after clear-cutting: a modelling study. Hydrology and Earth System Sciences, 9(6): 657-674.

LeBoutillier, D.W., Kells, J.A., Putz, G.J. 2000. Prediction of pollutant load in stormwater runoff from an urban residential area. Canadian Water Resources Journal, 25(4): 343-359.

Lee, J.G., Heaney, J.P. 2003. Estimation of urban imperviousness and its impacts on storm water systems. Journal of Water Resources Planning and Management, 129(5): 419-426.

Leopold, L.B. 1968. Hydrology of urban land planning – A guidebook on the hydrologic effects of urban land use. Geological Survey Circular, 554. U.S. Department of the Interior, Washington, USA.

Line, D.E., White, N.M. 2007. Effects of development on runoff and pollutant export. Water Environment Research, 79(2): 185-190.

Line, D.E., White, N.M., Osmond, D.L., Jennings, G.D. & Mojonnier, C.B. 2002. Pollutant export from various land uses in the Upper Neuse River Basin. Water Environment Research, 74(1): 100-108.

Liscum, F. 2001. Effetcs of urban development on stormwater runoff characteristics for the Houston, Texas, metropolitan area. U.S. Geological Survey, Water-Resources Investigation Report 01-4071. 35 p.

Liu, A. 2011. Influence of rainfall and catchment characteristics on urban stormwater quality. Doctoral thesis. Queensland University of Technology, 271 p.

Lloyd-Davies, D.E. 1906. The elimination of storm water from sewerage systems. Proc. Inst. Civ. Eng., London. 164: 41-67.

Maestre, A., Pitt, R., Durrans, S.R., Chakraborti, S. 2005. Stormwater quality descriptions using the three parameter lognormal distribution. In: James, W., Irvine, K.N., McBean, E.A., Pitt, R.E. (Eds.) Effective Modeling of Urban Water Systems Conference Proceedings, Monograph 13. CHI, Guelph, Ontario. pp. 247-274.

Maksimović, Č. 1996. Part 3: Measurements of water quantity in urban areas. In: WMO. Rain and floods in Our Cities: Gauging the problem. Maksimović, Č. (Ed.) World Meteorological Organization, Geneva. Technical Reports in Hydrology and Water Resources No. 53 (WMO/TD-No. 741), pp. 95-144.

Maksimović, Č. 2000. General overview of urban drainage principles and practice. In: Sægrov, S., Milina, J., Thorolfsson, S. (Eds.) Urban drainage in specific climates, Vol. 2: Urban drainage in cold climates. Paris, UNESCO. IHP-VI, Technical documents in Hydrology, 40(2): 1-21.

Mallin, M.A., Johnson, V.L., Ensign, S.H. 2009. Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. Environmental Monitoring and Assessment, 159: 475-491.

Malmqvist, P.-A. 1983. Urban stormwater pollutant sources: An analysis of inflows and outflows of nitrogen, phosphorus, lead, zinc, and copper in urban areas. Doctoral thesis, Chalmers University of Technology. ISBN 91-7032-106-X.

Maniquiz, M.C., Lee, S., Lee, E., Kong, D.-S., Kim, L.-H. 2009. Unit soil loss rate from various construction sites during a storm. Water Science and Technology, 59(11): 2187-2196.

Marsalek, J. 1973. Instrumentation for field studies of urban runoff. Research Program for the Abatement of Municipal Pollution under the Provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. Ontario Ministry of the Environment. Project 73-3-12.

Marsalek, J. 1990. Evaluation of pollutant loads from urban nonpoint sources. Water Science and Technology 22(10/11):23-30.

Marsalek, J. 1991. Pollutant loads in urban stormwater: review of methods for planning level estimates. Water Resources Bulletin, 27(2): 283-291.

Marsalek, J., Oberts, G., Exall, K., Viklander, M. 2003. Review of operation of urban drainage systems in cold weather: water quality considerations. Water Science and Technology, 48(9):11-20.

Marsalek, J., Oberts, G., Viklander, M. 2000. [Chapter 4:] Urban water quality issues. In: Maksimovic, C. (Ed.) et al. Urban drainage in specific climates, Vol 3: Urban drainage in cold climates. IHP-V, Technical documents in hydrology, No. 40, Vol. 2, UNESCO, Paris. pp. 97-117.

Matheussen, M.V. 2004. Effects of anthropogenic activities on snow distribution, and melt in an urban environment. Doctoral thesis. Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway.

Mattsson, T., Finér, L., Kenttämies, K., Ahtiainen, M., Haapanen, M., Lepistö, A. 2006. Avohakkuun vaikutus fosforin, typen ja kiintoaineen huuhtoumiin; raportti VALU-tutkimushankkeen ja Siuntion Rudbäckin alueiden tutkimuksista (in Finnish). In: Kenttämies, K., Mattsson, T. (Eds.) 2006. Metsätalouden vesistökuormitus. MESUVE-projektin loppuraportti. Suomen ympäristö 816. ISBN 952-11-2170-X.

Mattsson, T., Finér, L., Kortelainen, P., Sallantaus, T. 2003. Brook water quality and background leaching from unmanaged forested catchments in Finland. Water, Air, and Soil Pollution, 147: 275-297.

Mays, L.W. 2001. [Chapter 1.1:] Historical perspectives of storm drainage. In: Mays, L.W. (ed.) Stormwater collection systems design handbook. McGraw-Hill. ISBN 0-07-135471-9. pp. 1.1-1.14.

McLeod, S.M., Kells, J.A., Putz, G.J. 2006. Urban runoff quality characterization and load estimation in Saskatoon, Canada. Journal of Environmental Engineering, 132(11): 1470-1481.

Melanen, M. 1980. Quality of runoff in the Finnish urban areas (in Finnish, summary in English). Tiedotus 197. Vesihallitus, National Board of Waters, Helsinki, Finland. ISBN 951-46-4971-0. 138 p.

Melanen, M. 1981. Quality of runoff water in urban areas. Publications of the Water Research Institute 42. National Board of Waters, Helsinki, Finland. ISBN 951-46-6066-8. pp. 123-188.

Melanen, M. 1982. Valtakunnallisen hulevesitutkimuksen tulokset. Vesitalous, 3/1982. S. 1-20.

Melanen, M., Laukkanen, R. 1980. Urban storm runoff quality and its dependence on some rainfall and catchment characteristics. Publications of the Water Research Institute, 38, National Board of Waters, Helsinki, Finland. ISBN 951-46-5306-8. pp. 29-40.

Melanen, M., Laukkanen, R. 1981. Quantity of storm runoff in urban areas. Publications of the Water Research Institute 42. National Board of Waters, Helsinki, Finland. ISBN 951-46-6066-8. pp. 3-39.

Metsäranta, N., Kotola, J., Nurminen, J. 2005. Effects of urbanization on runoff water quantity and quality: Experiences from test catchments in Southern Finland. International Journal of River Basin Management, 3(3): 229-234.

Mitchell, G. 2005. Mapping hazard from urban non-point pollution: a screening model to support sustainable urban drainage planning. Journal of Environmental Management, 74: 1-9.

Michell, V.G., Mein, R.G., McMahon, T.A. 2001. Modelling the urban water cycle. Environmental Modelling & Software, 16(7):615-629.

Minnesota Stormwater Manual, 2008. Version 2. Minnesota Pollution Control Agency, St. Paul, Minnesota, USA. Available at: http://www.pca.state.mn.us.

Modaresi, R., Westerlund, C., Viklander, M. 2010. Estimation of pollutant loads transported by runoff by using a GIS model. Case study: Luleå city centre. In: Proc. Novatech 2010, Lyon, France.

Mourad, M., Bertrand-Krajewski, J.-L. & Chebbo, G. 2005. Sensitivity to experimental data of pollutant site mean concentration in stormwater runoff. Water Science and Technology, 51(2): 155-162.

Mulvaney, T.J. 1850. On the use of self-registering rain and flood gauges in making observations on the relations of rainfall and flood discharges in a given catchment. Trans., Inst. Civ., Eng. Ireland, 4: 18-31.

Mustonen, S. 1973. Hydrologia (in Finnish). Vesirakennus RIL 92, Helsinki. pp. 9-73.

Nash, J.E. 1957. The form of instantaneous unit hydrograph. IAHS Publication 45. International Association of Scientific Hydrology, Wallingford. p. 114-121.

Nelson, J. 1996. Characterizing erosion processes and sediment yields on construction sites. MSc thesis. Department of Civil and Environmental Engineering, University of Alabama at Birmingham. 94 p.

Nelson, E. J., Booth, D.B. 2002. Sediment sources in an urbanizing, mixed land-use watershed. Journal of Hydrology, 264: 51-68.

Nie, L., Lindholm, O.G., Åstebøl, S.O., Sægrov, S., Thorolfsson, S. 2011. Integrated urban stormwater management in Norway – Best Management Practices (BMPs) in cold climate. In: Proc. 12th Int. Conf. Urban Drainage, Porto Alegre, Brazil.

Niemczynowicz, J. 1996. Part 1: Rainfall measurement, processing and application in urban hydrology. In: WMO. Rain and floods in Our Cities: Gauging the problem. Maksimović, Č. (Ed.) World Meteorological Organization, Geneva. Technical Reports in Hydrology and Water Resources No. 53 (WMO/TD-No. 741), pp. 3-78.

Niemi, J., Heinonen, P. (Eds.) 2003. Environmental monitoring in Finland 2003 – 2005 (in Finnish, summary in English). The Finnish Environment 616, Finnish Environment Institute, Helsinki.

Novotny, V. 1992. Unit pollutant loads – their fit in abatement strategies. Water Environment & Technology, 4(1): 40-43.

Novotny, V. 2003. Water quality: diffuse pollution and watershed management. John Wiley & Sons, Inc., New York, USA. 864 p. ISBN 0-471-39633-8.

Novotny, V., Chesters, G. 1981. Handbook of nonpoint source pollution: Sources and management. Van Nostrand Reinhold, New York, USA. 555 s. ISBN 0-442-22563-6.

Oberts, G. 1982. Water resources management: Nonpoint source pollution technical report. Metropolitan Council, St. Paul, Minnesota. Publication No. 10-82-016. 253 p.

Oberts, G. 1990. Design considerations for management of urban runoff in wintry conditions. In: Proc. Urban hydrology under wintry conditions, Narvik, Norway. p. 1-23.

Oberts, G. 1994. Influence of snowmelt dynamics on stormwater runoff quality. Watershed Protection Techniques, 1(2): 55-61.

Oberts, G.L., Marsalek, J., Viklander, M. 2000. Review of water quality impacts of winter operation of urban drainage. Water Quality Research Journal of Canada, 35(4):781-808.

Overton, D.E., Meadows, M.E. 1976. Stormwater modeling. Academic Press, New York, USA. 358 s. ISBN 0-12-531550-3.

Park, M.-H., Swamikannu, X. Stenstrom, M.K. 2009. Accuracy and precision of the volume-concentration method for urban stormwater modeling. Water Research, 43: 2773-2786.

Pejman, A.H., Nabi Bidhendi, G.R., Karbassi, A.R., Mehrdadi, N., Esmaeili Bidhendi, M. 2009. Evaluation of spatial and seasonal variations in surface water quality using multivariate statistical techniques. International Journal of Environmental Science and Technology, 6(3): 467-476.

Phillips R., Clausen J., Alexopoulos J., Morton B., Zaremba S. and Cote M. (2003). BMP research in a low-impact development environment: The Jordan Cove Project. Stormwater, 4(1).

Pitt, R. 1987. Small storm urban flow and particulate washoff contributions to outfall discharges. Doctoral thesis, University of Wisconsin-Madison. 514 p.

Pitt, R. 1999. Small storm hydrology and why it is important for the design of stormwater control practices. In: James. W. (Ed). Advances in modeling and the management of stormwater impacts, Vol. 7. Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press.

Pitt, R., Clark, S. 2003. [Chapter 5:] Emerging stormwater controls for critical source areas. In: Field, R., Sullivan, D. 2003. Wet-weather flow in the urban watershed: Technology and management. CRC Press LLC. p. 103-139. ISBN 1-56676-916-7.

Pitt, R., Maestre, A. 2005. Stormwater quality as described in the National Stormwater Quality Database (NSQD). Proc. 10th Int. Conf. Urban Drainage, Copenhagen, Denmark.

Pitt, R., Clark, S., Lake, D. 2007. Construction site erosion and sediment controls: Planning, design and performance. DEStech Publications Inc, Lancaster, Pennsylvania, USA. 381 p. ISBN 1-932078-38-X.

Pitt R., Clark S., Parmer, K., Field R. 1996. Groundwater Contamination from Stormwater Infiltration. Ann Arbor Press, USA. 219 p. ISBN 1-57504-015-8

Pitt, R., McLean, J. 1986. Humber River Pilot Watershed Project. Ontario Ministry of the Environment, Toronto, Canada. 483 p.

Pitt, R., Vorhees, J.G. 2003. [Chapter 4:] SLAMM: The source loading and management model. In: Field, R., Sullivan, D. 2003. Wet-weather flow in the urban watershed: Technology and management. CRC Press LLC. p. 79-102. ISBN 1-56676-916-7.

Puustinen, M., Tattari, S., Koskiaho, J. Linjama, J. 2007. Influence of seasonal and annual hydrological variations on erosion and phosphorus transport from arable areas in Finland. Soil & Tillage Research 93: 44-55.

Rabuñal, J.R., Puertas, J., Suáres, J., Rivero, D. 2007. Determination of the unit hydrograph of a typical urban basin using genetic programming and artificial neural networks. Hydrological Processes, 21: 476-485.

Radojković, M., Maksimović, Č. 1986. UDM Data Base – Guidelines for application and first results. In: Maksimović, Č., Radojković, M. (Eds.) Urban drainage modelling. Proc. International symposium on comparison of urban drainage models with real catchment data, Dubrovnik, Yugoslavia. Pergamon Press. p. 27-42. ISBN 0-08-032558-0.

Rao, R.A., Delleur, J.W. 1974. Instantaneous unit hydrographs, peak discharges and time lags in urban basins. Hydrological Sciences Bulletin, 19(2): 185-198.

Reinosdotter, K. 2007. Sustainable snow handling. Doctoral thesis, Division of Architecture and Infrastructure, Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, Sweden.

Reinosdotter, K., Viklander, M. 2005. A comparison of snow quality in two Swedish municipalities – Luleå and Sundsvall. Water Air and Soil Pollution, 167: 3-16.

Reinosdotter, K., Viklander, M. 2006. Handling of urban snow with regard to snow quality. Journal of Environmental Engineering, 132(2): 271-278.

RIL, 2004. Water Supply and Sewerage II (in Finnish). Association of Finnish Civil Engineers RIL, Helsinki. 688 p. ISBN 951-758-438-5.

Ristimäki, M., Oinonen, K., Pitkäranta, H., Harju, K. 2003. Population changes in urban regions and urban growth (in Finnish, abtract in English). The Finnish Environment 657, Ministry of the Environment, Helsinki. ISBN 952-11-1532-7. 196 p.

Roberts, B.C. 2001. [Chapter 13:] Subsurface stormwater management systems. In: Mays, L.W. (Ed.), Stormwater collection systems design handbook. McGraw-Hill, New York. ISBN 0-07-135471-9. pp. 13.1-13.13.

Roesner, L. A. 1999. The hydrology of urban runoff quality management. In: Rowney, A. C., Stahre, P., Roesner, L.A. (Eds.) 1999. Sustaining water resources in the 21st century. ASCE, Reston, VA. p. 229-241.

Roesner, L.A., Bledsoe, B.P., Brashear, R.W. 2001. Are Best-Management-Practice criteria really environmentally friendly? Journal of Water Resources Planning and Management, 127: 150-154.

Roy, A.H., Wenger, S.J., Flecther, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D., Thurston, H.W., Brown, R.R. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. Environmental Management, 42: 344-359.

Ruth, O. 2004. Hydrogeography of urban streams: three examples of catchments in Helsinki (in Finnish, abstract in English). Doctoral thesis. Helsingin yliopiston maantieteen laitoksen julkaisuja B50. ISBN 952-10-2244-2. 139 p.

Said, A., Downing, H. 2010. Estimating connected impervious areas as function of rainfall depth. In: Proc. AWRA 2010 Spring Specialty Conference, March 29-31, 2010, Orlando, Florida, USA.

Sansalone, J.J., Buchberger, S.G. 1997. Characterization of solid and metal element distributions in urban highway stormwater. Water Science and Technology, 36(8-9): 155-160.

Sansalone, J.J., Glenn, D.W. 2002. Accretion of pollutants in snow exposed to urban traffic and winter storm maintenance activities. Journal of Environmental Engineering, 128(2): 151-166.

Samposalo, S. 2007. Properties of snow in urban areas (in Finnish, abstract in English). M.Sc. thesis, Department of Civil and Environmental Engineering, Helsinki University of Technology. 144 p.

Saxton, G., Siftar, K., Fowler, P. 1996. Quantifying the pollutant characteristics of snow versus snowmelt runoff in a reliable and economical manner at Eielson Air Force Base, Alaska. In: Proc. 69th WEF Annual Conference and Exposition, Dallas, Texas. pp. 137.

Schueler, T.R. 1994. The importance of imperviousness. Watershed Protection Techniques, 1(3): 100-111. In: Schueler, T.R. & Holland, H.K. (Eds.) 2000. The practice of watershed protection. Center for Watershed Protection. ISBN 0-9720052-0-X. pp. 7-18.

Schueler, T. R. 2000. Performance of sediment controls at Maryland construction sites. Watershed Protection Techniques, 1(3): 145-146. In: Schueler, T.R. & Holland, H.K. (Eds.) 2000. The practice of watershed protection. Center for Watershed Protection. ISBN 0-9720052-0-X. S. 345-347.

Schueler, T.R., Fraley-McNeal, L., Cappiella, K. 2009. Is impervious cover still important? Review of recent research. Journal of Hydrologic Engineering, 14(4): 309-315.

Semádeni-Davies, A. 1999a. Urban snowmelt processes: Modelling and observation. Doctoral thesis. Department of Water Resources Engineering, Lund Institute of Technology, Lund University, Sweden. 52 p.

Semádeni-Davies, A. 1999b. Snow heterogeneity in Luleå, Sweden. Urban Water 1: 39-47.

Semádeni-Davies, A. 2000. Representation of urban snow in urban drainage models. Journal of Hydrologic Engineering, 5(4): 363-370.

Semádeni-Davies, A., Bengtsson, L. 1998. Snowmelt sensitivity to radiation in the urban environment. Hydrological Sciences, 43(1): 67-89.

Semádeni-Davies, A., Bengtsson, L. 1999. The water balance of a sub-arctic town. Hydrological Processes, 13(12-13): 1871-1885.

Semádeni-Davies, A., Bengtsson, L. 2000. [Chapter 1:] Theoretical background. In: Sægrov, S., Milina, J., Thorolfsson, S. (Eds.) Urban drainage in specific climates, Vol. 2: Urban drainage in cold climates. Paris, UNESCO. IHP-VI, Technical documents in Hydrology, 40(2): 23-40.

Semádeni-Davies, A., Lundberg, A., Bengtsson, L. 2001. Radiation balance of urban snow: a water management perspective. Cold Regions Science and Technology, 33: 59-67.

Semádeni-Davies, A., Titus, D. 2003. Seasonal pollution flows in stormwater from an urban area. In: Proc. Northern Research Basins, 14th Int. Symposium and Workshop, Kangerlussuaq/Sdr. Strømfjord, Greenland. pp. 173-182.

SEPA, 2008. The water environment (controlled activities) (Scotland) Regulations 2005, A practical guide. Version 5, June 2008. SEPA, Scottish Environment Protection Agency.

Shaver, E., Horner, R., Skupien, J., May, C. & Ridley, G. 2007. Fundamentals of urban runoff management: Technical and institutional issues. 2nd ed., North American Lake Management Society, Madison, Wisconsin, USA. 327 p.

Sheeder, S.A., Ross, J.D., Carlson, T.N. 2002. Dual urban and rural hydrograph signals in three small watersheds. Journal of the American Water Resources Association, 38(4): 1027-1040).

Sheng, Y. 2004. Modelling event-based coupled hydrologic and mass transport in small urban watersheds. Doctoral thesis, Department of Civil and Environmental Engineering, Lousiana State University. 280 p.

Sherman, L.K. 1932. Streamflow from rainfall by unit-graph method. Engineering News Record, 108: 501-505.

Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E. Smith, D.R. 2005. Impacts of impervious surface on watershed hydrology: A review. Urban Water Journal, 2(4): 263-275.

Shuster, W., Fletcher, T.D., Deletic, A. 2008. [Chapter 17:] Stormwater. In: Fletcher, T.D., Deletic, A. (Eds.) Data requirements for integrated urban water management. Urban Water Series, Vol. 1. UNESCO. p. 225-241. ISBN 978-92-3-104059-7.

Sillanpää, N., Koivusalo, H. 2013. Catchment-scale evaluation of pollution potential of urban snow at two residential catchments in southern Finland. Water Science and Technology (in press).

Singh, S.K. 2005. Clark's and Espey's unit hydrographs vs the gamma unit hydrograph. Hydrological Sciences Journal, 50(6): 1053-1067.

Smullen, J.T., Cave, K.A. 2003. [Chapter 3:] National stormwater runoff pollution database. In: Field, R., Sullivan, D. (Eds.) Wet-weather flow in the urban watershed: Technology and management. CRC Press LLC. Boca raton, Florida, USA. p. 67-78. ISBN 1-56676-916-7.

Solantie, R. 1981. Lumipeitteen vesiarvon keskimaksimi Suomessa. Vesitalous, 5: 21-22.

Sonzogni, W.C., Chesters, G., Coote, D.R., Jeffs, D.N., Konrad, J.C., Ostry, R.C. & Robinson, J.B. 1980. Pollution from land runoff. Environmental Science & Technology, Vol. 14, No. 2. S. 148-153.

Soranno, P., Hubler, S., Carpenter, S., Lathrop, R. 1996. Phosphorus loads to surface waters: A simple model to account for spatial pattern of land use. Ecological Applications, 6(3): 865-878.

Stern, L.D. 2010. A visual approach to SPSS for Windows. 2nd Ed. Pearson Education Inc., Boston, USA. 420 p. ISBN 978-0-205-70605-1.

Stockholm Vatten. 2001. Klassificering av dagvatten och recipienter samt riktlinjer för reningskrav - del 2 (in Swedish). Available at: http://www.stockholmvatten.se/commondata/rapporter/avlopp/dagvatten/dagvattenklassificeringdel2.pdf

STS Sensors, 2013. Analog 4-20 mA depth/level transmitter ATM/N Fact Sheet. Available at: http://www.sts-sensors.com/us/LinkClick.aspx?link=ATM_N_4-20mA_10.00.0217.E.pdf&tabid=400&mid=896

Sutherland, R.C. 2000. Methods for estimating the effective impervious area of urban watersheds. In: Schueler, T.R., Holland, H.K. (Eds.) The practice of watershed protection. Center for Watershed Protection. pp. 193-195. ISBN 0-9720052-0-X.

Sänkiaho, L., Sillanpää, N. (eds.) 2012. Stormwater-project; Final Report (in Finnish, abstract in English). Aalto-yliopiston julkaisusarja TIEDE+TEKNOLOGIA 4/2012. 60 p. ISBN 978-952-60-4555-9.

Sänkiaho, L., Sillanpää, N., Setälä, H. 2011. Developing stormwater management through research and practice: experiences from a Finnish pilot programme. In: Proc. Cities of the Future: Sustainable Urban Planning and Water Management, 22-25 May 2011, Stockholm, Sweden.

Taylor, C.H. 1977. Seasonal variations in the impact of suburban development on runoff response: Peterborough, Ontario. Water Resources Research 13(2): 464-468.

Taylor, C.H. 1982. The effect on storm runoff response of seasonal variations in contributing zones in small watersheds. Nordic Hydrology, 13: 165-182.

Taylor, G.D., Fletcher, T.D., Wong, T.H.F., Breen, P.F., Duncan, H.P. 2005. Nitrogen composition in urban runoff – implications for stormwater management. Water Research, 39: 1982-1989.

Thorolfsson, S. 2000. [Chapter 5:] Specific problems in urban drainage in cold climate. In: Sægrov, S., Milina, J., Thorolfsson, S. (Eds.) Urban drainage in specific climates, Vol. 2: Urban drainage in cold climates. Paris, UNESCO. IHP-VI, Technical documents in Hydrology, No. 40, Vol. 2, pp. 119-147.

Thorolfsson, S.T., Brandt, J. 1996. The influence of snowmelt on urban runoff in Norway. In: Proc. 7th Int. Conf. Urban Storm Drainage, Hannover, Germany.

Toronto Water. 2006. Wet weather flow management guidelines. Toronto Water, Water Infrastructure Management, Toronto, Canada. 110 p.

Urbonas, B. et al. 1990. Optimization of stormwater quality capture volume. In: Urban stormwater quality enhancement – Source control, retrofitting and combined sewer technology. ASCE, New York.

U.S. EPA, Environmental Protection Agency. 1983. Results of the nationwide urban runoff program. Volume 1, Final Report. Water Planning Division, Washington, D.C.

U.S. EPA, Environmental Protection Agency. 2000. Storm Water Phase II Final Rule: Construction Site Runoff Control minimum control measure. EPA 833-F-00-008, January 2000, Fact Sheet 2.6.

Valeo, C., Ho, C.L.I. 2004. Modelling urban snowmelt runoff. Journal of Hydrology, 299: 237-251.

Valtanen, M., Sillanpää, N., Setälä, H. 2009. Stormwater research in Finland – seeking solutions through strategic research. In: Proc. 6th Int. Conf. Water Sensitive Urban Design, Perth, Australia. pp. 972-978.

Vakkilainen, P., Alakukku, L., Koskiaho, J., Myllys, M., Nurminen, J., Paasonen-Kivekäs, M., Peltomaa, R., Puustinen, M., Äijö, H. 2010. Pellon vesitalouden optimointi: Loppuraportti 2010 (in Finnish). Salaojituksen tutkimusyhdistys ry:n tiedote 30, Helsinki. ISBN 978-952-5345-23-0. 112 p.

Vakkilainen, P., Kotola, J., Nurminen, J. (Eds.) 2005. Urban waters and runoff water management practices in built environment (in Finnish, abstract in English). The Finnish Environment 776, Ministry of the Environment, Helsinki. p. 116. ISBN 951-731-319-5.

Van Buren, M.A., Watt, W.E., Marsalek, J. 1997. Application of the log-normal and normal distributions to stormwater quality parameters. Water Research, 31(1): 95-104.

Viklander, M. 1996. Urban snow deposits – pathways of pollutants. The Science of the Total Environment, 189/190: 379-384.

Viklander, M. 1997. Snow quality in urban areas. Doctoral thesis. Division of Sanitary Engineering, Department of Environmental Engineering, Luleå University of Technology.

Viklander, M. 1999. Substances in urban snow. A comparison of the contamination of snow in different parts of the city of Luleå, Sweden. Water, Air, and Soil Pollution, 114: 377-394.

Viklander, M., Malmqvist, P.-A. 1993. Melt water from snow deposits. In: Proc. 6th Conf. Urban Storm Drainage, Ontario, Canada. pp. 429-434.

Viklander, M., Malmqvist, P.-A. 1994. The composition of melt water from urban snow: A laboratory study. In: Proc. Polartech '94, Luleå, Sweden. pp. 285-295.

Vuorenmaa, J., Rekolainen, S., Lepistö, A., Kenttämies, K., Kauppila, P. 2002. Losses of nitrogen and phosphorus from agricultural and forest areas in Finland during the 1980s and 1990s. Environmental Monitoring and Assessment, 76: 213-248.

Wakida, F.T., Lerner, D.N. 2002. Nitrate leaching from construction sites to groundwater in the Nottingham, UK, urban area. Water Science and Technology, 45(9): 243-248.

Wakida, F.T., Lerner, D.N. 2005. Non-agricultural sources of groundwater nitrate: a review and case study. Water Research, 39: 3-16.

Walesh, S.G. 1989. Urban surface water management. John Wiley & Sons, New York. ISBN 0-471-83719-9.

Waller, D.H., Hart, W.C. 1986. Solids, nutrients, and chlorides in urban runoff. In: Torno, H. C., Marsalek, J. & Desbordes, M. (Eds.) Urban runoff pollution. NATO ASI Series, Vol. G10. Springer-Verlag Berlin Heidelberg. pp. 59-85.

Walling, D.E. 1974. Suspended sediment production and building activity in a small British basin. In: Effects of man on the interface of the hydrological cycle with the physical environment. IAHS Publication No. 113, pp. 117-122.

WEF-ASCE, Water Environment Federation and American Society of Civil Engineers. 1998. Urban runoff quality management. ISBN 1-57278-039-8 and 0-7844-0174-8.

Wenger, S.J., Roy, A.H., Jackson, C.R., Bernhardt, E.S., Carter, T.L., Filoso, S., Gibson, C.A., Hession, W.C., Kaushal, S.S., Martí, E., Meyer, J.D., Palmer, M.A., Paul, M.J., Purcell, A.H., Ramírez, A., Rosemond, A.D., Schofield, K.A., Sudduth, E.B., Walsh, C.J. 2009. Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. Journal of the North American Benthological Society, 28(4): 1080-1098.

Westerlund, C. 2007. Road runoff quality in cold climates. Doctoral thesis, Division of Architecture and Infrastructure, Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, Sweden.

Westerlund, C., Viklander, M. 2006. Particles and associated metals in road runoff during snowmelt and rainfall. Science of the Total Environment, 362: 143-156.

Westerlund, C., Viklander, M., Bäckström, M. 2003. Seasonal variations in road runoff quality in Luleå, Sweden. Water Science and Technology, 48(9): 93-101.

Westerström, G. 1984. Snowmelt runoff from Porsön residential area, Luleå, Sweden. In: Proc. 3rd Int. Conf. Urban Storm Drainage, Vol. 1, Analysis and design of stormwater systems. Pp. 315-324. ISBN 91-7032-128-0.

Westphal, J. 2001. [Chapter 4:] Hydrology for drainage system design and analysis. In: Mays, L.W. (Ed.), Stormwater collection systems design handbook. McGraw-Hill, New York. ISBN 0-07-135471-9. pp. 4.1-4.44.

Wollheim, W.M., Pellerin, B.A., Vörösmarty, C.J., Hopkinson, C.S. 2005. N retention in urbanizing headwater catchments. Ecosystems, 8: 871-884.

Wolman, M., Schick, A. 1967. Effects of construction on fluvial sediment, urban and suburban areas of Maryland. Water Resources Research, 3(2), 451-464.

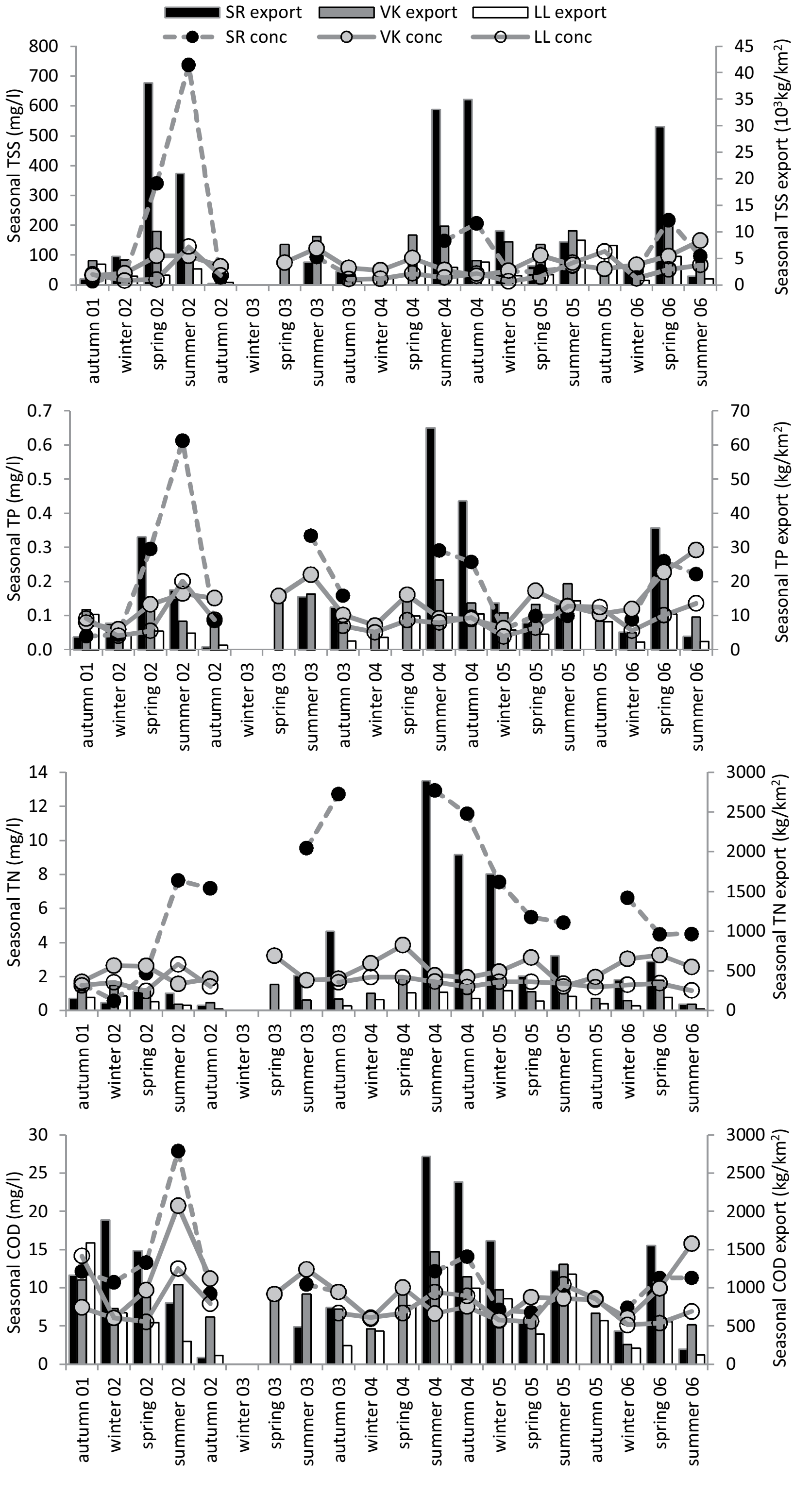
Wolman, M.G. 1975. Erosion in the urban environment. Hydrological Sciences Bulletin, 20: 117-125.

Yue, S., Wang, C.Y. 2002a. The influence of serial correlation on the Mann-Whitney test for detecting a shift in median. Advances in Water Resources, 25: 325-333.

Yue, S., Wang, C.Y. 2002b. Power of the Mann-Whitney test for detecting a shift in median or mean of hydro-meteorological data. Stochastic Environmental Research and Risk Assessment, 16: 307-323.

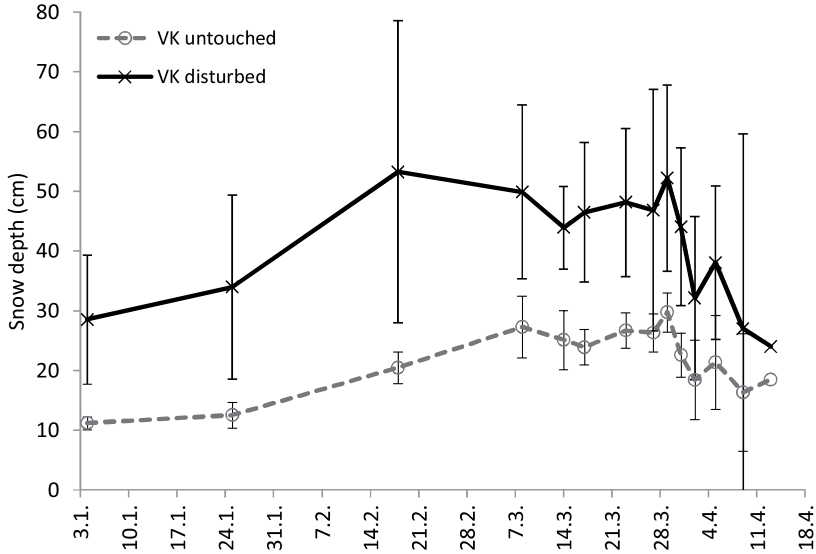
Zhou, F., Yong, L., Guo, H. 2007. Application of multivariate statistical methods to water quality assessment of the watercourses in Northwestern New Territories, Hong Kong. Environmental Monitoring and Assessment, 132: 1-13.

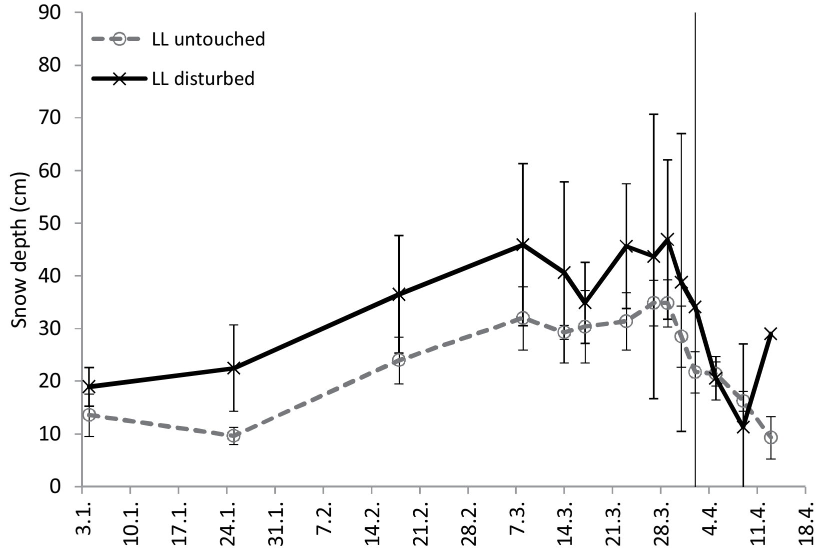
APPENDIX A. Seasonal concentrations and export rates.



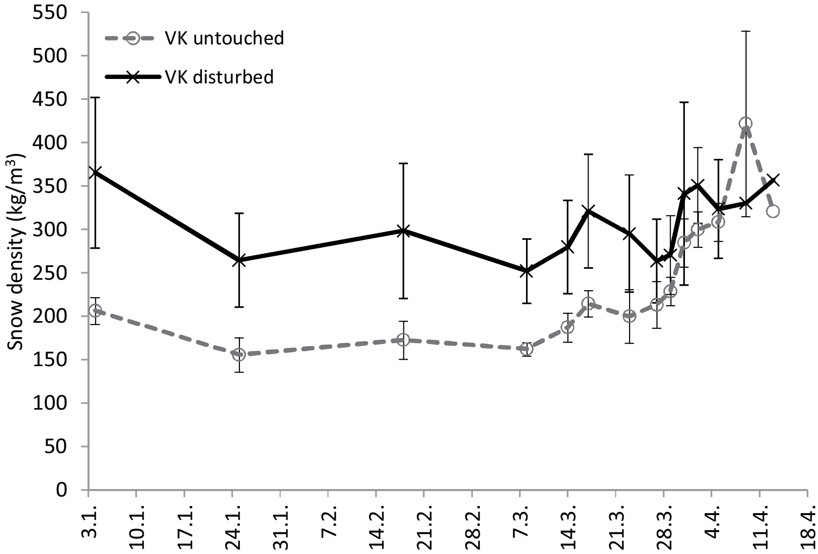
APPENDIX B. Survey-specific snow depths, densities and SWEs

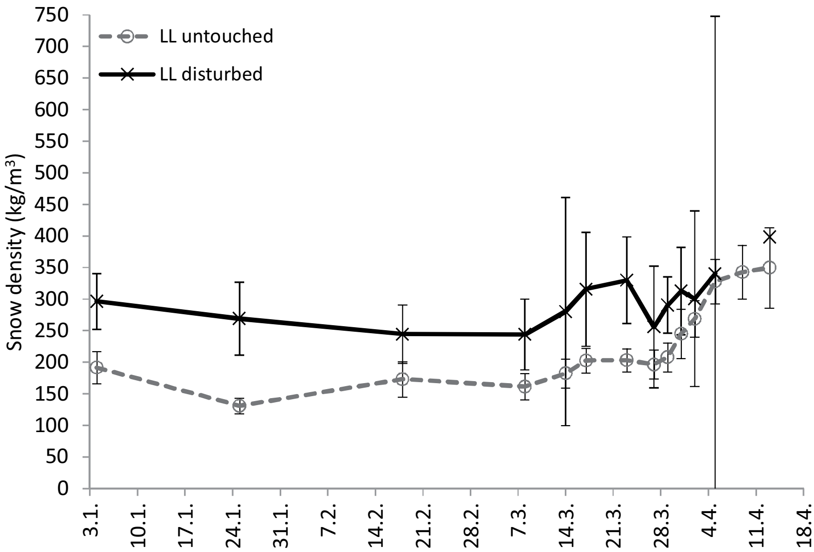
Average snow depths of untouched and disturbed snow with their 95% confidence intervals based on the Student's t distribution at the medium-density VK catchment and the low-density LL catchment.



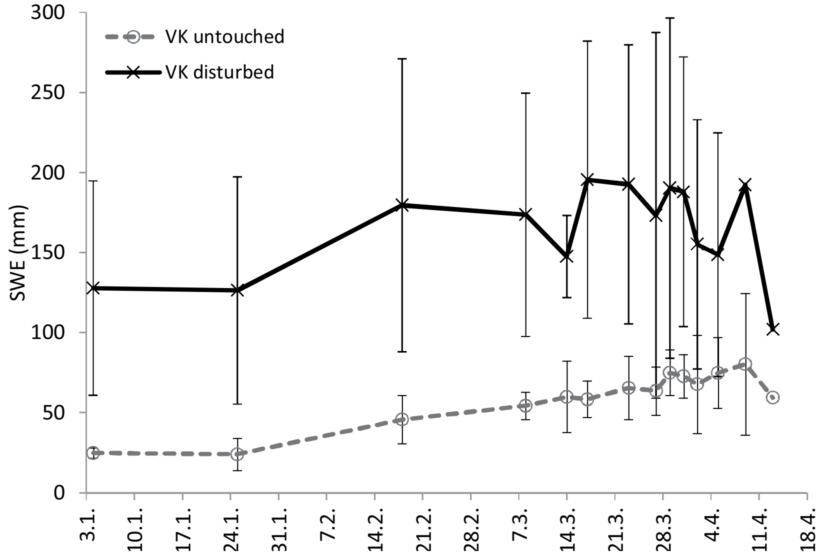


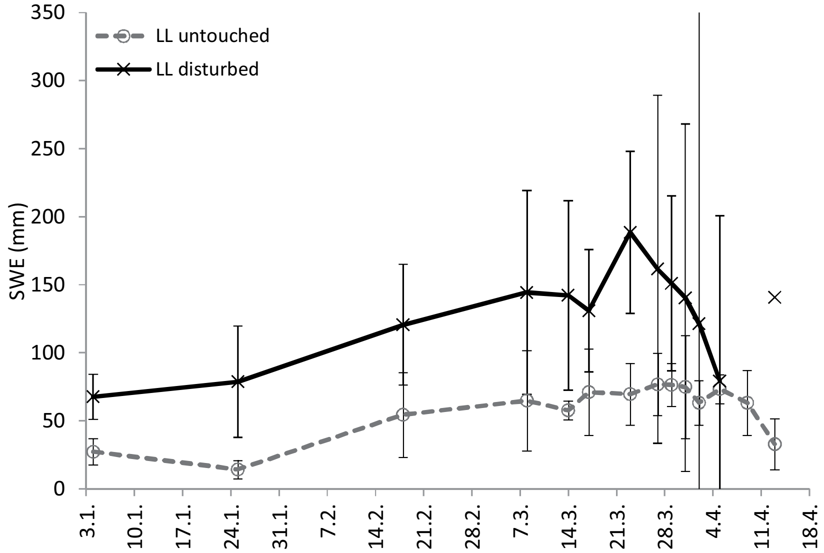
Average snow densities of untouched and disturbed snow with their 95% confidence intervals based on the Student's t distribution at the medium-density VK catchment and the low-density LL catchment.





Average SWEs of untouched and disturbed snow with their 95% confidence intervals based on the Student's t distribution at the medium-density VK catchment and the low-density LL catchment.





APPENDIX C. Summary characteristics of warm period rainfall events.

Events without noticeable direct runoff have been excluded, i.e. events with only 0.2 mm of rain and less than 0.01 mm of direct runoff. Descriptions of the variables are shown in Table 7.

	P_{TOT}	P_{MAX}	P_{DUR}	P_{MEAN}	R_{TOT}	R_{EFF}	Q_{MAX}	R_{DUR}	R_{MEAN}	C_{VOL}	DAYS	PREC1/3/5/7
	mm	mm/10 min	h	mm/h	mm (m^3)	mm	l/s	h	mm/h	-	d	mm
SR 2001-2003: 44 events												
Median	7.0	1.0	8.1	0.7	0.3 (35.7)	0.1	1.4	19.1	0.02	0.01	1.1	0.3/3.1/5.8/7.5
Mean	12.2	1.5	39.3	0.9	2.7 (275)	1.8	4.6	61.1	0.03	0.06	2.6	1.6/4.7/8.9/12.6
Min	1.0	0.4	0.3	0.1	0.03 (2.8)	0.01	0.2	1.7	0.002	0.01	0.1	0.0/0.0/0.0/0.0
Max	60.6	10.8	295.3	4.8	25.9 (2981)	17.2	78.7	336.9	0.14	0.43	23.6	16.3/18.7/39.8/60.9
COV	1.2	1.2	1.8	1.0	2.2	2.5	2.8	1.4	1.0	1.7	1.6	2.0/1.1/1.1/1.2
SR 2005-2006: 82 events												
Median	2.7	0.6	2.9	1.0	0.6 (80.6)	0.5	27.4	6.2	0.08	0.19	1.8	0.3/2.9/6.6/9.4
Mean	5.6	1.1	7.7	2.2	1.6 (207)	1.4	57.9	14.6	0.11	0.19	3.7	1.8/7.5/12.2/16.6
Min	0.4	0.2	0.1	0.2	0.03 (4.1)	0.01	1.0	1.2	0.01	0.02	0.1	0.0/0.0/0.0/0.0
Max	40.2	10.6	189.3	20.4	21.7 (2864)	18.8	268.9	208.5	0.72	0.47	25.2	15.8/40.3/54.8/57.2
COV	1.3	1.3	2.8	1.4	1.8	1.8	1.2	1.8	0.9	0.3	1.4	1.7/1.3/1.1/1.0
LL 2001-2006: 177 events												
Median	4.4	1.0	5.5	0.7	0.5 (145)	0.2	8.6	22.3	0.02	0.06	2.5	0.0/1.3/3.7/6.8
Mean	11.4	1.5	28.2	1.2	2.8 (855)	2.1	21.1	48.9	0.03	0.08	3.9	0.7/4.2/7.5/10.5
Min	0.4	0.2	0.2	0.1	0.01 (2.9)	0.01	0.3	1.8	0.003	0.00	0.1	0.0/0.0/0.0/0.0
Max	119.6	9.8	352.7	10.4	48.6 (15078)	45.5	181.2	446.0	0.17	0.41	26.7	13.6/43.3/66.7/67.8
COV	1.6	1.0	2.1	1.3	2.7	3.0	1.5	1.5	0.9	1.0	1.1	2.4/1.6/1.3/1.1
VK 2001-2006: 298 events												
Median	2.6	0.6	3.7	0.8	1.0 (125)	0.8	51.3	10.7	0.09	0.28	1.7	0.2/2.4/7.3/9.9
Mean	6.9	1.2	11.1	1.3	3.2 (420)	2.9	63.0	22.7	0.11	0.28	3.7	1.3/6.3/10.7/13.9
Min	0.4	0.2	0.1	0.1	0.01 (1.8)	0.01	0.3	1.1	0.003	0.02	0.0	0.0/0.0/0.0/0.0
Max	124.4	10.4	297.5	12.0	69.5 (9031)	65.0	363.7	319.5	0.57	0.68	28.7	14.7/39.2/93.1/105.2
COV	1.9	1.3	2.5	1.2	2.3	2.4	1.2	1.8	0.8	0.5	1.3	2.1/1.3/1.2/1.1

APPENDIX D. Summary characteristics of cold period runoff events.

A full winter season includes all separate runoff events from December to the end of spring snow melt in April. In LL and SR winter 02-03 and several mid-winter and spring events from the winter 03-04 have been excluded due to freezing problems. Descriptions of the variables are shown in Table 7.

	R_{TOT} mm (m^3)	R_{EFF} mm	Q_{MAX} l/s	R_{DUR} h	R_{MEAN} mm/h	DAYS d	R_{SUM}1/3/5/7 mm
SR 2001-2004: 24 events[1]							
Median	1.9 (220)	0.5	2.4	39.3	0.05	8.8	0.8/2.9/4.6/6.9
Mean	13.7 (1294)	10.0	6.7	108.8	0.08	9.2	0.9/3.5/5.2/8.1
Min	0.1 (15.7)	0.01	0.4	3.7	0.008	0.2	0.1/0.4/0.8/1.2
Max	98.5 (9044)	78.6	41.5	450.5	0.42	24.5	1.8/12.4/9.6/16.5
COV	1.9	2.2	1.5	1.2	1.1	0.8	0.4/0.7/0.5/0.5
SR 2004-2006: 40 events[2]							
Median	0.8 (111)	0.4	6.2	14.6	0.07	9.4	0.5/1.6/2.9/4.5
Mean	8.3 (1100)	6.3	16.3	59.3	0.09	22.9	0.9/3.1/6.0/9.5
Min	0.02 (2.7)	0.01	0.3	3.6	0.002	0.1	0.0/0.1/0.2/0.3
Max	76.9 (10157)	62.6	87.5	582.5	0.42	68.9	3.4/14.0/24.4/47.1
COV	2.1	2.2	1.3	1.9	1.0	1.1	1.1/1.2/1.2/1.3
LL 2001-2006: 64 events[3]							
Median	1.0 (307)	0.3	4.8	23.7	0.04	4.7	0.4/1.5/2.8/3.9
Mean	8.7 (2687)	6.6	14.6	101.7	0.05	14.7	0.6/2.0/3.6/5.8
Min	0.004 (1.2)	0.000	0.4	1.2	0.003	0.0	0.1/0.2/0.3/0.4
Max	80.8 (25050)	77.9	93.2	677.8	0.2	73.1	1.9/6.8/14.3/26.3
COV	2.0	2.3	1.4	1.5	0.8	1.4	0.8/0.8/0.8/0.9
VK 2001-2006: 111 events[4]							
Median	0.6 (82.5)	0.2	2.6	18.8	0.04	3.7	0.4/1.5/2.9/4.0
Mean	4.9 (640)	3.9	18.6	54.4	0.07	9.8	0.7/2.5/3.9/6.6
Min	0.01 (1.3)	0.001	0.2	1.7	0.003	0.0	0.0/0.1/0.2/0.3
Max	64.4 (8367)	51.9	117.3	526.8	0.5	63.6	5.2/17.9/20.4/28.4
COV	2.3	2.5	1.7	1.8	1.2	1.5	1.1/1.3/1.1/1.1

1) Full winter period 01-02 (10 events) including 14 events from the mid-winter 03-04.

2) Full winter periods 04-05 (18 events) and 05-06 (22 events).

3) Full winter periods 01-02 (21 events), 04-05 (9) and 05-06 (13) including some mid-winter and spring events from the winter 03-04 (21).

4) Full winter periods 01-02 (31 events), 02-03 (21), 03-04 (18), 04-05 (23), and 05-06 (18).

APPENDIX E. Pearson correlation matrices for the rainfall-runoff event characteristics.

Descriptions of the variables are shown in Table 7. Correlation coefficients are shown for log-transformed variables for events with at least 1 mm of rain.

SR Phase 1: 2001-2003 (73 events)

	R_{TOT}	R_{EFF}	Q_{MAX}	R_{MEAN}	R_{DUR}	P_{TOT}	P_{MAX}	P_{MEAN}	P_{DUR}	C_{VOL}	DAYS	PREC1	PREC3	PREC5	PREC7
R_{TOT}	1														
R_{EFF}	0.796***	1													
Q_{MAX}	0.849***	0.734***	1												
R_{MEAN}	0.678***	0.526***	0.808***	1											
R_{DUR}	0.900***	0.723***	0.636***	0.296*	1										
P_{TOT}	0.811***	0.728***	0.654***	0.301**	0.873***	1									
P_{MAX}	0.422***	0.497***	0.451***	0.063	0.511***	0.654***	1								
P_{MEAN}	-0.597***	-0.391***	-0.349**	-0.217	-0.660***	-0.406***	-0.014	1							
P_{DUR}	0.851***	0.685***	0.614***	0.313**	0.924***	0.871***	0.434***	-0.803***	1						
C_{VOL}	0.784***	0.969***	0.695***	0.543***	0.696***	0.665***	0.434***	-0.401***	0.649***	1					
DAYS	-0.378**	-0.193	-0.331**	-0.200	-0.370**	-0.302*	-0.241*	0.370**	-0.392***	-0.202	1				
PREC1	0.113	0.036	0.066	-0.056	0.164	0.178	0.162	-0.202	0.222	0.018	-0.728***	1			
PREC3	0.355**	0.250*	0.348**	0.252*	0.295*	0.302*	0.182	-0.268*	0.336**	0.262*	-0.770***	0.620***	1		
PREC5	0.316**	0.250*	0.391**	0.287*	0.241*	0.229	0.090	-0.309**	0.312**	0.220	-0.718***	0.520***	0.826***	1	
PREC7	0.259*	0.192	0.338**	0.240*	0.192	0.199	0.100	-0.322**	0.300*	0.165	-0.648***	0.468***	0.717***	0.888***	1

SR Phase 3: 2005-2006 (62-64 events)

	R_{TOT}	R_{EFF}	Q_{MAX}	R_{MEAN}	R_{DUR}	P_{TOT}	P_{MAX}	P_{MEAN}	P_{DUR}	C_{VOL}	DAYS	PREC1	PREC3	PREC5	PREC7
R_{TOT}	1														
R_{EFF}	0.996***	1													
Q_{MAX}	0.668***	0.703***	1												
R_{MEAN}	0.436***	0.467***	0.650***	1											
R_{DUR}	0.825***	0.801***	0.326*	-0.149	1										
P_{TOT}	0.986***	0.988***	0.644***	0.445***	0.804***	1									
P_{MAX}	0.679***	0.704***	0.915***	0.611***	0.363**	0.678***	1								
P_{MEAN}	-0.027	0.002	0.387**	0.557***	-0.379**	-0.029	0.321**	1							
P_{DUR}	0.728***	0.709***	0.202	-0.056	0.834***	0.738***	0.270*	-0.695***	1						
C_{VOL}	0.698***	0.715***	0.727***	0.406**	0.512***	0.596***	0.581***	0.139	0.335**	1					
DAYS	-0.165	-0.140	-0.043	-0.098	-0.119	-0.109	-0.116	0.059	-0.119	-0.237	1				
PREC1	0.088	0.071	-0.037	0.034	0.076	0.046	0.004	-0.196	0.166	0.160	-0.789***	1			
PREC3	0.066	0.044	0.079	0.199	-0.053	0.009	0.156	0.077	-0.046	0.187	-0.758***	0.550***	1		
PREC5	-0.001	-0.021	0.060	0.177	-0.112	-0.051	0.134	0.139	-0.131	0.119	-0.733***	0.486***	0.885***	1	
PREC7	0.036	0.013	0.061	0.159	-0.061	-0.009	0.161	0.113	-0.083	0.109	-0.707***	0.430***	0.813***	0.926***	1

LL 2001-2006 (154-161 events)

	R_{TOT}	R_{EFF}	Q_{MAX}	R_{MEAN}	R_{DUR}	P_{TOT}	P_{MAX}	P_{MEAN}	P_{DUR}	C_{VOL}	DAYS	PREC1	PREC3	PREC5	PREC7
R_{TOT}	1														
R_{EFF}	0.981***	1													
Q_{MAX}	0.900***	0.937***	1												
R_{MEAN}	0.856***	0.812***	0.806***	1											
R_{DUR}	0.926***	0.928***	0.806***	0.596***	1										
P_{TOT}	0.915***	0.957***	0.895***	0.703***	0.905***	1									
P_{MAX}	0.537***	0.620***	0.758***	0.422***	0.525***	0.663***	1								
P_{MEAN}	-0.366***	-0.304***	-0.118	-0.190*	-0.430***	-0.265**	0.183*	1							
P_{DUR}	0.842***	0.837***	0.691***	0.597***	0.870***	0.846***	0.362***	-0.739***	1						
C_{VOL}	0.940***	0.926***	0.870***	0.848***	0.838***	0.776***	0.484***	-0.315***	0.717***	1					
DAYS	-0.304***	-0.291***	-0.321***	-0.390***	-0.187*	-0.239**	-0.245**	0.033	-0.185*	-0.320***	1				
PREC1	0.143	0.137	0.168*	0.252***	0.038	0.115	0.135	0.052	0.051	0.148	-0.627***	1			
PREC3	0.250**	0.246**	0.222**	0.326***	0.150	0.213**	0.185*	-0.033	0.166*	0.257**	-0.705***	0.391***	1		
PREC5	0.285***	0.270**	0.265**	0.304***	0.219**	0.214**	0.205*	-0.099	0.205*	0.306***	-0.665***	0.254**	0.803***	1	
PREC7	0.282***	0.278***	0.280***	0.305***	0.214**	0.224**	0.215**	-0.059	0.189*	0.311***	-0.671***	0.238**	0.704***	0.879***	1

VK 2001-2006 (227-233 events)

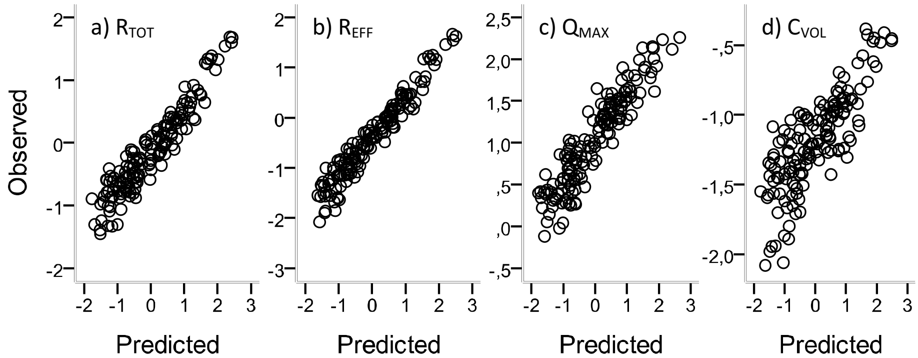
	R_{TOT}	R_{EFF}	Q_{MAX}	R_{MEAN}	R_{DUR}	P_{TOT}	P_{MAX}	P_{MEAN}	P_{DUR}	C_{VOL}	DAYS	PREC1	PREC3	PREC5	PREC7
R_{TOT}	1														
R_{EFF}	0.993***	1													
Q_{MAX}	0.727***	0.759***	1												
R_{MEAN}	0.678***	0.695***	0.652***	1											
R_{DUR}	0.858***	0.836***	0.506***	0.206**	1										
P_{TOT}	0.968***	0.971***	0.676***	0.601***	0.867***	1									
P_{MAX}	0.636***	0.662***	0.855***	0.429***	0.535***	0.662***	1								
P_{MEAN}	-0.031	0.005	0.318***	0.262***	-0.230***	-0.046	0.296***	1							
P_{DUR}	0.766***	0.747***	0.331***	0.307***	0.808***	0.800***	0.333***	-0.636***	1						
C_{VOL}	0.791***	0.805***	0.762***	0.742***	0.536***	0.640***	0.484***	0.130*	0.416***	1					
DAYS	-0.116	-0.086	-0.127	-0.207**	-0.008	-0.034	-0.060	0.057	-0.061	-0.195**	1				
PREC1	0.098	0.085	0.098	0.194**	-0.006	0.046	0.034	-0.118	0.107	0.159*	-0.658***	1			
PREC3	0.118	0.091	0.100	0.215**	0.002	0.062	0.061	-0.041	0.073	0.140*	-0.712***	0.477***	1		
PREC5	0.136*	0.107	0.084	0.178**	0.054	0.093	0.082	-0.061	0.109	0.114	-0.665***	0.392***	0.861***	1	
PREC7	0.190**	0.159*	0.107	0.214**	0.101	0.141*	0.111	-0.058	0.144*	0.164*	-0.620***	0.343***	0.777***	0.917***	1

*** $p<0.001$, ** $p<0.01$, * $p<0.05$, ($p>0.05$ is not significant statistically

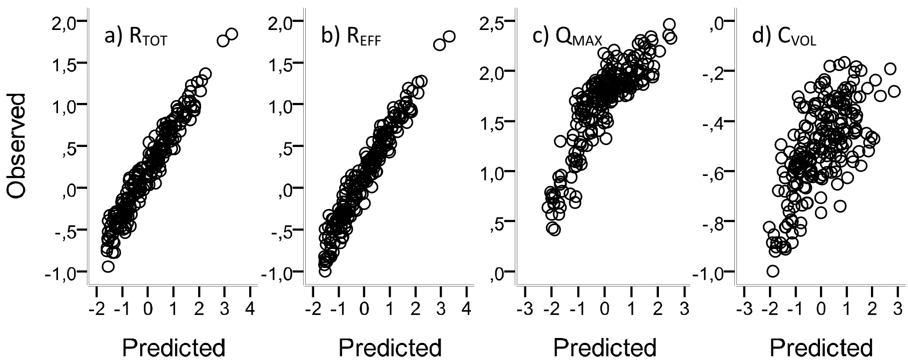
APPENDIX F. Observed versus predicted scatter plots for the runoff MLR models

Scatter plots (observed vs. predicted values) for the best MLR models presented in Section 5.1.5 for each catchment: the dependent variables are the total event runoff depth (R_{TOT}), the event direct runoff (R_{EFF}), the peak flow (Q_{MAX}), and the volumetric runoff coefficient (C_{VOL}). The chosen models have the highest R^2 values in Tables 32-38. For the developing SR catchment, separate plots for the years 2001-2003 and 2005-2006 are shown. The combined models include the data for the low-density LL catchment, the medium-density VK catchment and the developing SR catchment during the years 2005-2006.

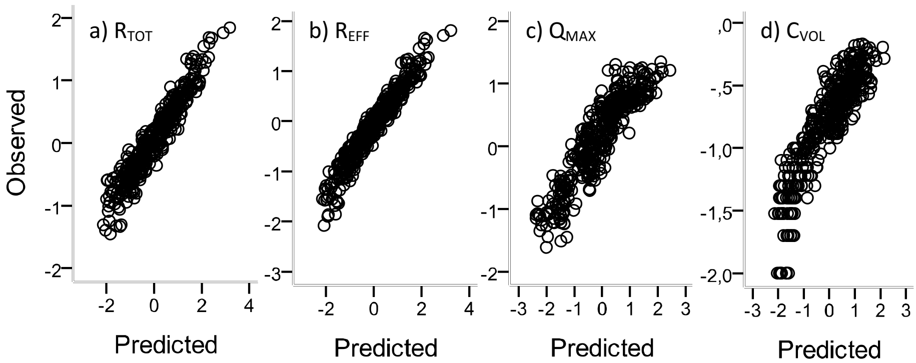
THE LOW-DENSITY LL CATCHMENT



THE MEDIUM-DENSITY VK CATCHMENT

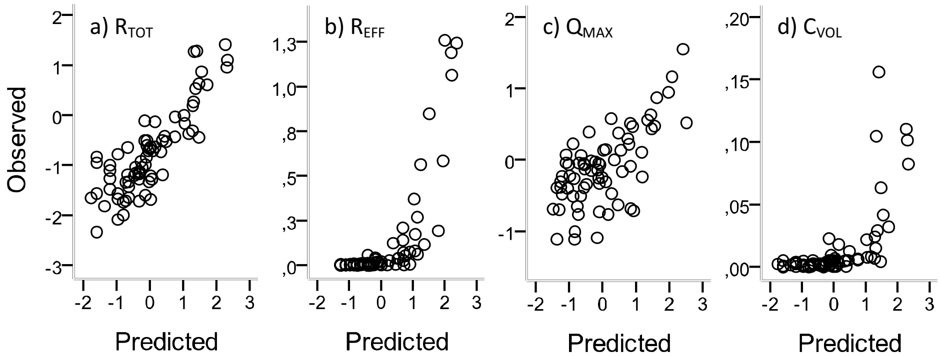


THE COMBINED MODELS

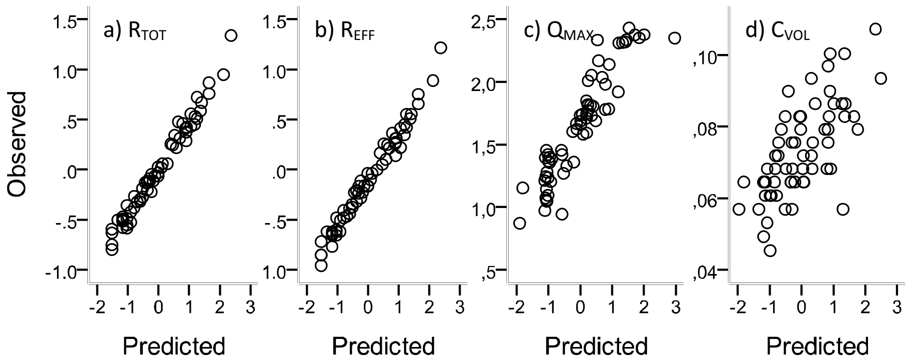


THE DEVELOPING SR CATCHMENT

The years 2001-2003



The years 2005-2006



APPENDIX G. Warm period correlation matrices for EMCs and EMLs

Pearson correlation coefficients for event mass loads (EML) and event mean concentrations (EMC) for the warm period runoff events in the developing SR catchment during the years 2001-2003 (8-9 events) and 2004-2006 (48-57 events). Descriptions of all variables are shown in Table 7.

*** p<0.001, ** p<0.01, * p<0.05, (p>0.05 is not significant statistically)

SR 2001-2003 (all variables log-transformed)

	COD		TN		TP		TSS	
	EML	EMC	EML	EMC	EML	EMC	EML	EMC
R_{TOT}	0.985***	0.065	0.885**	-0.447	0.644	-0.560	0.826**	0.209
R_{EFF}	0,973***	0.076	0.870**	-0.447	0.596	-0.600	0.788*	0.156
Q_{MAX}	0.872**	0.317	0.944***	0.059	0.867**	-0.089	0.916***	0.585
R_{MEAN}	0.837**	0.117	0.730*	-0.401	0.656	-0.331	0.708*	0.204
R_{DUR}	0,931***	0.027	0.846**	-0.410	0.547	-0.607	0,775*	0.182
P_{TOT}	0,905**	0.236	0.838**	-0.269	0.554	-0.513	0.753*	0.228
P_{MAX}	0.820*	0.546	0.824**	0.008	0.773*	-0.081	0.872**	0.623
P_{MEAN}	-0.388	0.565	-0.342	0.409	-0.071	0.559	-0.265	0.152
P_{DUR}	0.818*	-0.172	0.752*	-0.418	0.405	-0,666*	0.651	0.061
C_{VOL}	0.941***	-0.045	0.810**	-0.532	0.569	-0.604	0.739*	0.091
DAYS	-0.683	-0.296	-0.405	0.639	-0.137	0.687	-0.495	0.079
PREC1	0.192	0.422	0.038	-0.285	-0.322	-0.477	-0.004	-0.273
PREC3	0.578	0.255	0.250	-0.747	-0.161	-0.833*	0.213	-0.493
PREC5	0.759	0.255	0.714	-0.254	0.432	-0.552	0.712	0.194
PREC7	0.763	0.234	0.616	-0.293	0.331	-0.554	0.635	0.153
EML	1	0.223	1	0.018	1	0.272	1	0.723*
EMC	0.223	1	0.018	1	0.272	1	0.723*	1

SR 2004-2006 (all variables log-transformed)

	COD		TN		TP		TSS	
	EML	EMC	EML	EMC	EML	EMC	EML	EMC
R_{TOT}	0.896***	-0.291*	0.886***	0.296*	0.767***	-0.107	0.723***	-0.105
R_{EFF}	0.890***	-0.275*	0.827***	0.196	0.759***	-0.103	0.753***	-0.045
Q_{MAX}	0.556***	0.054	0.347**	-0.072	0.561***	0.202	0.673***	0.401**
R_{MEAN}	0.355**	-0.046	0.194	-0.159	0.344**	0.060	0.566***	0.305*
R_{DUR}	0.768***	-0.286*	0.841***	0.398**	0.637***	-0.146	0.512***	-0.277
P_{TOT}	0.768***	-0.288*	0.824***	0.22	0.755***	-0.083	0.686***	-0.120
P_{MAX}	0.646***	0.017	0.545***	0.176	0.659***	0.219	0.685***	0.272
P_{MEAN}	-0.179	0.128	-0.211	-0.082	-0.004	0.293*	-0.058	0.186
P_{DUR}	0.643***	-0.260	0.641***	0.188	0.463***	-0.243	0.487***	-0.196
C_{VOL}	0.624***	-0.132	0.520***	0.055	0.480***	-0.118	0.655***	0.172
DAYS	-0.155	0.270*	-0.273*	-0.161	-0.183	0.061	-0.170	0.002
PREC1	0.012	-0.176	0.043	-0.042	0.064	-0.012	0.058	0.081
PREC3	0.058	-0.294*	0.214	0.167	0.053	-0.155	0.125	-0.017
PREC5	0.012	-0.316*	0.182	0.154	0.056	-0.104	0.074	-0.046
PREC7	0.072	-0.386**	0.279*	0.222	0.094	-0.160	0.065	-0.185
EML	1	0.163	1	0.705***	1	0.555***	1	0.610***
EMC	0.163	1	0.705***	1	0.555***	1	0.610***	1

Pearson correlation coefficients for event mass loads (EML) and event mean concentrations (EMC) for the warm period runoff events at the low-density LL catchment (81-83 events) and the medium-density VK catchment (151-153). Descriptions of all variables are shown in Table 7.

*** p<0.001, ** p<0.01, * p<0.05, (p>0.05 is not significant statistically)

LL 2001-2006 (all variables log-transformed)

	COD		TN		TP		TSS	
	EML	EMC	EML	EMC	EML	EMC	EML	EMC
R_{TOT}	0.968***	0.102	0.981***	0.213	0.936***	-0.053	0.868***	0.052
R_{EFF}	0.966***	0.138	0.971***	0.216	0.957***	0.037	0.890***	0.116
Q_{MAX}	0.861***	0.234*	0.845***	0.232*	0.932***	0.338**	0.926***	0.413***
R_{MEAN}	0.818***	0.087	0.822***	0.147	0.791***	-0.042	0.773***	0.124
R_{DUR}	0.884***	0.092	0.902***	0.221*	0.854***	-0.050	0.764***	-0.012
P_{TOT}	0.884***	0.092	0.902***	0.221*	0.854***	-0.050	0.764***	-0.012
P_{MAX}	0.519***	0.458***	0.474***	0.370***	0.634***	0.638***	0.728***	0.723***
P_{MEAN}	-0.333**	0.129	-0.349**	0.067	-0.248*	0.346**	-0.092	0.369***
P_{DUR}	0.821***	0.086	0.830***	0.165	0.775***	-0.099	0.659***	-0.091
C_{VOL}	0.875***	-0.031	0.891***	0.057	0.848***	-0.129	0.789***	0.000
DAYS	-0.187	0.144	-0.195	0.147	-0.168	0.168	-0.174	0.031
PREC1	0.046	-0.106	0.043	-0.154	0.012	-0.180	0.026	-0.053
PREC3	0.161	-0.004	0.164	0.011	0.128	-0.103	0.137	-0.014
PREC5	0.199	-0.079	0.217	-0.005	0.188	-0.097	0.201	0.000
PREC7	0.157	-0.123	0.167	-0.110	0.162	-0.083	0.135	-0.010
EML	1	0.349**	1	0.397***	1	0.303**	1	0.541***
EMC	0.349**	1	0.397***	1	0.303**	1	0.541***	1

VK 2001-2006 (all variables log-transformed)

	COD		TN		TP		TSS	
	EML	EMC	EML	EMC	EML	EMC	EML	EMC
R_{TOT}	0.814***	-0.449***	0.877***	-0.401***	0.761***	-0.297***	0.656***	-0.203*
R_{EFF}	0.829***	-0.415***	0.872***	-0.399***	0.782***	-0.258**	0.680***	-0.166*
Q_{MAX}	0.725***	0.087	0.629***	-0.053	0.752***	0.251**	0.792***	0.389***
R_{MEAN}	0.415***	-0.257**	0.392***	-0.345***	0.433***	-0.108	0.405***	-0.032
R_{DUR}	0.705***	-0.371***	0.794***	-0.261**	0.632***	-0.283***	0.530***	-0.220**
P_{TOT}	0.705***	-0.371***	0.794***	-0.261**	0.632***	-0.283***	0.530***	-0.220*
P_{MAX}	0.600***	0.064	0.520***	-0.055	0.621***	0.199*	0.689***	0.362**
P_{MEAN}	0.061	0.255**	-0.091	0.023	0.106	0.290***	0.193*	0.357***
P_{DUR}	0.532***	-0.471***	0.661***	-0.311***	0.474***	-0.377***	0.349***	-0.352***
C_{VOL}	0.603***	-0.194*	0.612***	-0.202*	0.562***	-0.107	0.504***	-0.047
DAYS	0.178*	0.395***	0.123	0.388***	0.119	0.274***	0.064	0.160
PREC1	-0.171*	-0.205*	-0.204*	-0.323***	-0.185*	-0.222**	-0.125	-0.127
PREC3	-0.215**	-0.434***	-0.153	-0.423***	-0.182*	-0.352***	-0.124	-0.224**
PREC5	-0.205*	-0.469***	-0.127	-0.434***	-0.186*	-0.399***	-0.115	-0.260**
PREC7	-0.157	-0.517***	-0.039	-0.414***	-0.157	-0.458***	-0.089	-0.304***
EML	1	0.154	1	0.088	1	0.394***	1	0.606***
EMC	0.154	1	0.088	1	0.394***	1	0.606***	1

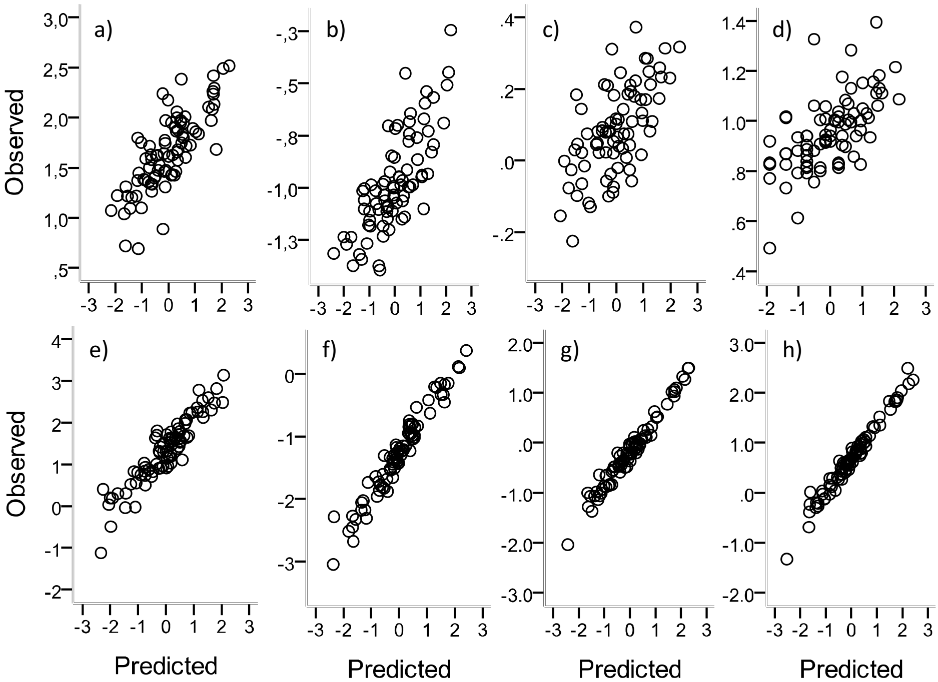
APPENDIX H. Observed versus predicted scatter plots for the water quality MLR models

Scatter plots (observed vs. predicted values) for the best MLR models presented in Section 5.1.8. For each catchment, the first row of scatter plots includes the EMC models and the second row the EML models:

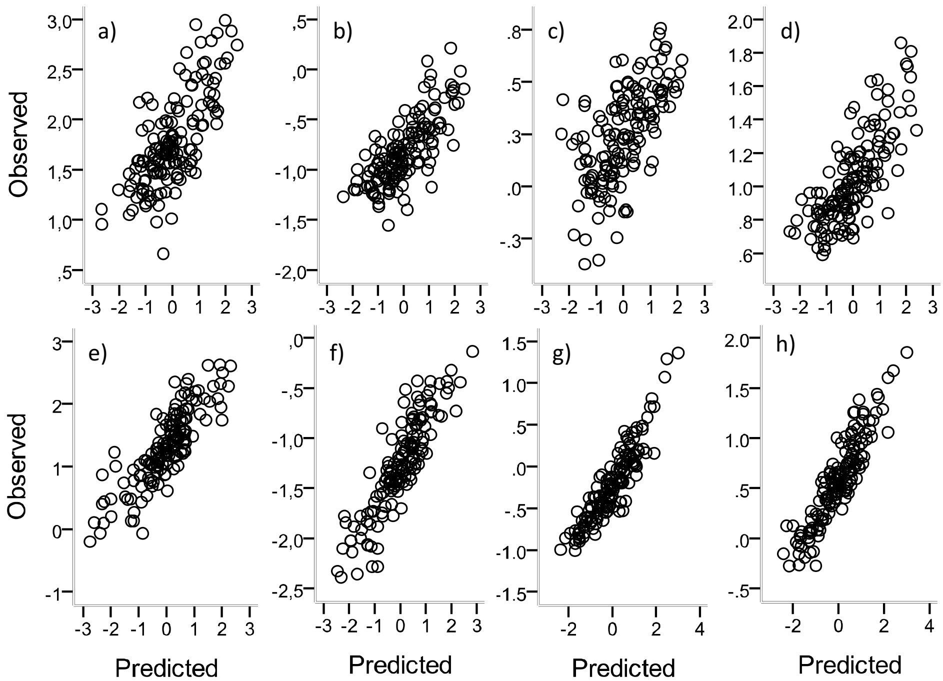
- a) TSS EMC, b) TP EMC, c) TN EMC, d) COD EMC,
- e) TSS EML, f) TP EML, g) TN EML, h) COD EML.

The chosen models have the highest R^2 values in Tables 42-44. For the developing catchment SR, a model for TN EMC could not be constructed.

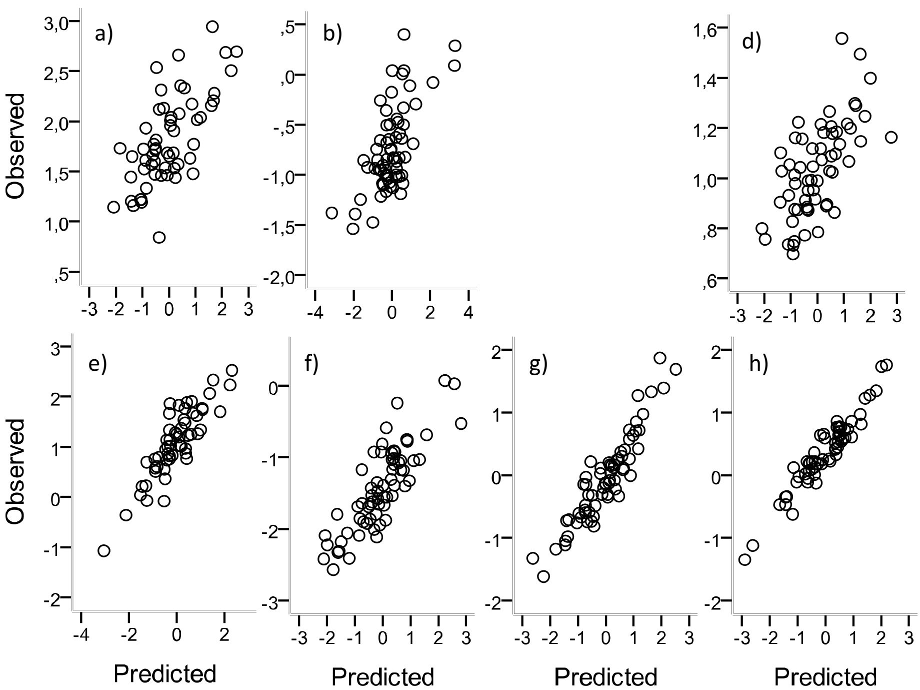
THE LOW-DENSITY LL CATCHMENT



THE MEDIUM-DENSITY VK CATCHMENT



THE DEVELOPING SR CATCHMENT



Aalto-DD 160/2013

ISBN 978-952-60-5373-8
ISBN 978-952-60-5374-5 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934
ISSN 1799-4942 (pdf)

Aalto University
School of Engineering
Department of Civil and Environmental Engineering
www.aalto.fi

BUSINESS +
ECONOMY

ART +
DESIGN +
ARCHITECTURE

SCIENCE +
TECHNOLOGY

CROSSOVER

DOCTORAL
DISSERTATIONS